ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

A SEMI-AUTOMATIC FAÇADE GENERATION METHODOLOGY OF ARCHITECTURAL HERITAGE FROM LASER POINT CLOUDS: A CASE STUDY ON ARCHITECT SINAN

Ph.D. THESIS

Cemal Özgür KIVILCIM

Department of Geomatics Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

LAZER NOKTA BULUTLARINDAN MİMARİ MİRASIN CEPHE ELEMANLARININ YARI OTOMATİK MODELLENMESİ: MİMAR SİNAN ÜZERİNE ÖRNEK BİR ÇALIŞMA

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Cemal Özgür KIVILCIM, a Ph.D. student of ITU Graduate School student ID 501092604, successfully defended the dissertation entitled "A SEMI-AUTOMATIC FAÇADE GENERATION METHODOLOGY OF ARCHITECTURAL HERITAGE FROM LASER POINT CLOUDS: A CASE STUDY ON ARCHITECT SINAN", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To Ada,

"Halk içinde mu'teber bir nesne yok devlet gibi
olmaya devlet cihân da bir nefes sıhhât gibi"
Kanuni Sultan Süleyman (1494-1566)

FOREWORD

Since the dawn of time, humanity has built structures to fulfill functional needs, such as defense, housing, or worshiping, but also to advance design, aesthetic and technical challenges, and, finally to mark their lagacy in a physical form. This Ph.D. thesis emerged from my interest in cultural heritage since childhood, and my curiosity to understand and contribute to preserving humanity's outstanding universal values for future generations. Following my MSc. thesis on geospatial data/information management for cultural heritage, I decided to pursue my Ph.D. with the intent to contribute to the documentation of cultural heritage work for historical-architectural restoration projects. I could not think of a better subject than mosques, particularly the work of architect Sinan, who made invaluable contributions to moque design beyond his time. The automatization of documentation and 3D modeling of cultural heritage topics has gained popularity in recent years, and this thesis is a result of my interest in adding to international research efforts on this subject.

I would like to present my sincere thanks to my advisor, Assoc. Prof. Dr. Zaide DURAN, on her result-oriented approach dedication, my thesis committee members' support and dedication, to Prof. Dr. Orhan ALTAN for gaining my topic an international scientific perspective and Prof. Dr. Devrim AKÇA for his valuable scientific discussions and insights through my study.

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TABLE OF CONTENTS

Page

ABBREVIATIONS

AEC	: Architecture Engineering and Construction
AI	: Artificial Intelligence
ALS	: Airborne Laser Scanning
BIM	: Building Information Modeling
BREP	: Boudary Representation
CAD	: Computer Aided Design
CGA	: Computer Generated Architecture
CH	: Cultural Heritage
CIPA	: International Committee of Architectural Photogrammetry
DL	: Deep Learning
DSM	: Digital Surface Model
DTM	: Digital Terrain Model
GIS	: Geographical Information System
HBIM	: Heritage Building Information Modeling
ICOMOS	: International Council on Monuments and Sites
IFC	: Industry Foundation Class
JSON	: JavaScript Object Notation
ML	: Machine Learning
NURBS	: Non-Uniform Rational Basis Spline
OpenGL	: Open Graphical Library
PCA	: Principal Component Analysis
Pops	: Point Cloud Operations Module
RANSAC	: Random Sample Consensus
TLS	: Terrestrial Laser Scanner
ToF	: Time of Flight (scanners)
UNESCO	: United Nations Educational, Scientific and Cultural Organization
VTK	: Visualization Tool Kit

LIST OF TABLES

LIST OF FIGURES

Page

A SEMI-AUTOMATIC FAÇADE GENERATION METHODOLOGY OF ARCHITECTURAL HERITAGE FROM LASER POINT CLOUDS: A CASE STUDY ON ARCHITECT SINAN

SUMMARY

Tangible cultural assets from different periods and civilizations reinforce historical and cultural memories that are passed from generation to generation. However, due to natural events, lack of proper maintenance, or wars, the heritage structures can be damaged or destroyed over time. To preserve tangible cultural assets for the future, it is crucial to ensure that these buildings' maintenance, repair, and restoration are of high quality. Hence, the preliminary phase in any architectural heritage project is to obtain metric measurements and documentation of the building and its individual elements. In this direction, the acquired data and derived models are used for various purposes in the fields of engineering and architectural applications, digital modeling and reconstructions, virtual or augmented reality applications. However, conventional measurement techniques require tremendous resources and lengthy project completion time for architectural surveys and 3D model production. With technological advances, laser scanning systems became a preferred technology as a geospatial data acquisition technique in the heritage documentation process. Without any doubt, these systems provide many advantages over conventional measurement techniques since the data acquisition is carried out effectively and in a relatively short time.

On the other hand, obtaining final products from point clouds is generally time-consuming and requires data manipulation expertise. To achieve this, the operator, who has the knowledge about the structure, must interpret the point cloud, select the key points representing the underlying geometry and perform the vectorizing process over these points. In addition, point data contains systematic and random errors. The noisy point cloud data and ambiguities make this process tedious and prone to human error.

The purpose of this thesis is to reduce the user's manual work cycle burden in obtaining 3D models and products from point cloud data: A semi-automatic user-guided methodology with few interventions is developed to easily interpret the geometry of architectural elements and establish fundamental semantic relationships from complex, noisy point clouds.

First, the conventional workflow and methodologies in cultural heritage documentation were researched, and the bottlenecks of the current workflow were examined. Then, existing methodologies used in point cloud-based 3D digital building reconstruction were assessed. From this, semi-automatic methods are evaluated for a more suitable approach to 3D digital reconstruction of cultural heritage assets, which are more complex than modern buildings.

Recently, Building Information Modeling (BIM) process applications have gained momentum. BIM systems make many contributions to project management, from the

design to the operation of new modern buildings. Research on the applications for existing buildings in BIM has increased. Particularly, such applications and research in cultural heritage are gathered under the term of Heritage/Historic-Building Information Modeling (HBIM). In HBIM, dedicated architectural style libraries are generated, and geometric models are produced by associating the geometries of architectural elements with point clouds. Such applications generally come for Western architectural elements, in which construction techniques and geometrical relations of architectural rules and orders have been documented with sketches and drawings for centuries.

Detailed descriptions and fine sketches pertaining to the rules and style studies of Ottoman architecture are limited. Having been the capital of many civilizations, historic Istanbul is crowned with the many mosques of Architect Sinan, dating from the 16th century, the golden era of the Ottoman Empire. For his innovative structures, Architect Sinan is considered an architectural and engineering genius. Unfortunately, Sinan did not leave enough written or visual documentation of his works, and although many aspects of Sinan's works have been researched, few have worked on the geometry of the facade elements.

Previous architectural research examines the ratios and compares the general architectural elements of Sinan's works (comparing the dimensions and location of the elements). Building on this and our observations of Sinan's mosques, we designed an object-oriented library of parametric objects for selected architectural facade elements. In addition, some fundamental semantic relations of the prepared object library elements were introduced. A case study for procedural modeling was then carried out.

In the next stage, we evaluated that an algorithmic approach can be used to obtain parametric architectural elements from noisy point cloud data. We benefited from the Random Sample Consensus (RANSAC) algorithm, which has a wide range of applications in computer vision and robotics. The algorithm is based on the purpose of obtaining the parameters of a given mathematical model; it is a non-deterministic method based on selecting the required number of random data from the data set to create the model and measuring the extent to which the hypothesis produced is compatible with the entire data set by evaluating the model. The basics of this method work with a certain number of iterations and return outputs of the most suitable model parameters, the dataset that makes up the model, and the incompatible data. In addition, model-specific criteria and rules based on architectural knowledge were added to the developed methodology to reduce the number of iterations.

All algorithmic codes were produced in Python language. In addition, we used libraries such as NumPy and for arrays and mathematical operations. For visualization studies, the open graphics library (Open Graphics Library, OpenGL) was carried out using the Visualization Tool Kit (VTK) on the graphics application development interface. In addition, python modules of VTK C++ source libraries were compiled using CMake software and Microsoft Visual Studio.

As the application area of the study, one of the most important mosques of Istanbul Şehzade Mosque, which is Mimar Sinan's first selatin complex, was chosen. Point cloud data acquired with a terrestrial laser scanner for the documentation studies of the mosque was obtained for this study. Different case areas were determined from the point cloud datasets. Windows on the Qibla direction façade and the domes from the roof covering of the mosque were used, respectively. While making this choice, we considered the variety of window elements and Sinan's use of the dome influenced.

In the case applications, the point cloud selected from the window areas was segmented semi-automatically using proposed method recursively at different window levels from the inside to the outside. In the other case study, the algorithm performed the segmentation of the main dome. As a result of this segmentation, point groups that are not included in the model are evaluated once more time using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm from Python's scikit-learn and presented to the user as a guiding output in the determination of architectural elements and deformations.

Using the above-mentioned Sinan architectural dome typology relations with the main dome of the mosque, it was ensured that point clusters were formed in the modeling of other dome structures in the mosque. Finally, as an example, the parametric dome model was converted to Industry Foundation Class (IFC) format using open source CAD software.

Integrity and accuracy comparisons were made using the outputs of the presented methodology and the CAD drawings produced by the restoration architects using the same data. The results were within acceptable limits for general-scale studies. Additionally, the presented method contributed to the interpretation of the data by saving time for expert users.

In summary, a method has been developed for the semi-automatic extraction of architectural parametric models working directly on the 3D point cloud, specific to the Ottoman Classical Era Mosque, particularly Architect Sinan's works, using a data and model-oriented hybrid 3D building reconstruction approach.

LAZER NOKTA BULUTLARINDAN MİMARİ MİRASIN CEPHE ELEMANLARININ YARI OTOMATİK MODELLENMESİ: MİMAR SİNAN ÜZERİNE ÖRNEK BİR ÇALIŞMA

ÖZET

Farklı çağ ve uygarlıklara ait taşınmaz kültür varlıkları inşaa edildikleri dönemlerin beşeri hafızasının nesiller boyunca aktarımında önemli görevler üstlenir. Doğa olayları, yetersiz bakım veya savaşlar gibi nedenler ile eserler zaman içerisinde yıpranarak tahrip olmakta veya tamemen yok olabilmektedir. Bu nedenle, günümüze kadar süregelen eserlerin yaşatılması, bakım ve onarımlarının gerçekleştirilmesi için nesnel belgelendirme çalışmalarına ihtiyaç duyulmaktadır. Bu doğrultuda eserlerin dijital kopya ve modelleri, mühendislik ve mimarlık uygulamaları, dijital modelleme ve rekonstrüsiyonlar, sanal veya arttırılmış gerçeklik uygulamaları gibi birçok alanda farklı amaçlarla kullanılmaktadır. Lazer tarayıcı sistemler, ölçme çalışmalarının etkin ve saha çalışmalarının kısa sürede gerçekleştirilmesinden dolayı yukarıda belirtilen amaçlarla yürütülen jeomekansal veri üretimi ve değerlendirme çalışmalarında sıklıkla tercih edilen bir teknolojidir. Öte yandan veri üretimi çalışmaları sonucu elde edilen nokta bulutlarından nihai ürünlerin elde edilmesi, uzun çalışma süreleri gerektirebilmektedir. Eser hakkında bilgisi olan uzman operatör noktalar kümesini yorumlayarak altında yatan geometriyi temsil eden noktaları seçmeli ve bu noktalar üzeriden çizim işlemini gerçekleştirmelidir. Bu işlemler oldukça meşakkatli ve insan hatasına açıktır. Ayrıca, nokta verileri sistematik ve rastgele hatalar da barındırmaktadır. Yürütülen bu tez çalışmasında nokta bulutu verilerinden 3D model ve ürünlerinin elde edilmesinde kullanıcıya bağlı manuel iş döngüsü yükünü azaltmak hedefiyle, mimari elemanların geometrisinin karmaşık nokta bulutu kümelerinden geliştirilen metodoloji ile kolay yorumlanması ve anlamsal ilişkilerinin kurulabilmesi için, kullanıcı rehberliğinde bir strateji uygulamak ve az müdahale ile otomasyonu arttırmak amaçlanmıştır.

Öncelikle kültürel mirasın belgelendirilmesinde takip edilen konvansiyonel iş akışı ve metodolojileri incelenmiş, bu çalışmalarda dikkat edilmesi gereken temel hususlar ve mevcut iş akışındaki darboğaz noktaları irdelenmiştir. Literatür taramasında nokta bulutu tabanlı 3D dijital bina rekonstrüksiyonunda kullanılan metodolojiler incelenmiştir. Modern binalara kıyasla daha karmaşık eserler olan kültür mirası varlıklarının 3D dijital rekonstrüksiyonunda yarı otomatik yöntemlerin daha uygun olduğu görülmüş ve araştırma çalışması bu doğrultuda ilerletilmiştir.

Ayrıca son yıllarda Yapı Bilgi Modelleme (Building Information Modeling, BIM) süreç çalışmaları hız kazanmıştır. Modern binaların tasarımından işletilmesine kadar olan sürecin proje yönetiminde birçok katkı sunan bu sistemin mevcut yapılarda uygulanması, taşınmaz kültür varlıklarının da bu sistemlere entegre edilmesi araştırma çalışmaları da ivme kazanmıştır. Eski eserlere yönelik gerçekleştirilen uygulamalar Miras-Yapı Bilgi Modelleri (Historic Building Information Modeling, H-BIM) başlığı altında toplanmaktadır. Bu yöntemde farklı mimari akım ve kültürlere ait mimari

kütüphaneler oluşturulmakta ve mimari elemanların geometrileri nokta bulutları ile ilişkilendirilerek temel modeller hazırlanmaktadır. Bu türden uygulamalar ağırlıkla mimari kural ve elemanlara ait, yapım teknikleri ve geometrik ilişkilerinin eskiz ve çizimlerle yüzyıllardır belgelendirildiği Batı mimarisi çalışmalarıdır. Buna karşılık, Osmanlı mimarisine ilişkin kurallar ve üslup çalışmaları hakkında ayrıntılı betimlemeler ve detaylı eskizler yeterli değildir. Farklı uygarlıklara başkentlik yapmış İstanbul, Osmanlı İmparatorluğu'nun altın dönemi olan 16.yy'da, bu topraklarda yetişmiş, mimari ve mühendislik dehası kabul edilen Mimar Sinan'ın camileri ile adeta süslenmiştir. Ancak, Sinan bu konuda yazılı ve görsel yeterli bilgi bırakmamıştır. Literatürde Sinan eserlerinin birçok farklı yönü araştırılmış olmasına rağmen, cephe elemanlarının geometrisine yönelik sınırlı araştırma yapıldığı görülmektedir. Bahsedilen bu nedenlerle, araştırmalarda Sinan'a ait eserler üzerinden çeşitli oran ve kıyaslara gidilerek inceleme ve kabuller yapılmıştır. Bu oranlar ve yapılan uygulamalara ek olarak yapıların genel tasarımında görülen diğer oran ve ilişkiler de ele alınarak, örnek mimari cephe elemanlarına yönelik parametrik objeler olarak hazırlanmış, nesne yönelimli bir obje kütüphanesi tasarlanmıştır. Ayrıca, Sinan'ın cami eserlerinde yer alan farklı uygulamalarının ortak belirleyici özellikleri de göz önüne alınarak, hazırlanan obje kütüphanesi elemanlarına ait bazı temel semantik ilişkiler de tanıtılmıştır. Böylece işleve dayalı (procedural) modellemeye yönelik altlık bir çalışma da gerçekleştirilmiştir.

Sonraki aşamada parametrik mimari elemanların nokta bulutu verilerinden elde edilmesinde kullanılan çeşitli algoritmlardan yararlanılabileceği değerlendirilmiş, bu doğrultuda bilgisayarlı görü ve robotik alanlarında geniş bir kullanım alanı bulunan Rastgele Örnek Uzlaşımı (Random Sample Consensus, RANSAC) algoritmasından yararlanılmıştır. Algoritma, temelinde matematiksel bir modelin parametrelerinin elde edilmesi amacıyla; veri kümesinden modeli oluşturmak için gereken sayıda rastgele verilerin seçilmesi ve üretilen hipotez modelin tüm veri kümesi ile değerlendirilerek ne oranda uyumlu olduğunun ölçülmesine dayanan deterministik olmayan bir yöntemdir. Belli bir sayıda yenileme ile çalışan metod en uygun model parametrelerini, modeli oluşturan veri kümesini ve uyuşumsuz veri kümesini çıktı olarak vermektedir. Ayrıca, iterasyon sayısını azaltmak üzere veri kümesinden seçilecek noktaların modele özel ön seçim kriterleri de geliştirilen metodolojiye eklenmiştir.

Hazırlanan tüm algoritma yardımcı programlar Python dilinde kodlanmış, dizi ve matematiksel işlemler gibi çalışmalarda numpy gibi temel kütüphanelerinden yararlanılmıştır. Görselleştirme çalışmaları için açık grafik kütüphanesi (Open Graphics Library, OpenGL), grafik uygulama geliştirme arabirimi üzerinde Visualisation Tool Kit (VTK), kullanılarak gerçekleştirilmiştir. VTK C++ kaynak kütüphaneleri CMake yazılımı ve Microsoft Visual Studio kullanılarak derlenen Python modülleri kullanılmıştır.

Çalışmanın uygulama alanı olarak İstanbul'un önemli camilerinden, Mimar Sinan'ın ilk selatin külliye eseri olan, Şehzade Camisi seçilmiştir. Caminin belgelendirme çalışmaları amacıyla yersel lazer tarayıcı ile elde edilmiş nokta bulutu verisi temin edilmiştir. Daha sonra nokta bulutu üzerinden farklı test alanları belirlenmiştir. Bunlar sırasıyla Kıble cephesi yönündeki pencere alanları ve cami çatı örtüsünü oluşturan kubbe alanlarıdır. Bu seçim yapılırken Sinan'ın kullandığı pencere elemanlarının çeşitliliği ve Sinan'ın kubbeyi kullanımı etkili olmuştur.

Gerçekleştirilen ilk uygulama çalışmasında, pencere alanlarına ait seçilen nokta bulutları algoritmanın pencere iç ve dış farklı seviyelerinde özyinelemeli çalıştırılmasıyla, yarı-otomatik olarak segmente edilmiştir. Diğer örnek çalışmada, kullanılan algoritma ile ana ve farklı kubbelerin segmentasyonu gerçekleştirmiştir. Bu segmentasyon sonucunda modele dahil olmayan nokta grupları scikit-learn modülünde yer alan Gürültülü Uygulamaların Yoğunluğa Dayalı Mekansal Kümelenmesi (Density Based Spatial Clustering of Applications with Noise, DBSCAN) algoritması kullanılarak elde edilen nokta kümeleri, kullanıcıya mimari elemanların ve deformasyonların tespitinde yol gösterici bir çıktı olarak da sunulmuştur.

Elde edilen cami ana kubbesi ile yukarıda bahsedilen Sinan mimari kubbe tipoloji ilişkilerinden yararlanılarak camide yer alan diğer kubbe yapılarının modellenmesinde nokta kümelerinin oluşturulması sağlanmıştır. Sonuçta örnek olarak parametrik kubbe modeli açık kaynaklı CAD yazılımı kullanılarak Endüstri Temelli Sınıf (Industry Foundation Class, IFC) formatına dönüştürülmüştür.

Yürütülen çalışmalar ile restoratör mimar uzmanların aynı verileri kullanarak hazırlamış olduğu CAD çizimleri arasında bütünlük ve doğruluk kıyaslamaları yapılmış ve sonuçların genel ölçekli çalışmalar için kabul edilebilir sınırlar içerisinde olduğu görülmüştür. Ayrıca, verilerin yorumlanmasında uzman kullanıcılara zaman kazandırarak katkı sağlanmıştır.

Özetle, veri ve model odaklı hibrit bir 3D yapı rekonstrüksiyon yaklaşımı kullanılarak, doğrudan 3D nokta bulutu verileri üzerinde çalışan mimari parametrik modellerin yarı-otomatik çıkarımına yönelik Osmanlı Klasik Dönem Camii Mimar Sinan yapıtları özelinde bir metod geliştirilmiştir.

1. INTRODUCTION

In recent years, interest in the idea of generating a digital twin of the Earth and its content has accelerated. Within this framework, Cultural Heritage (CH) structures' digital documentation has gained significant importance. Moreover, 3D models are conventionally used for many applications such as restoration, tourism, urban planning, telecommunication, emergency and risk management, entertainment, and even computer gaming. Whether to encapsulate as part of a virtual Earth or provide an architectural survey before any intervention, point cloud based documentation and modeling of CH is widely used. However, understanding and interpreting the data to describe the final output is time-consuming and requires expertise in data manipulation. Moreover, the pipeline from data acquisition to product requires new methodologies and algorithms to address automation needs and increase the efficiency of the existing methods of the models' geometrically and semantically. In this section, we present our primary motivation, describe our research aims and objectives, the scope of our work, and the general outline of the methodological steps.

In brief, the documentation of CH assets is an information and knowledge transferring process. UNESCO and International Council on Monuments and Sites (ICOMOS) dictate the crucial importance of complete and most detailed documentation of CH (ICOMOS, 1996). Since the release of the Venice Charter in 1964 and subsequent guidelines, organizations and committees, such as The International Committee for Heritage Documentation (CIPA) and national bodies and agencies for heritage preservation such as English Heritage, have worked towards establishing best practices and guidance to achieve these standards. In order to maintain and preserve cultural heritage structures, documentation specific to the CH are a precondition for any intervention (ICOMOS Türkiye, 2013). Therefore, metric-based survey products and 3D models are needed for different expert groups working towards an array of goals in conservation, engineering, and visualization (Foni et al, 2010). From this standpoint, metric-based documentation plays a critical role in better understanding heritage structures (Altan, 2006) and in assisting restoration works that will ensure their sustainability into the future.

The use of laser scanning systems, generally accompanied with digital imagery and other sensor systems such as GNSS and IMU, has been one of the main developments for data acquisition methods in the geomatics field. These systems became prominent among users in heritage works and well accepted for the applications in the cultural heritage domain for documentation, conservation, and restoration projects (Kivilcim, 2009). Laser scanning systems are a fast and accurate data acquisition technique; recent affordability for consumer-grade scanning system, market accessibility of compact systems, and advances in computational capacity and performance (with acquisition rates of hundreds of millions of points per second) availability of distributed and cloud based solutions, provide many advantages for documentation projects (Spring, 2020). However, describing the underlying geometry in the point cloud is a tedious task. Therefore, algorithms and methodologies are needed to automate processing cycles from data acquisition to the final products (Remondino, 2011). In the case of real-life applications, numerous steps in the work process depend on the diligent work of expert users. This is both costly and open to human error and dramatically extends the overall project completion times. The scene complexity, variations in architectural elements, and data acquisition norms are the primary issues. The past decade has seen increased interest from the geomatics, computer vision, computer graphics, and reverse engineering research communities to close the automation process gaps in building modeling from laser point clouds.

This thesis addresses a method to decrease the user-dependent manual work cycle, which is currently based primarily on user interpretation of point clouds and vectorizing point-to-point to produce final 3D models and other products. Our goal is to implement a strategy with user guidance to increase the automation with few interventions. Our research concentrates on Ottoman Historic structures; we selected our research examples from Ottoman Classical Era Mosques. Despite being widely appreciated for their outstanding historical value, limited research has explored automating the process of as-is documentation; reasons include: the limitations to data acquisition and availability and the limited computational capacities in the past.

1.1 Research Objectives and Scope of the Thesis

The availability of digital entities of heritage structures can improve the planning and management of conservation and restoration projects. Photogrammetry has been widely used for heritage assets' image-based documentation and modeling of heritage assets (Remondino and El-Hakim, 2006). Despite its low cost, it requires further planning and time devoted to the modeling process (Debevec et al., 1996; Duran, 2003). Being a robust measurement method, developments in hardware and the increased affordability for end-users, have earned laser-scanning systems a favorable reputation for a wide range of surveying and other applications in cultural heritage documentation.

The general use of point clouds from laser scanning and digital photogrammetry is limited to visualization for documentation. Expert operators conduct primary measurements to interpret the underlying geometry and vectorize the structural elements in cultural heritage documentation. Therefore, methods and approaches are needed to easily interpret the geometry of architectural elements and establish their semantic relationships for the basis of heritage projects and Heritage Building Information Modeling (HBIM) works, which have recently gained importance. Nevertheless, generating 3D digital models of complex buildings is still an open and challenging task, and therefore semi-automatic processes have been on the research agenda (El-Hakim et al., 2006; Garcia-Dorado et al., 2013).

Construction techniques and geometric patterns of architectural elements have been documented in Western architecture for millennia, such as Vitruvius's (Wetmore et al., 1916). In contrast, the Ottoman architectural structure elements' style and shape grammars lack detailed descriptions and sketches, and only minimal documentation exists (Aksoy Varol, 2001; Erzen, 1981). However, between civilizations, architectural heritage structures' complex and irregular shapes, and the variations in their architectural styles, require different knowledge bases and algorithms to support and decrease the time-consuming parametric component construction process (López et al., 2018).

This thesis aims to contribute in a semi-automated fashion to "point to BIM" or "scan-to-BIM" approaches that use parametric geometrical elements. Furthermore, the main pipeline is executed using an open-source software environment. In this research, our main objective is to investigate whether it is possible to apply a semi-automated procedural-based parametric modeling methodology for documenting variations of CH landmarks, particularly Ottoman Architecture Classical Era of Architect Sinan's mosque designs, using a combination of data and model-driven methods for object recognition.

The research methodology works directly on 3D point cloud data to extract architectural features using a hybrid approach of data and model driven approaches. The presented research methodolgy is focused on Ottoman Classical Era Mosque Designs of Architect Sinan. A semi-automated methodology for point cloud processing is developed to decrease the existing manual process for generating 3D models.

1.2 Thesis Organization

In this chapter, we have given the motivation and scope of this research briefly. In the second chapter, the use of laser scanning and BIM technologies are explained. In the third chapter, methods and the state of art examples of as-is and as-built engineering works for the cultural documentation domain, particularly with the mentioned technologies, are discussed. In the fourth chapter, the developed methodology and its steps are presented. Information and data about the Şehzade Mosque as the case study of our research is given, followed by the implementation of the developed methodology applied at various levels in case study; the results are presented with the evaluation of the proposed methodology in the fifth chapter. Finally, in chapter six, the thesis concluded with the practical applicability of the presented method and directions for future research.

2. BACKGROUND AND LITERATURE REVIEW

This chapter briefly describes laser-scanning technology, its use in heritage documentation and outlines procedures starting from data acquisition to obtaining surveys for architectural, engineering, and concepts of 3D building modeling.

2.1 Laser Scanning for Heritage Documentation Projects

Despite its cost, laser scanners are robust systems, providing dense point cloud data in 3D. Nevertheless, the physical properties of the project site and the purpose of the application determine the use of laser scanning, scanner type, and the platform. Standard delivered data products may include point clouds in raw form, co-registered in a local or georeferenced coordinate system, or classified. The point cloud datasets are delivered as unstructured or re-produced based on a fixed-point distance in a unified way. Point cloud derived products can be triangulated mesh models with/out images textured on ortho-images, DTM, DSM, plan, elevation, section CAD drawings, 3D models, or even BIM applications (Kivilcim, 2009; Boardman and Bryan, 2018). Even though conventionally, CAD drawings in 2D are the most widely used by conservation experts, working with the 3D point clouds provide further investigations, assessments, models, and visualization (Boardman and Bryan, 2018). Conventional Terrestrial Laser Scanner (TLS) based applications follow the workflow presented in (Figure 2.1). Each step in conventional work will be covered in next section.

Data Acquisition	Point Cloud Acquisition Pre-Processing Registration Georeferencing
Interpretation and Processing	Cleaning Segmentation Classification Meshes, Vectorisation, Modeling
Delivered Products	Plans, profiles, sections, elevation (CAD, BIM), 3D Model Animation, Visualization Products and Applications A/VR

Figure 2.1 : CH documentation steps and products (Boardman and Bryan, 2018).

2.1.1 Data acquisition

Laser scanning is an active remote sensing technology based on the computation of laser beams sent from the scanner and reflected from the surface object. The scanner's output is the 3D coordinates and, generally, intensity values from the reflected object from the emitted laser pulses. Laser Scanners are classified based on measurement techniques: triangulation, phase comparison, and time of flight scanners. Whilst triangulation-based scanners are used for small artifact measurements, phase-based and time-of-flight scanners (ToF) are used for building measurements. However, ToF systems are preferred over phase-based systems for general measurements because of their cost and efficiency in scan distance (Figure 2.2).

Figure 2.2 : Left: Scanning alcove with Faro laser arm application in the archeological museum, Right: demonstration of data acquisition with a Riegl brand ToF scanner.

Terrestrial Laser Scanner (TLS) can be used in different platforms for various environments (Figure 1.3). In order to acquire a good coverage of point clouds that represent the structures, it is essential to plan scans from multiple stations. Technological trends have been evolving in more compact and light versions, and the popularity of UAV and backpacked versions is increasing. Nevertheless, the scanner type selection is related to the site conditions, shape complexity, and project aims. A summary of the usage area of different scan systems with their typical metrics is presented in Table 2.1 in the work of (Boardman and Bryan, 2018).

Figure 2.3 : Use of TLS scanners in static (left), mobile (middle), and handheld.

Table 2.1 : Scanning systems typical metrics (Boardman and Bryan, 2018, p. 8).

Scanning System		Usage	Typical Accuracies (mm)	Typical Range (m)
Triangulation	Rotation Stage	Small objects taken to scanner. Replica production	0.05	0.1 – 1
	Arm mounted	Small objects. Lab or field. Replica production	0.05	0.1 – 3
	Tripod mounted	Small objects in the field. Replica production	0.1 1	0.1 – 2.5
	Close range handheld	Small objects. Lab. Replica production	0.03 - 1	0.2 – 0.3
	Mobile (handheld, backpack)	Awkward locations e.g. building interiors, caves	0.03 – 30	0.3 – 20
Pulse (TOF)	Terrestrial	Building exteriors/interiors. Drawings, analysis, 3D models	1 – 6	0.5 – 1000
	Mobile (vehicle)	Streetscapes, highways, railways. Drawings, analysis, 3D models	10 – 50	10 – 200
	UAS	Building roofscapes, archaeological sites. Mapping and 3D models	20 – 200	10 – 125
	Aerial	Large site prospecting and mapping	50 – 300	100 – 3500
Phase	Terrestrial	Building exteriors/interiors. Drawing , analysis, 3D models	2 - 10	1 - 300

While data acquisition is fast, precise, and accurate down to a few mm levels in factory conditions, errors can occur during data acquisition and post-processing due to scanner properties, object characteristics, environmental factors, and user errors. Therefore, scan station distribution, spatial resolution based on scan angle resolution and distance to the object, surface materials, and scene conditions such as light and atmospheric effects play essential roles in the results. Efficient site planning and error propagation models, such as in Ozendi et al. (2017) help minimize some of these errors. In addition, reflections from windows and the occlusion of irrelevant points, known as ghost points, can be captured due to obstacles between the scanner and the target objects, or gaps and variations of point densities, especially on edges (Aygün, 2018). Some systems simply filter points far from a given distance in the raw point cloud automatically in the pre-processing stage.

2.1.2 Pre-processing and registration

In each scan station, the point cloud is acquired based on its local coordinate of the system. Therefore, it is needed to transform to a common coordinate system for further process and interpretation of the data. This process is known as registration. Using tie or control points ensures consecutive point clouds are registered in the same coordinate system. It is essential to place the control points well distributed as they affect the accuracy. Furthermore, registration can be made on cloud based matching algorithms such as Iterative-Closest Point algorithm (ICP) (Besl and McKay, 1992), 3D Least Squares Surface Matching (Gruen and Akca, 2005). In mobile systems, simultaneous Localization and Mapping (SLAM) is also used to simultaneously keep the scanners' track, which is especially beneficial with handheld systems used in closed areas.

2.1.3 Data processing, interpretation and modeling

In the from point to 3D models pipeline, the main challenge is in interpreting the point into meaningful object entities; this is the case, particularly working with architectural datasets with complex structures in large areas. It requires continuous attention of experienced and skillful human laboring and requires cycles of tedious working periods. In the following chapter, we briefly explain the efforts for the automation of point cloud processing.

2.1.4 Vectorization

Making interpretations and extracting geometrical features from noisy point clouds acquired from platforms (airborne, terrestrial, or mobile) consume most of the post process. Hence, the management and interpretation of point data to extract models and useful products remain a challenging and tedious process.

In order to interpret the point cloud, the user needs to match her/his knowledge base with the point sets based on visual cognition skills. The user or the software needs to identify the key points representing the underlying geometric shape. In order to simplify the point cloud to work with these shapes, unnecessary and outlying points must first be eliminated (Kivilcim, 2009). The workflow for the conventional approach is presented as schematized in (Figure 2.4).

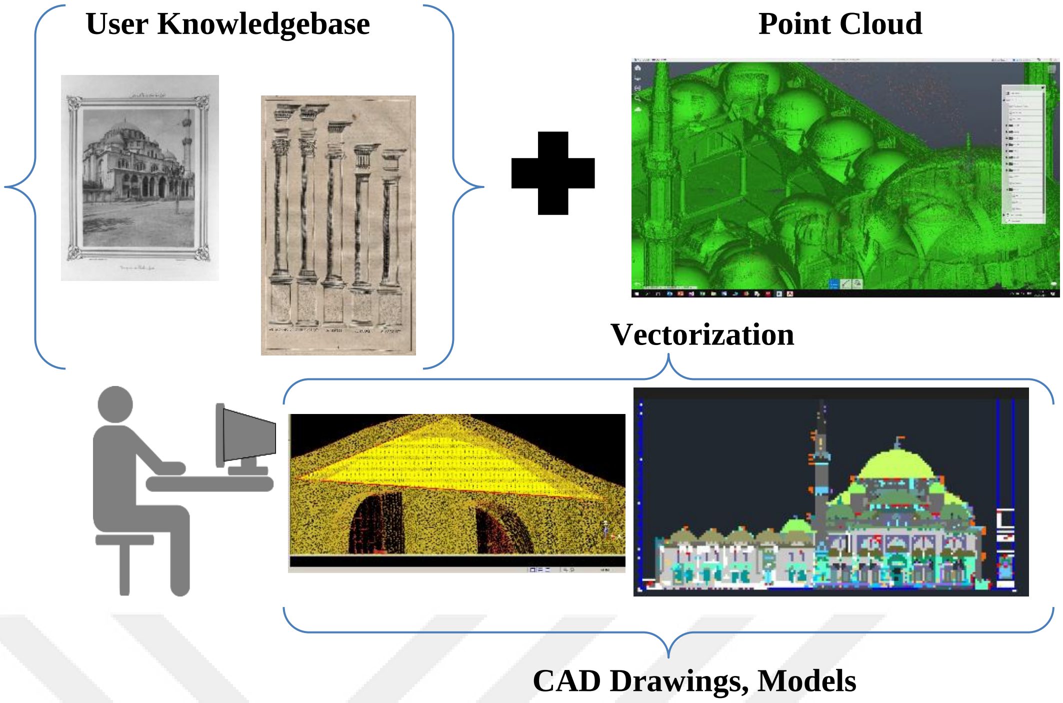

Figure 2.4 : Diagram depicting the process of conventional workflow from point cloud to products.

Sections play an essential role in Architecture, Engineering, and Construction (AEC) defining elements geometrically. By extending sections, rotating them alongside an axis, or simply extruding, 3D models of the geometrical shapes are obtained. However, uniformly applying this brings the issue of limitations such as loss of significant details to define the imperfections and deformations of the as-is status. Furthermore, missing parts due to occlusion and uncertainty occur in areas with low point density, resulting in the obtained sections and elevations that may not include such parts. In the work of Berger et al. (2014), the issues related to the point cloud and the object are demonstrated (Figure 2.5).

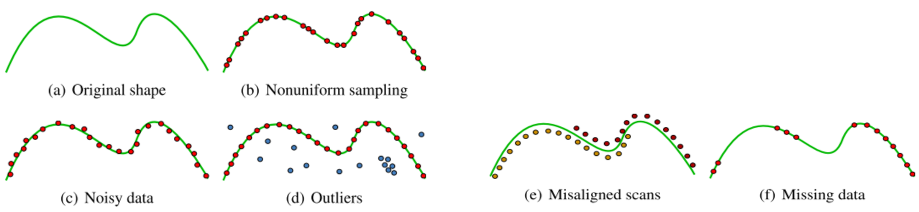

Figure 2.5 : Point cloud approximation issues to the real object as demonstrated as a curve in 2D (Berger et al., 2014).

Similar to our experience with available industry software solutions on automatic feature extraction shown in Figure 2.6, Canciani et al. (2013); Chiabrando et al. (2017) express that the CAD-based software does not meet the required best-fit geometry between the points and shapes. In addition, such programs require various parameters such as the thickness of a volume around the point cloud, tolerance range to control the noise, the minimal length of the segments, the minimal distance among the selected points.

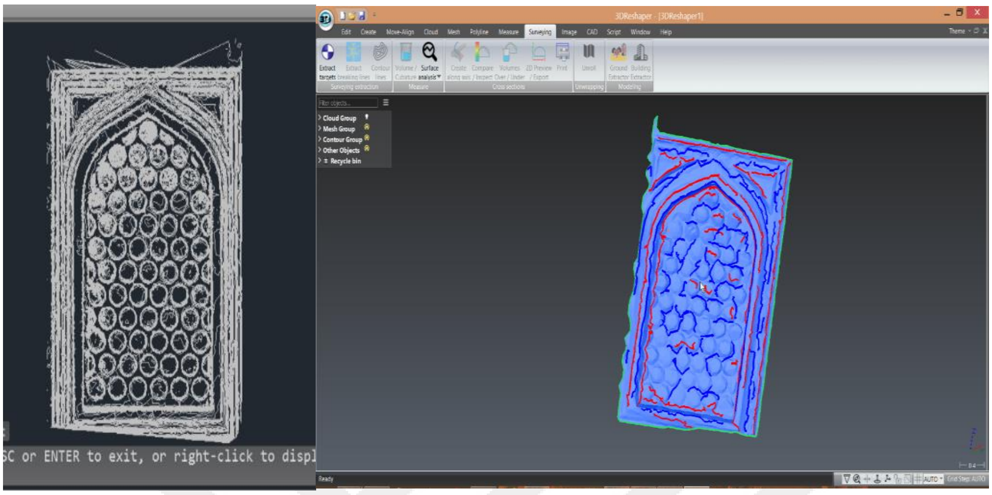

Figure 2.6 : Our experiment with Leica Cyclone and 3D reshaper software with automatic feature extracting algorithms.

Commonly, laser scanner producers supply relevant software for their products. Some of this software provides predefined object detection. However, these are primarily for industrial sites such as plants built of pipelines with rigid properties.

2.2 Architectural Products

For the past years, the direct useability of the 3D models has been in discussion among the AEC community; however, the majority of the final architectural survey products are cross-sections, elevations. Building Information Modeling (BIM) applications are attention taking, especially within the digitalization framework of design and construction, yet the application of BIM is preferred for the large project sites and places in mandatory regulations for a project. Even though there is an initial cost for software and training, it can be said that such technological shifts are more relevant to the mindset of the professionals. Therefore, the benefits of working with BIM will be explained next.

2.3 Concepts of 3D Object (Building) Reconstruction Methodologies from Point Clouds

2.3.1 From drafting tables to computer graphics

For centuries, architects, engineers, and drafters have used physical drawing tables to make their designs. In the second half of the 20th century, the emergence of computers and the development of CAD systems brought up a new platform for the projects to be drawn, manipulated, and visualized. Through this, the development of Constructive Solid Geometry (CSG) advanced the wireframe representation and provided computation of physical properties and Boundary Representation (BREP).

The tedious work cycle involves various experts specialized in heritage documentation. However, after deciding on the method and scan system, data acquisition to georeferencing steps are standard and robust.

B-spline of degree 3 is the closest representation of freeform objects (Canciani et al., 2013). Therefore, B-spline is a suitable option for the sculptural ornamental parts, which are common in Western Architecture. On the other hand, the simplicity of Islamic architecture allows it to be defined using lines and arcs or primitive shapes.

2.3.2 Surface meshing

Mesh generation is a 2.5D method used to visualize 3D. It is preferred for modeling complex structures; it is applied without any apriori information. Different mesh generation methods exist. Among them, Delaunay triangulation is commonly applied. The main principle of mesh generation can be explained with the Voronoi diagram. To get the best result using surface-based mesh generation, it is the convention that the point cloud is without outliers and noise, so the point cloud is usually resampled before the triangulation. Due to possible gaps and wrong triangles, parts of the initial result may require further manual editing, a final decimation of triangles is preferred based on the outcome and the purpose. Mesh generation can be computationally costly in dense point clouds. Following the mesh generation, it requires further manuel editing to correct the mesh. An example of this mesh based situation can be seen in (Figure 2.7).

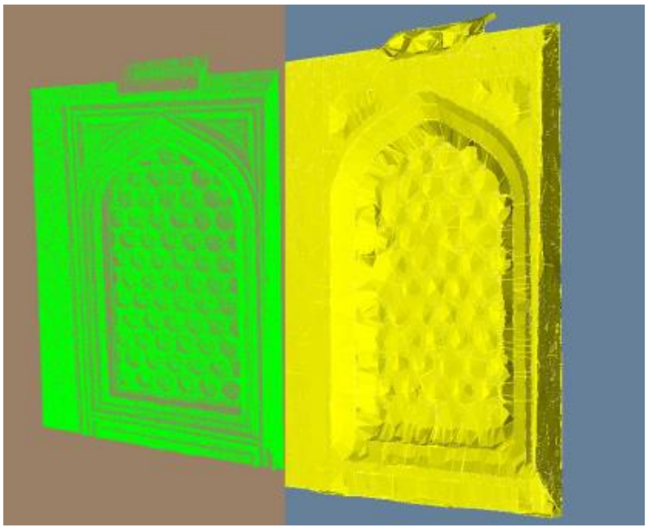

Figure 2.7 : Sample of a point cloud and implimenton of surface mesh based on Delanuay triangulation.

2.4 BIM For Existing Structures

The concept of Building Information Modeling (BIM) originated with Douglas C. Englebart's 1962 vision of a computerized augmented architecture of the future (Doughlas, 1962). A general definition of BIM is the process and technology that encapsulates the physical and functional properties of a building in digital form (Arayici et al., 2017). Only recently, with the development of commercial software and applications, BIM has gained its popularity and application. As a result, the conventional Architecture, Engineering, and Construction (AEC) industries transition with BIM.

BIM is a methodology that presents more than a geometric design model: it includes the physical and functional characteristics of the building structure while maintaining semantic relationships in a model that can be used for various analyses and applications. BIM also supports collaborative work where any change in the design is reflected automatically through the entire project, thus giving experts and stakeholders the ability to work efficiently and seamlessly. Additionally, BIM covers the life cycle of a building, from concept to completion, making it widely preferred in complex building designs and construction.

In order to provide data exchange among user groups and different commercial BIM software, an open data exchange format called Industry Foundation Class (IFC) was used. Initially, BIM governed the complete project management of new structures, from their design through construction phases. However, BIM’s use for existing buildings, from Facility Management (FM) requirements, simulations for energy efficiency and natural hazards, have arisen, thus extending the need for research in this area.

Tang et al., (2010) published a review of the as-built BIM covering the knowledge representation process in as-built BIM in geometric modeling, object recognition, and object relationship modeling.

Automation and high modeling/conversion effort come from (1) captured building data into semantic BIM objects, (2) updating of information in BIM, and (3) handling of uncertain data, objects, and relations in BIM occurring in existing buildings (Volk et al., 2014).

Historic Building Information Modeling (HBIM) is a term proposed as an addition to BIM for existing structures particularly the historical ones (Murphy et al., 2009). This method comprises two main stages: (i) producing parametric library elements of architectural components from historical data of classical architectural orders and (ii) interactively placing these parametric elements on point cloud data in a commercial BIM software.

As-built documentation and BIM applications for existing structures have increased in recent years; countries such as Canada and UK have already implemented regulations for the maintenance and restoration of the cultural heritage assets that require BIM methodology (Arayici et al, 2017). To provide data exchange among user groups and different commercial BIM software, software companies use an open data exchange format called Industry Foundation Class (IFC). In regional and international BIM standards, Level of Development and Level of Detail are two issues regarding the geometrical aspects of the BIM. For example, Chiabrando et al. defined a 3 grade level to match the architectural specifications of output models which are 1:200, 1:100 and 1:50 scale respectively from coarse to fine graphic representation of the 3D geometric features (Chiabrando et al, 2017). This grade scale is mostly based on the project aim and is important for the selection of the appropriate survey technique and parameters.

3. AUTOMATION OF OBJECT SEGMENTATION AND FEATURE EXTRACTION WITH EMPHASIS ON HERITAGE BUILDINGS

This section introduces the general approaches on façade and roof reconstruction parallel to our research objectives. Afterward, we present state of the art research and developments of the approaches in cultural heritage modeling, primarily using laser point cloud as the main data source.

3.1 Point Cloud Processing Steps For Building Detection

Manual 3D building modeling is tedious work even for experts in this field. Therefore, automation in building modeling from the point cloud is an active research topic in computer vision and geomatics. Laser scanning or image-based point cloud data acquisition are the most common sources for modern building structures and site documentation applications in heritage. Different methods for the automation of point cloud processing have been proposed over recent years. In this chapter, we present the main concepts of the object extraction with a focus on façade and roof covering elements. We limit the literature review to buildings, particularly the ones in the cultural heritage domain.

Generally, the management of a project and the decision on the modeling approaches are determined regarding the trade-off relation between visualization and geometric accuracy needed for the project. Specifically, building extraction can be defined as a three-step process starting with detection, reconstruction, and attribution (Baltsavias et al., 2001; Grün, 2000; Haala and Kada, 2010). In the first phase, regions of building objects are detected. Secondly, features geometries are extracted, and topologies are established in the reconstruction with semantic attribution of elements such as walls, the roof; this workflow concept is shown in Figure 3.1.

Modeling approaches are grouped into two main categories (Gruen, 1997). The bottom-up methods start from the data level to derive models. The top-down approach starts with apriori information of the models and applies to the available point cloud.

In this concept (Figure 3.2), Volk et al. present a complete categorization of systematic methods used in object recognition for buildings (Volk et al., 2014).

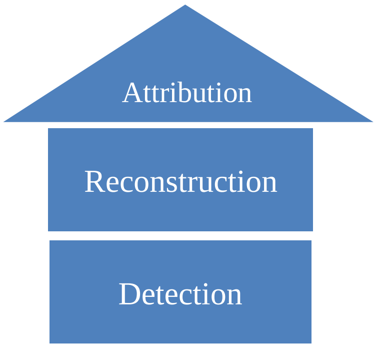

Figure 3.1 : Conceptual stages for building model extraction in a building form.

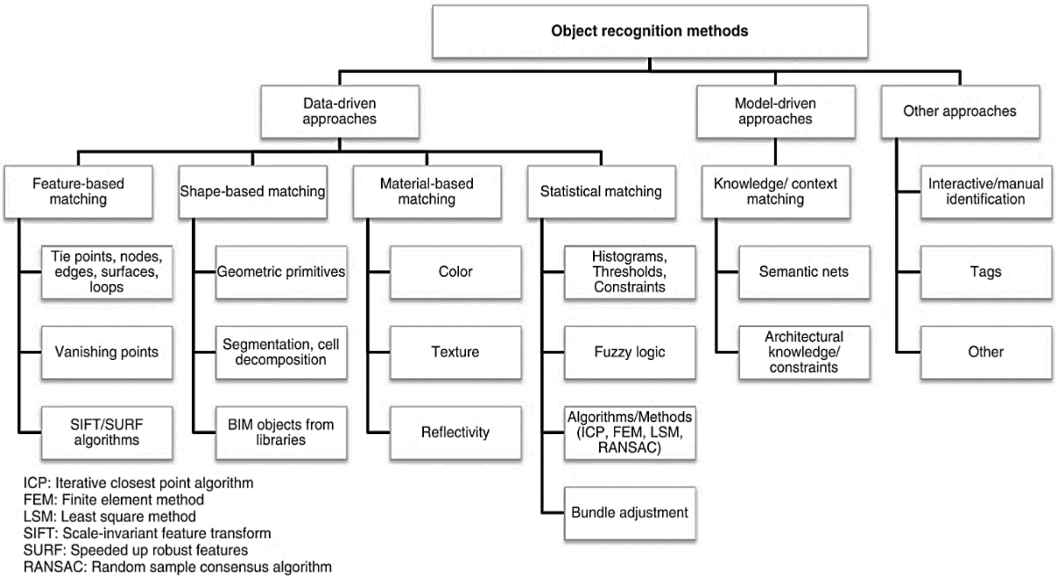

Figure 3.2 : Systematic review of building recognition methods (Volk et al. 2014).

As explained in the motivation section 1. introduction, automatic model generation from point cloud has been an active research topic aiming to derive less human intervention. The methodology in this research falls in a hybrid approach category using both data and model-driven methods. In principle, computer vision based, fully automatic, and semi-automatic approaches focus on a 3 step workflow; clustering, segmentation (labeling), and semantically enriching the point cloud datasets. Here, we briefly explain these steps.

3.2 Data-Driven Approaches

3.2.1 Clustering

Clustering is a statistical methodology applied across scientific domains for analyzing patterns in data. Generally, the clustering process organizes a given input data such as point clouds into groups of subsets based on similar properties. In clustering, the idea is that input points with similar properties will be placed in the same cluster while maximizing the difference among separate clusters from each other. Clustering algorithms apply the criteria in various levels, from a single point to another point, point to a cluster, and between clusters. Local criteria are applied, rather than global, such as the distance of each point tested among its neighbor as data with higher similarity tend to be also closer. The derived output of clusters is to provide the distribution of points closely related. Traditionally, clustering algorithms are categorized as partitioning and hierarchical algorithms.

3.2.2 Segmentation methods

3D points clouds are the simplest primitives and do not provide information regarding a higher entity alone. In contrast, grouping them with particular specifications provides area and volume segments that can represent objects' shape, size, position, and orientation properties in space. This process is called segmentation. In a recent update of the categorizing the popular point cloud methods and algorithms applied in the cultural heritage documentation and modeling, Grilli et al. (2017) present segmentation methods divided into five main branches: namely edge-based, region growing, model fitting, hybrid, and machine learning applications (Figure 3.3).

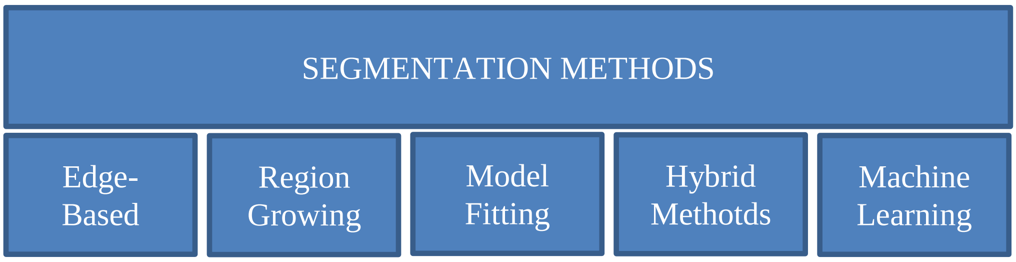

Figure 3.3 : Segmentation methods (Grilli et al, 2017).

While edge-based methods perform quickly, in the case of the unstructured and uneven density of point data, they may not produce such accurate results. In addition, 3D edge-based methods may result in disconnected edges, causing difficulty filling and interpreting closed segments (Castillo, 2013). Region Growing methods are categorized in two ways depending on how they are processed. Bottom-up approaches start with selecting some seed points and growing with areas containing points that show specific characteristics. In contrast, the top-down approaches start with all points assigned into one segment and are compared to a surface to determine the points that do not belong to this class. Introduced the first time by (Besl and Jain, 1988), region growing algorithms need a selection of seed points and criteria that determine the acceptance of candidate points and growing strategy. Therefore, region-growing methods are sensitive to the selection of the seed points and region growing conditions, causing under or over segmentation problems, especially in the boundaries of the regions.

Model fitting methods are based on fitting the primitive shapes such as plane, cylinder, torus, etc., onto the point cloud and segmenting the points that satisfy the mathematical model of the given primitives. One of the benefits of this method is that man-made built environment can be expressed by using primitive shapes. In such cases, the result of the segmentation is the result of classification. Some of the most used methods among model fitting algorithms are Hough Transformation and Random Sample Consensus (RANSAC). RANSAC is a robust statistical method introduced by (Fischler and Bolles, 1981) is widely used in the computer vision community for detecting shapes in both 2D imagery and 3D point clouds. The simplicity of this algorithm depends on two main steps, hypothesis generation and evaluation. The principle of finding the best model among the candidates is known as consensus voting, which reflects how well the points fit the candidate model within a given threshold. Several RANSAC variations have been proposed, and their performances were tested in various ways in the works of (Raguram et al., 2008) and (Choi et al., 2009). When the 3D point cloud is used, RANSAC is preferred due to its superior over Hough Transform (Tarsha-Kurdi et al., 2007). For these reasons, we also implemented RANSAC based segmentation as a part of our methodology. The hybrid Segmentation techniques are the results of the combination of two or more mentioned segmentation methods.

Machine Learning (ML) deals with computer programs that automatically improve with experiences. The computational power to understand and extract meaningful information from massive datasets and solutions to problems using ML in various fields is increasing as the availability of digital data admits significantly better predictions. Recently, Atik et al. experimented with different ML algorithms to built-up segment areas, ground, and vegetation in a supervised learning fashion from geometric features of point cloud data. Even though they were able to reach good results, they concluded that the best result for each dataset was a different algorithm (Atik et al., 2021). Matrone et al. used ML and Deep Learning (DL) classification approaches to semantically segment point clouds.

The complex scene of heritage structures is typical of the cultural heritage domain; thus, neither of the reported methods outperformed all classes resulting in lower metric accuracy. In addition,. the need for the labeled training datasets size dependencies, hyperparameter tuning, required hardware, and the complexity of heritage structures require further investigation on the ML (Matrone et al., 2020).

The proposed strategy in this research is a hybrid approach of Model and Data driven methods. We develop a database of architectural knowledge constraints and use shape based segmentation based on the statistical algorithm RANSAC.

3.2.3 Classification methods

The next step in the object recognition pipeline is the process of interpreting "tag/label" groups of segments for a higher level of identification; this is called classification. For instance, the segmented point clouds are classified as a wall, and the edges can be extracted from the boundaries of the segmented patch. In the final, the classified surfaces are organized into 3D model entities.

3.3 Model Driven Approaches

This section explains the use of model driven approaches, particularly procedural modeling and parametric libraries, for generating building models. After the definitions, exemplary model driven approach based applications specific to the cultural heritage domain will be explained.

3.3.1 Procedural modeling

A building model can be generated from transformations of an auxiliary data model or a shape grammar in procedural modeling. Müller et al. used Computer Generated Architecture (CGA) shape grammar and procedural modeling to demonstrate the generation of massive urban geometric models (Müller et al., 2006). Haegler et al. extended the use of these shape rules to turn the hypothetical city model of ancient Rome (Haegler et al, 2009). In our research, we investigate how procedure based modeling can be used to guide the area in fitting parametric elements directly on the point cloud.

3.3.2 Parametric libraries

Parametric objects are like blueprints for digital mockups. They can be resized, scaled, and translated. First, a parametric family and its elements were produced using existing architectural experience and knowledge for existing buildings. Parametric models can be produced from manual, semi-automatic, or automatic extraction from the point cloud. The main benefit of using parametric objects is the easiness of adapting the pre-generated architectural objects without defining each part (Chevrier et al., 2010). This condition is advantageous in applications where many model class instances are required for applications games and simulations in need of massive cityscape buildings production. It is worth mentioning that models produced from parametric elements result from the instances of generic shapes; therefore, they may not accurately represent an object's real-life status. Therefore, most parametric as-built applications require further editing to adapt imperfect and deformed structures, some of which can be made semi-automatically, although generally made using manual edits.

3.4 State of Art in Cultural Heritage Modeling

A complete automated methodology for urban modeling remains a challenging task; systems in academic and commercial producers are working on enhanced solutions. In practice, applications available in professional works for the existing built environment depend mainly on manual editing and digitization. However, the expansion of automatic methods into cultural heritage documentation and modeling is less common. The existing approaches focus on extracting simple primitive objects or modeling objects based on well-documented architectural knowledge in semi-automated methods. One core reason for semi-automatic approaches is due to the complex nature of the cultural heritage, deformations, and changes that occur over time due to human activity and the effects of the environment. In this respect, there has been a great interest in the research community from geomatics, photogrammetry, computer vision, and graphics to contribute to closing the gap in the pipeline of digital building modeling from point clouds.

Many algorithms work on extracting planar surfaces, since the majority of man-made structures are considered planar structures. For example, the work of Pu and Vosselman, and Böhm, define specific rules and conditions such as, the walls are accepted as vertical with a limited degree of displacement and, walls meet floors with right angle (Böhm et al., 2007; Pu and Vosselman, 2007). For extracting façade elements such as the doors and window openings, researchers developed algorithms that rely on fitting geometric primitives in low to no point density patches. In contrast, the point density may vary from the rest of the nearby area due to the obstacles or occlusions and can manipulate the results.

In an example from a heritage site application, point clouds of a tower and walls of a castle, derived from photogrammetric mesh, were input to segment and classify the rectangular wall boundaries and tower footprints (Lerones et al., 2010). However, mesh-based approaches over simple geometry generally have difficulties performing in management and semantic operations (Bruno and Roncella, 2018).

Boulaassal et al. (2007) claim that they adopted the RANSAC algorithm for the first time in order to extract planar facade elements from a modern building from TLS point clouds. Their findings report achieving 90% percent success in determining the windows, planar walls, and balconies. Their importance is that they apply RANSAC sequential process, so inliers from each iteration are removed from the next iteration. This approach guarantees that there is no intersection between two segments. The resulting segments form parallelepiped due to the given tolerance; these can be turned into a plane in the following segments. In addition, Boulaassal et al. (2007) note that the selected threshold value should be close to the thickness of the point cloud; this means that it should include the surface roughness. Furthermore, they explain that the materials of the facade elements affect the results directly. This work, is presented based on empirical values, demonstrates the power of applying RANSAC in the modeling domain.

In more recent work, (Boulaassal et al, 2009) aim to detect the simple planar facade borders from the TLS point cloud of modern buildings. To achieve this, first, they run an adaptive RANSAC algorithm, which detects planes from points in chronologic order. However, this intermediate result cause intertwined planes due to the points falling in other plane categories. To overcome this problem, they compute the Euclidean distance of all points and assign the wrong planes to their corresponding ones. In addition, they consider these points as intersections between planes and segment them based on the proximity criterion to their relevant plane. In the final step, they extract the contour points based on the length of the Delaunay 2D triangulation. First, they apply PCA to redefine the datasets of planes with X and Y coordinates and neglect the Z values. Then they extract points that have longer sides of triangles compared to the general outcome. In their comparison to the manually vectorized dataset, they claim that their methodology presents 96% success. However, this method only aims to segment planes and does not distinguish the higher elements of architectural elements. Moreover they mention that different parts, such as sills and window networks, are detected as separate planes. In their work, the threshold value is not clear (actually, they color code them to be distinguished) to recognize them as separate object elements and make a semantic relationship which is a weakness of their work. In our case, we focus on achieving higher different results for the architectural survey, which can support engineering drawings.

Unlike methods that use score function modification based derivations of RANSAC such as MLESAC and MSAC, the RANSAC Algorithm's performance was enhanced using a sampling strategy that adapts the size of the shapes and rules to determine when enough candidates have been drawn and a score evaluation on random subsets to consider as many points needed to determine the best shape. In these conditions, they were able to assign primitive shapes of planes, spheres, cylinders, cones, and tori in a given point cloud (Schnabel et al., 2007).

Schmittwilken and Plumer, (2010) presented a model based reconstruction and classification methodology that uses a prior model knowledge given in probability density functions. This prior information is used in each phase to decrease the computation complexity and increase the estimation. Their method is composed of three steps: Pre-Filtering, Estimation of most likely sample points, and estimation of the respective object boundaries. They use MLESAC with a scoring function that rates the size of the predictions and use decision trees to find the most evident features in assessed in the scoring function. Next, they apply cluster analysis to estimate the borders of the object that cannot be identified precisely by a parametric model. Authors demonstrate this automated method for windows and stairs with Mobile Mapping System (MMS) point cloud data sets that belong to building facades within a typical architectural style. Their works provide a satisfying result with a reconstruction of around %70 of the windows. However, the inaccurate estimation of reference points because of high deviation of height compared with the ground truth. Their approach has similarities in our method; however, our aim relies on the geometrical descriptive values and ratios of architectural elements within a specific percentage rather than probability density functions.

Arikan et al. presented a methodology to generate polygonal models from incomplete and noisy point clouds for general interactive applications such as GIS and urban modeling (Arikan et al., 2013). Their method is based on an automatic initial model base and an interactive one based on optimization based snapping. Based on a coarse selected area of a planar surface, their algorithm extracts adjacency relations between elements of the polygons. Their focus is rather on the automatic discovery of local adjacency relations between polygon elements (Nalani, 2014).

A more recent building modeling approach comes from computer vision society, Demir et al., (2015) used planar and non-planar object extraction via applying RANSAC and Euclidean clustering. Then by using consensus estimation and making a tree of construction matching templates, they segment structures with missing parts. Afterward, they use a pattern detection algorithm and convert the segmented data into parameterized content. Finally, they allow users for final manipulation, such as editing or adding additional parts. The work they present is promising for procedural city models, and they report limitations as the consensus model needs multiple instances of segments. Also, detection fails to recognize the spiral patterns.

Following and based on the BIM library elements of Murphy, Dore developed an HBIM approach that uses procedural modeling rules to overlay a procedural model on the point cloud by developing a graphical user interface to position them. He also included new rules grammar shapes and provided modeling from cut sections, displaying the deformation and irregular objects in HBIM. In the following section, we would like to emphasize dome modeling since the reconstruction of dome elements is one of the main applications of our method.

3.4.1 Dome modeling

The dome like structures is a less researched topic in the literature. In this section, we explain the most relevant research work close to our scope. HBIM is a relatively new research area, and there are few studies related to domes. In one study, Chizhova et al. (2017) pre-segmented dome blocks of specific Orthodox Church design and extracted onion type profile curves using a second-order polynomial function. In order to document structural deformations in the work of Chiabrando et al. (2017), the authors investigate the problem of how to handle visualizing stratigraphy, decay analysis, and previous survey/interventions in HBIM. They come up with a solution of displaying polygons with movable vertices on the parametric elements in BIM. In the proposed research method, we focus on object extraction from noisy point clouds and identifying the geometrical deterioration from the ideal case.

Dore (2017) works on implementing a modeling strategy that uses cut cross-sections to generate a 3D model into HBIM. His work aims to extract deformed structures within this concept. However, the system has no assumptions about where the changes occur in data. Therefore, the user must select the number of cut sections and their interval from input point cloud segments into the system.

Capone and Lanzara (2019) used a parametric tool based on the existing European Treaties for Dome structures. They use meridian curves for defining parametric dome shape and compare which is suitable with a vertical section of the point cloud (Capone and Lanzara, 2019). However, this process is still tedious, since selecting the arch to represent the whole must be done carefully and accurately. It is also notified that such detailed documentation in the Islamic architectural world is limited or undocumented, particularly for Ottoman Mosque design.

In this research study, we limit our scope of object extraction from noisy point clouds with a RANSAC based approach directly on 3D object extraction. We also investigate whether the noisy point cloud is a deformed structure of the ideal or noise from the acquisition.

4. METHODOLOGY

4.1 Outline of the Methodology

Based on the scope of the research questions and the literature review analysis, the proposed methodology takes two main directions: (a) parametric feature extraction (b) accelerating the segmentation process with a knowledge base. The proposed method follows a hybrid object recognition approach using data and model building reconstruction approaches in a hierarchical-based procedural manner:

i. The research method extracts simple primitive shapes representing the architectural structure from noisy point clouds semi-automatically.

ii. The patches of points derived from the extracted geometric shape are investigated, thus guiding the user to distinguish possible alterations of the ideal geometry in the noisy unstructured point cloud.

iii. The output of the extracted parametric geometric element can be used as a seed to initialize the architectural composition based on a hierarchical order of architectural typology.

The whole methodology is executed in four main steps. The overview of the methodological sections is given in Figure 4.1.

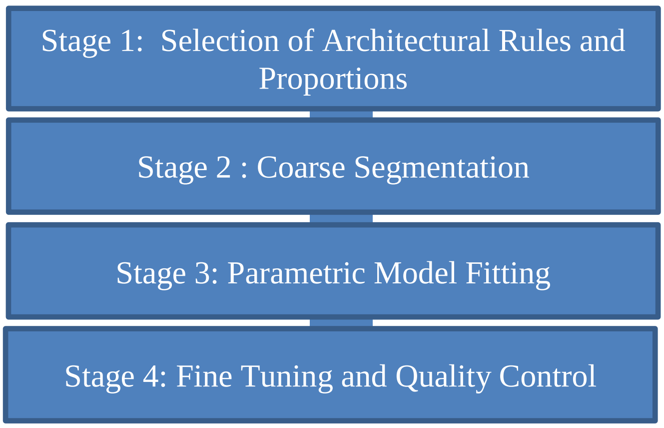

Figure 4.1 : Overview of the proposed methodology.

The developed method is applied to different architectural components of the mosque structure and considers window openings and domes using architectural knowledge in Ottoman Classical Era Mosque Design. The geometric model reconstruction workflow is presented in (Figure 4.2).

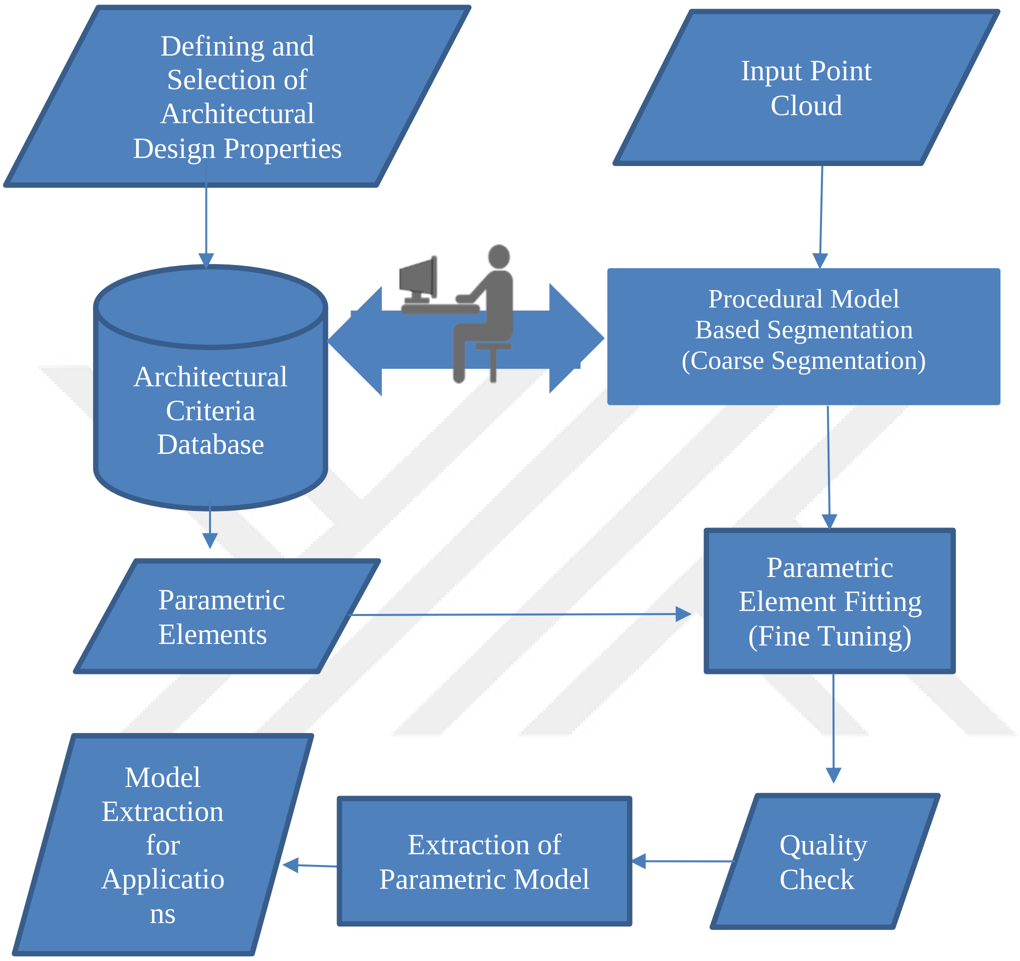

Figure 4.2 : Workflow of methodology.

4.2 Architectural Knowledge

Geometry, particularly domes in religious structures, is associated with spiritual symbolism and a manifestation of the divine in various civilizations and religions such as Christianity and Islam (Grupico, 2011). Consequently, mosque design syntax has evolved and become significantly varied through the centuries and across geographies. Among these, Ottoman architects made contributions to mosque design by applying new construction techniques and aesthetic innovations that allowed the unification of interior space and thus gained value as monumental structures (Kuban, 1986).

According to Kuban, (1986), Ottoman mosques became the symbol of the Islamic world, especially with the design and developments of domes and minarets.

Semantic rules of existing architectural rules and applications are investigated for relationships of mosque architectural elements based on previous architectural works detailed in the following section. First, we consider a number of derived generic rules to lay the foundations of our architectural knowledge base in a hierarchical tree-like structure for the mosque design elements from the available architectural knowledge in the Ottoman Classical Era. Next, we detail these aforementioned properties, starting with a short introduction of Ottoman Mosque design principles.

4.2.1 Evolution of Ottoman mosque design

Edirne Üç Şerefeli Camii, built-in 1447, is accepted as the prototype of classical-era mosque design in the Ottomans. Following this mosque, İstanbul Beyazıt Camii (1506) extended the dimensions of this in size. The general significance of these mosque types is composed of a cubic main body, vaults (dome), mihrab, courtyard, porticos, and iwan. These properties form fundamental typological components in the Ottoman classical mosque design. Kuban reports that Architect Sinan succeeded in previous contributions in the following century and mastered this typology into a mature state both in size and design (Kuban, 2016). The specifications of this era compose formal, geometrical construct and proportional harmony (as cited in Özgüleş, 2008). However, even though the classical era mosque design has continued through ages, the distortions of geometrical aspects play a significant deterioration in mosque design (Aksoy Varol, 2001). In this sense, Aksoy schematized and grouped plan typologies and analyzed shape grammar for Sinan's mosque design to provide a base for understanding the core relations to construct the shape grammar groups. Therefore, we benefit from Aksoy Varol's work, our observations, and other sources to define generic rules for the mosque design criteria. The details of these rules will be explained in detail in the following sections.

4.2.2 Architect Sinan and classical era Ottoman mosque design

As introduced in previous section 4.2.1 , the design syntax of the mosques has altered through civilizations in different geographies. Ottomans contributed to the development of the mosque design by specializing in new construction techniques and aesthetic design, where new styles allowed the unification of the interior space and gaining the monumental values to structure (Kuban, 1986). Outputs of these brought a distinctive design which provided the possibility to start examining the structural composition in detail. However, unlike Western world architecture, where architectural elements are well documented in construction techniques and geometrical and semantic patterns of rules in detail, such as European classical architecture, there is not much research in the literature on Ottoman Architectural styles and grammar (Erzen, 1981; Aksoy Varol, 2001).

The renowned *Chief Imperial Architect Mimar Sinan Bin Abdülmennan*, known as Architect Sinan (1489 -1588) in short, was an engineer and an architect beyond his time. Without any doubt, his innovative contributions to Ottoman architecture in defining the functional and structural totality of spatial design makes him not only a pioneer of today's Turkish architects but also a genius of his era. He served under the reign of five sultans throughout his career and was the chief of architects and engineers in the Ottoman Empire for half a century. Among numerous structures, he is affiliated as the Architect of such places as palaces, tombs, madrassahs, hospitals, baths, aqueducts, etc. his various mosque structures play the most significant influential importance.

Today, according to Turkish Religious Affairs, there are at least 350 mosques solely in the historical peninsula of Istanbul and 3,530 in the Istanbul Metropolitan area (*T.C. Diyanet İşleri Başkanlığı*, 2021). The majority of these mosques designs contain traces of Sinan's works. However, unlike Western architecture, historic treaties do not explicitly define the geometries, profiles, combinations, and proportional relations (Erzen, 1981).

4.3 Geometric Rules of Mosque Layout and Proportions

As we explained in section 2.3, feature extraction algorithms are used to extract components of the building models. The presented method describes a 3D architectural elements library based on primitive geometric shapes that define and contain mosque compositions relations between components examined in our observations and previous research available from architectural resources. In an example of the available works Şener and Görgül, (2008), the authors presented an educational software to analyze the Ottoman mosque grammar interacting the user and classical era mosque plans for possible limited layouts, hence directing the students to learn the proper relations of the mosques and their components, such as the height ratio of the minarets to the mosque dimensions.

Based on the available architectural knowledge and according to the observations carried out both on the point clouds and several historical mosques of Sinan, the significant elements of the mosque were classified into three parts in the form of geometrical shapes:

a. Linear (planar) features

b. Circular (arc) features

c. Details (complex geometric ornaments)

We formed an object-oriented class, and we subdivided the main mosque structure objects. It is important to mention that our hierarchical class definition is based on the principal elements considered in our research scope (Figure 4.3).

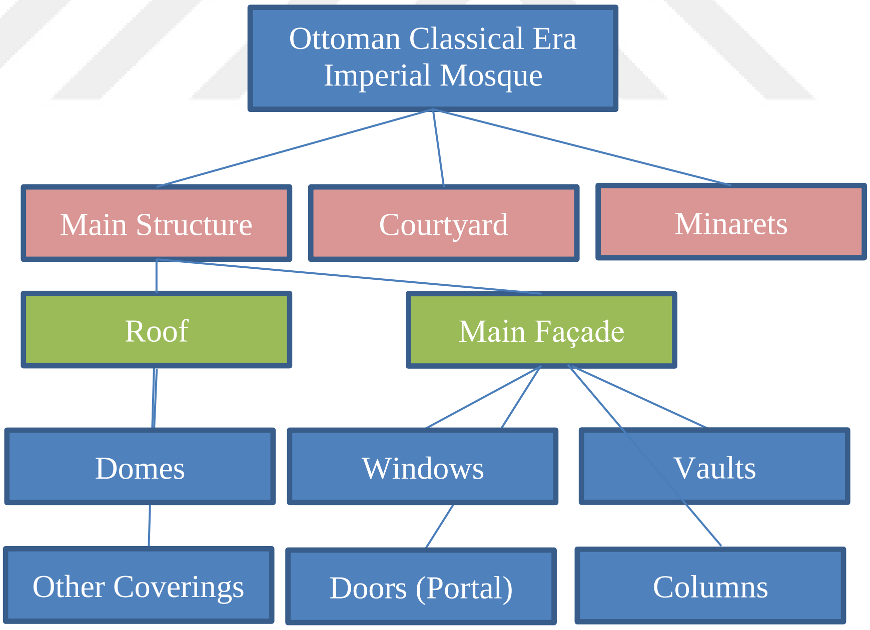

Figure 4.3 : Ottoman classical era imperial mosque hierarchical elements.

Visual consistency, similarities, and recurring structure are observed in architectural elements of Sinan Mosques and his successors (Figure 4.4). Kuban, (1986), emphasizes that Ottoman's used the semi-spherical dome as the sole element of roof covering and based on the knowledge of the East and Western architecture and Sinan harmonized it into a spatial form-based of a system of domed baldachin, which gives the basic design of the monumental domed structures. These visual relationships followed for centuries in the mosque design are perceived in the Historic Peninsula at a glance.

Figure 4.4 : From right to left: Rüstempaşa Mosque was built in 1563, Süleymaniye Complex 1558, both famous works 16th century Architect Sinan. Yeni Cami, 1665 on the left.

The specifications of this era compose formal, geometrical construct and proportional harmony. Even though the classical era mosque design has continued through ages, the distortions of geometrical aspects play a significant role in the deterioration in mosque design (Aksoy Varol, 2001). The Ottoman architecture used semi-spherical domes used for the roofing gave the silhouette footprint of domes as the signature of Istanbul. There have been numerous works describing the contributions of Sinan in making the structural design and perfection of the dome in harmonizing it with the building mass. Another key for his mosques is the unification of the praying area. However, there are limited resources on the façade elements and architectural shape grammar of the Sinan Era mosque design (Erzen, 1981). Ottoman classical mosque only in the plan layout, the 3D syntax such as windows type and localization were evaluated only in 2D layout.

4.3.1 Geometric rules of domes layout and proportions

Perhaps, the most researched architect of Anatolia, Sinan, used some essential topological structural characters in his imperial mosque designs. Sinan used five different typologies of layouts in his mosque designs based on the number of domes and their relation to the main dome and walls. Single domed, multiple domed, side unit based dome, semi-dome used on the side of the main dome and polygonal layout Kuban (1986). In the methodology presented in this research, we limit our work to his semi-dome supported variations of mosque design. The variations of possible semi-dome (in blue) compared to the central dome in the layout organization adopted from Kuban can be seen in (Figure 4.5).

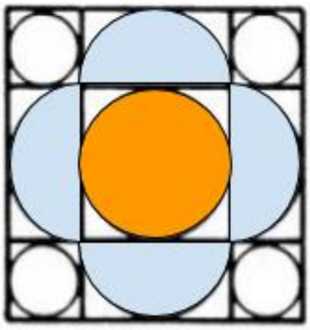

Figure 4.5. : Conceptual variations of semi-dome layout in Sinan’s designs adapted from Kuban, (1987).

Based on architectural reviews of classical era mosque design, we consolidated Sinan's design syntax's geometric and semantic relations. Generally, the main mosque building has a cube-like structure based on a square plan. The main structure's height is between 1.2 to 2 times the width of the main building (Aksoy Varol, 2001). The central dome is followed by the expansion of the other domes in lower vertical levels of the domes (Şener and Görgül, 2008). According to Kuban, the Ottoman architecture style differentiates from others because they used semi-spherical domes formed the only form of roofing (Kuban, 1986). Therefore, one focus of our research interest stays in these particular structures. As mentioned earlier, the Ottoman classical era mosque architecture can be defined by the schema of the mosque dome layout (Kuban, 1986). According to these, dome composition has some specific rules. We considered some of the principles defined by Aksoy Varol, (2001) within our model parameters and special constraints.
These are:

- Central dome and the center of the mosque structure lay at the same point.
- The width of the side unit is equal to the radius of the semi-dome, and the length of the side unit is equal to the diameter of the semi dome
- The width of the side unit is equal to the width of the small dome diameter.

These variations are graphically visualized in Figure 4.6, combining two small domes on the right and four on the left side of the main structure. combining two small domes on the right and four on the left side of the main structure.

A network for the mosque roof layout starts with the main dome for the procedural-based modeling step of the mosque. These variable parameters are included in the python class MosqueParam encoded in JavaScript Object Notation (JSON) format. We preferred JSON because of its flexibility for data exchange and readability by humans and machines.

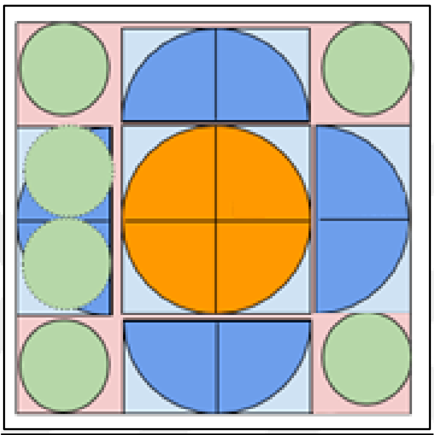

Figure 4.6 : Zones displaying the possible compositions of Sinan's dome design layout syntax at different levels adapted from Aksoy Varol, (2001).

The architectural rules presented in this section provide an approximation of the input point cloud to determine the mosque type and coarse segmentation of the roof level structures following the initialization of the main dome.

As we mentioned earlier, further proportional ratios and variations in literature are limited. Therefore, historical drawings and maps from Gurlitt, (1912); Pervititch, (1934), Ülgen, (1951) in Figure 4.7 were considered as additional information to make a general comparison with the already available information for our case.

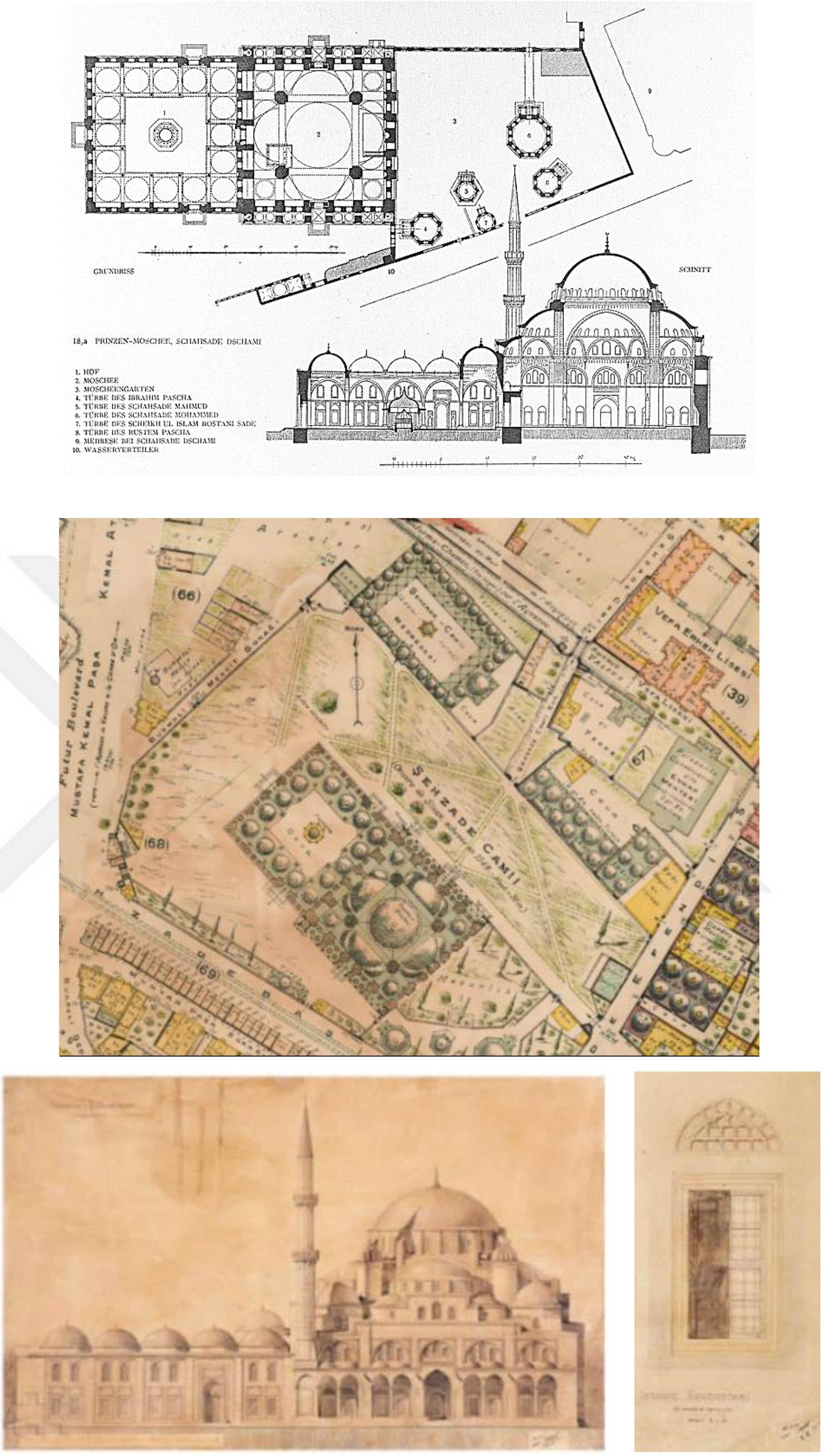

Figure 4.7 : Examples of historic drawings left page: drawings of Gurlitt, (1912), below Jacques Pervititch's insurance maps (1935), bottom: drawings of Architect Ali Saim Ülger (1951).

In addition, we formulated the following rules Figure 4.8 :

- The central dome has the highest elevation and center among all the other domes among all domes.
- Only minaret spires can be the highest elements compared to domes.
- Domes at a similar elevation are expected to have similar properties in vertical such as diameter and positioning on the plan.

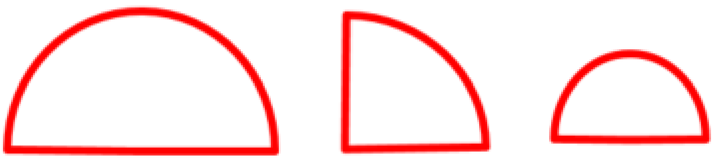

Figure 4.8 : Schematic view of domes; main, semi, and minor follow a radius based hierarchy.

4.3.2 Geometric rules of window openings

In Sinan’s windows, the simple parallelepiped rectangular window openings can yield sophisticated ornamental lintels and pediments as well as circular or pointed arches. Erzen's (1981) work describes the design with a simple facet view of windows (Figure 4.9).

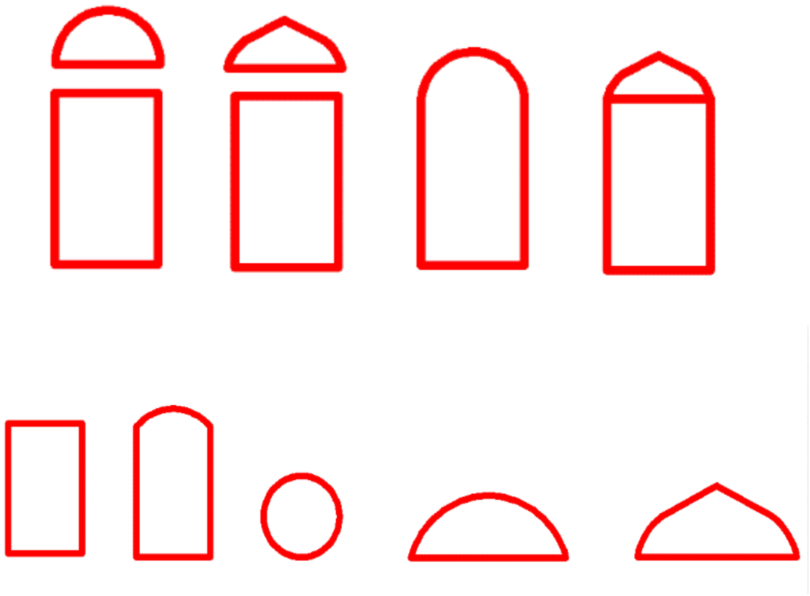

Figure 4.9 : Reproduction of Sinan’s window types from Erzen 1981.

Although Erzen didn’t considered, the details of the lintels, cornices, pediments are included in this research by grouping them.

Repetition of façade elements is expected. Therefore, this study considers that similar window openings would follow similar ornamental styles on the same wall surface. In Western architecture, such as in the works of (Dore, 2017; Nalani, 2014), repetition patterns determine the parameters of the buildings and strictly follow the vertical and horizontal distribution. Although Sinan’s window organization follows similar distribution, especially at horizontal levels (Erzen, 1981), some may differ in dimensions and ornaments. Examples of window organization on the same facade of the Şehzade Mosque (Figure 4.10).

Figure 4.10 : Various sizes and types of window openings used by Sinan.

In the work of (Chevrier et al, 2010) and (Murphy et al, 2009), the parametric shape of the 3D model of window elements is selected, and numeric values are assigned to define the parameters and the final adjustment on the point cloud. They used the work of (Boulaassal et al, 2007) to compute the straight lines and curves to guide the user to adjust the parameters and integrate mesh models of sculptural elements. Our method strategy for Sinan’s dome and window patterns uses defined typological rules and parametric object extraction, which will be explained next.

4.4 Parametric Object Extraction

Parametric elements are essential in defining 3D building model elements for various reasons. RANdom SAmple Consensus (RANSAC) algorithm introduced by (Fischler and Bolles, 1981) is an efficient algorithm widely used in computer vision for detecting simple shapes in 2D and 3D noisy point clouds. It is reported that it can return successful results compared to similar algorithms even in cases where the outliers ratio is high. On the other hand, the area for segmentation and model needed to be defined for the algorithm because it will look for a model at one time.

In the literature, RANSAC is commonly used to extract primitive shapes such as spheres, cylinders, and planes from point clouds. Moreover, it is a common method for detecting planar roof surfaces, such as in (Gonultas et al, 2020; Atik et al, 2018). In earlier works presented (Kivilcim and Duran, 2016; Kivilcim and Duran, 2021), , we presented a RANSAC based methodology for extracting parametric elements of the mosque facade. In general, the pseudocode of the presented method for geometrical model extraction from the noisy point cloud is as follows:

- User Input: the point cloud
- User Input: Selection of the primitive shape model
- Pick *n* random points based on the model
- Check preconditions: coplanarity/ colinearity based on model condition
- Estimate model
- Test the model, compare it to the previous best model
- Based on the outputs, return the parametric object properties, dome center and radius, inlier/outlier point data, and the success rates or select a new candidate.

As it can be seen, the proposed method follows a general RANSAC for various primitive objects that form the base of parametric architectural elements.

4.4.1 Geometric primitives

This section gives the properties of the standard geometric primitives of the plane, sphere, and circle.

4.4.1.1 Plane

In R^3, the general equation of the plane is given in equation (4.1).

$$ax_i + by_i + cz_i + d = 0 \tag{4.1}$$

The normal vector for the plane can be computed as in equation (4.2).

$$\vec{n} = (a, b, c) \tag{4.2}$$

A set of points whose coordinates (x, y, z) satisfy the condition of the plane when the cross product of any two vectors (u, v) derived from any 3 arbitrary points on the plane would be orthogonal to both vectors. Since both of these vectors are in the plane, the cross product would be perpendicular to the plane and give us $\vec{n}$ = uxv. So the equation of the plane could be retrieved. Planes in Euclidean space can be defined with three points. Walls, ceilings, and many other geometric patterns of any man made structure include planes as their core primitive shape.

4.4.1.2 Sphere

A sphere in R^3 Euclidean space is formed by a set of points that are in a constant distance (r) to a given point (center). In analytic geometry the sphere equation is given in equation 4.3 where the center coordinates are (x_0, y_0, z_0) and (x,y,z) are each point.

$$(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 = r^2 \tag{4.3}$$

In order to determine the four unknowns of a sphere (r and center coordinates), we would need at least four linearly independent equations; hence four points that are non-coplanar is enough to solve the unknowns with the determinant equation 4.4 and shown in the Figure 4.11.

$$\begin{vmatrix} x_0^2 + y_0^2 + z_0^2 & x_0 & y_0 & z_0 & 1 \\ x_1^2 + y_1^2 + z_1^2 & x_1 & y_0 & z_0 & 1 \\ x_2^2 + y_2^2 + z_2^2 & x_2 & y_0 & z_0 & 1 \\ x_3^2 + y_3^2 + z_3^2 & x_0 & y_0 & z_0 & 1 \\ x_4^2 + y_4^2 + z_4^2 & x_0 & y_0 & z_0 & 1 \end{vmatrix} = 0 \tag{4.4}$$

Examples of spherical geometry can be found as domes in many historical mosques in Anatolia. Domes became an essential element during Ottoman architecture, especially those commissioned by sultans and their families, and it continues to dominate today's conventional mosque design.

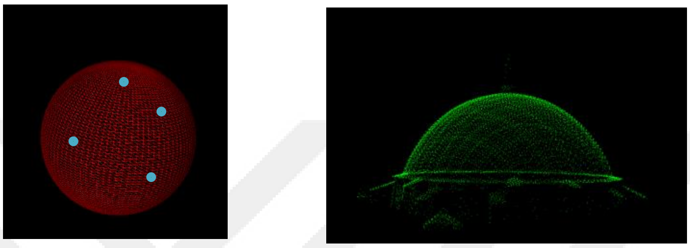

Figure 4.11 : Left: Four non-coplanar points define a sphere in R^3, right: example of the spherical dome in the point cloud.

4.4.1.3 Cylinder

A cylinder is defined as the set of the points in R^3 space that are in a fixed distance to the axis of the cylinder and the perpendicular planes to the axis. In analytical geometry a cylinder is defined by radius (r), height (h) and cylinder axis r. Nevertheless, the cylinder can be considered extraction of a circle along the cylinder's axis. Therefore, non-collinear points are enough to define a circle on a plane (Figure 4.12).

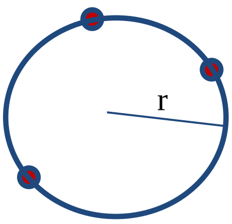

Figure 4.12 : Circle passing from 3 non-colinear points.

The plane which contains the circle passes through three points is defined as:

$$ax_i + by_i + cz_i + d = 0 \tag{4.5}$$

The normal of this plane through the center of the circle would give the axis of the cylinder. Radius (r) and the center coordinates of the circle center (c) can be calculated because the distance between the points to the center is constant and equals the radius.

olving the linear equations of the distance between the points and the radius would give the r and c values.

General equation of a circle:

$$(x - x_o)^2 + (y - y_o)^2 - r^2 = 0 \tag{4.6}$$

Any point located perpendicular to the given plane and in the radius distance would be the in the cylinder surface. Thus, the cylinder can be extracted until the last parallel plane within the extracted path.

We implemented the adaptive RANSAC method from (Hartley and Zisserman, 2004) using the formula given in equation (4.7) to determine the maximum number of iteration (N), where (s) size of the sample set, (e) is the outlier ratio, (p) is the probability of no outliers is selected as 0.99 conventionally.

$$N = \log(1\text{-}p)/\log(1\text{-}(1\text{-}e)^S) \tag{4.7}$$

In practice, the outlier ratio e is almost unknown a priori; therefore, computations can start based on worst case possibility such as %50 of outlier ratio and, the algorithm can be adapted as more inliers are found in (Hartley and Zisserman, 2004). In applying the proposed research methodology, this fact is considered since the point cloud datasets have an unknown inlier ratio vs. the given primitive models.

$$N = \infty,\ \text{sample\_count} = 0 \tag{4.8}$$

While N > sample_count, choose a sample and count the number of inliers. Set e_0 = 1 – (number of inliers) / (total number of points). If $e_0 < e$ Set $e = e_0$ and recompute N from e.

For establishing the candidate model, a sphere in R^3 euclidean space center coordinates of a sphere (x_0, y_0, z_0) and each point (x,y,z) satisfy the basic equation (4.9).

$$(x\text{-}x_0)^2 + (y\text{-}y_0)^2 + (z\text{-}z_0)^2 = r^2 \tag{4.9}$$

At least four linearly independent equations determine the four unknowns of a sphere (radius and center coordinates); our script checks the selected four points to be non-coplanar. Therefore it is enough to solve the unknowns with the determinant (Kivilcim and Duran, 2021).

5. APPLICATION

This chapter gives information about our case study site Şehzade Mosque and its significance for the presented research. Following the introduction, available datasets, and application of the proposed methodology in different cases. Finally, interpretation of the findings and discussion of the method results are given at the end.

5.1 Study Area

Sinan built Şehzade Mosque in 1548, a time that corresponds to the peak years of the golden era of the Ottoman Empire under the regime of Kanuni Sultan Süleyman, known as the Kanuni the Magnificent by Westerners. The mosque was dedicated to Kanuni's son, prince Mehmet who died at an early age. The complex is the first significant mosque for the sultanate by renowned Architect Sinan, who, according to some, defined it as his apprenticeship. However, his design of the spatially centralized symmetric plan of this mosque was replicated countless times over centuries throughout the lands of the Ottoman Empire, such as in the design of the famous Sultan Ahmet Mosque (1609). Şehzade Mosque is situated on the third hill of the peninsula, in the heart of the historical district of Istanbul's UNESCO World Heritage (Göncüoğlu and Kumbasar, 2006).

The symmetrical layout plan is enriched with an elegant distribution of domes and arches with the central dome around 19 meters radius and 37 meters height carried by four elephant pillars (*Istanbul Governorship*, 2017). The change of environment in the mosque's vicinity within the past century can be seen in Figure 5.1; it is a living monument and thus requires continuous maintenance.

Figure 5.1 : Views of Şehzade Complex from various years; 1910s (IBB Ataturk Lib.), 1960s (source unknown) and 2020.

5.2 Available Data

In recent years, Istanbul Metropolitan Municipality procured a survey and restoration project for Şehzade Mosque Complex and its surrounding area as a base point for future conservation works (Figure 5.2). Scans were acquired from 530 for the documentation survey campaign, using a TLS of RIEGL VZ-400. The nominal measurement accuracy of this scanner is 5mm and with a precision of 3mm at 100m range according to the manufacturer’s technical specifications. In order to minimize possible gaps in the point cloud, a particular emphasis was given during the data acquisition. Therefore, various scan stations were planned to acquire point cloud data inside and outside of the structure. All the data received from this project was delivered as georeferenced in the Turkish national coordinate system.

Figure 5.2 : Data acquisition in various sections of the mosque. Dataset produced by Istanbul Metropolitan Municipality reported as approx 1 billion point data.

We experimented presented methodology in 3 different real-life cases: beginning first with the implementation of a single window, where the main components are planar; secondly, extracted the main dome and analyzed non-dome labeled segments; and finally on the decomposition of the roof composition structure with the example of other domes (Figure 5.3).

Figure 5.3 : Positions of case study areas on Şehzade Mosque.

The developed point cloud process module was named Point cloud operations (Pops) was coded to apply the methodology of the research. When the relevant class is initialized, the module automatically generates a file to initialize properties of the study area as it is more convenient to work using a hierarchical schema. As introduced in the previous section, point clouds were used as inputs for the case studies.

In order to start the point cloud process, the user needs to coarsely select the point cloud of interest before running the rest of the program. In order to ease the selection, a bounding box is placed and can be adjusted to the limits; alternatively, coordinates can be measured and entered manually. First, the point cloud is read using the Pops module written in Python. Next, the cartesian coordinates are simplified by subtracting the unused digits of the coordinate system, and the orientation is transformed by convention since it can cause problems in the working environment of OpenGL, which we use in our implementation. Following this, the point cloud data is forwarded through a decimal simplification script, allowing the unnecessary parts of the point coordinates to be subtracted for better performance and avoid OpenGL performance issues.

The implementation was coded with Python and, the visualizations were carried out using Visualization Tool Kit (VTK). We preferred Python because it is an object-oriented programming language and implementation of algorithms is relatively easy. Furthermore, VTK is a library developed for scientific visualization purposes, and the python wrappings for the integration of its C++ library are provided by Kitware (Schroeder et al., 2006). In addition, we used some modules of Python such as NumPy and scikit-learn in our codes for matrices and numerical and other operations.

After extracting the parametric objects, the results were exported to FreeCAD using its Python module and handled in Autodesk Revit using IFC export/import methods.

We made our initial test of our applications with a mid-range consumer-grade laptop with a quad-core Intel i7 5th generation processor with 8 GB RAM, running Windows 10. At the same time, the processing time for the applications was only a few minutes level.

5.3 Results and Discussion

5.3.1 Segmentation

As our first case, we used the point cloud of a single window of the Şehzade Mosque to segment unstructured point cloud data for architectural façade elements. First, we applied a transformation to rotate the points on the XY axis. Then, a moving threshold value measured in the fieldwork and point cloud was introduced (Figure 5.4) to extract the highest possible level of detail. The threshold value was limited to the search space on the input point cloud, and its parameter shifted each time the algorithm ran. In the following, the depth changes on the threshold can be seen (Figure 5.55). Finally, the point cloud was segmented in various planar details of a single-window entity (Figure 5.6).

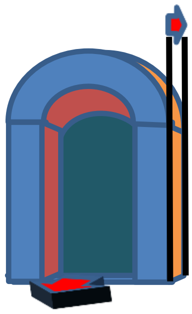

Figure 5.4 : Definition of the threshold depth value.

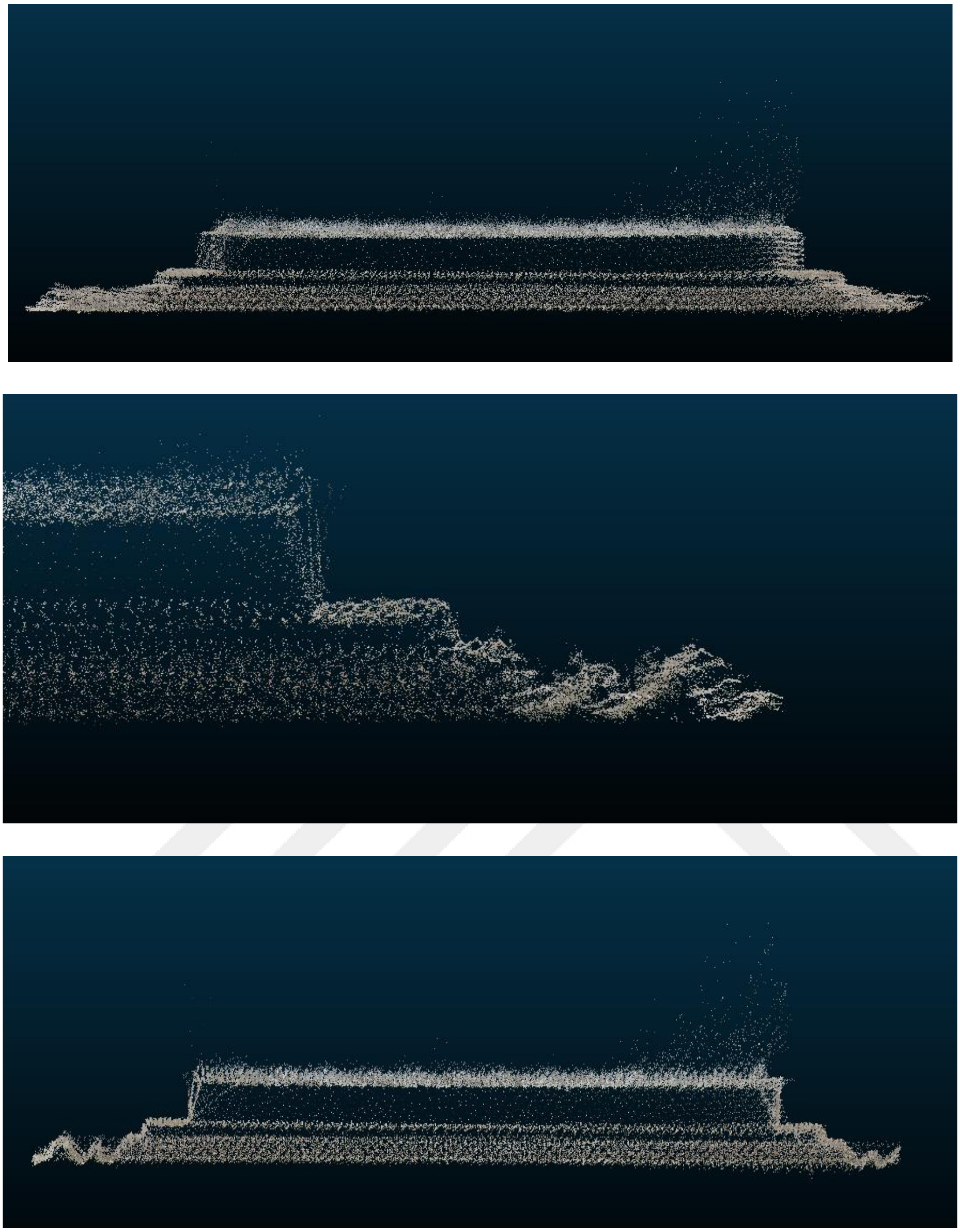

Figure 5.5: Examples of the cross sections for defining the depth threshold structure.

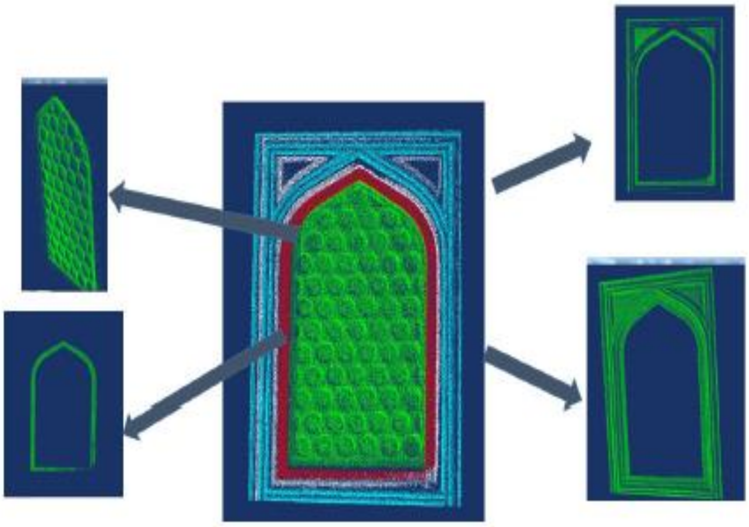

Figure 5.6 : Segmentation result of a complex arch window element.

Further, we applied the segmentation algorithm using the same parameters to a group of windows sharing the same part of the wall. The user needed to identify the window type from the architectural library to initialize the number of sequences the algorithm ran. The algorithm was applied to segment a group of windows on a planar wall shown in R,G,B colors in Figure 5.7 semi-automatically. The resulted segments visualized in different colors.

Figure 5.7 : Input point cloud of a window group and result of the segmentation.

Following the application of the window group, we applied the methodology to the main dome of the mosque as our third case. For this part, the user selects a coarse area of the dome using a bounding box for both inside and outside in the scan data (Figure 5.8), then the algorithm is directly applied.

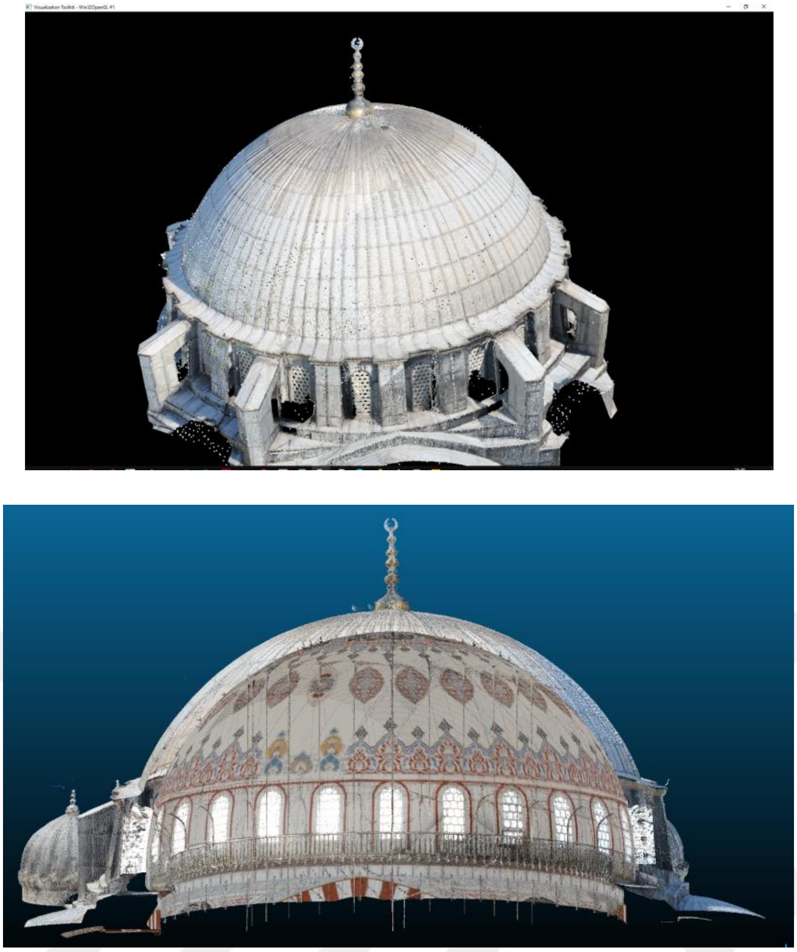

Figure 5.8 : Top: Dome view of the point cloud. Bottom: A cross section of the input point cloud, displaying both indoor and outside of the main dome.

The segmented point cloud clusters are displayed in Figure 5.9 and in Figure 5.10 as the green points that are the consensus of the parametric model of the dome.

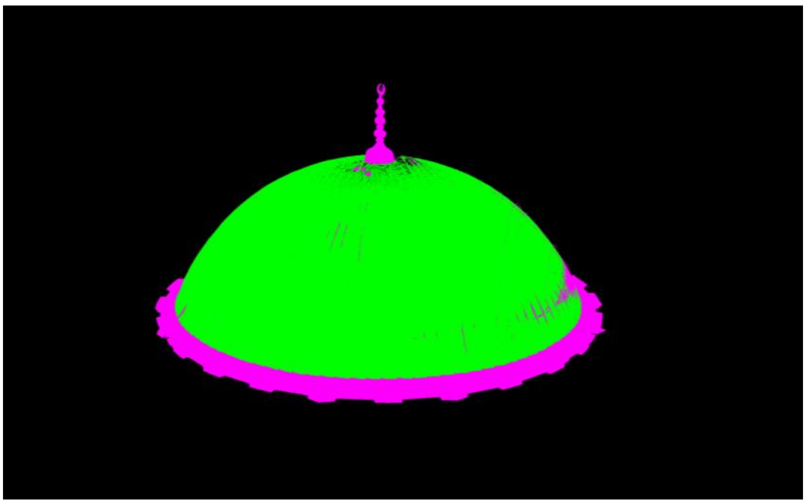

Figure 5.9 : Segmented point cloud of the outside dome.

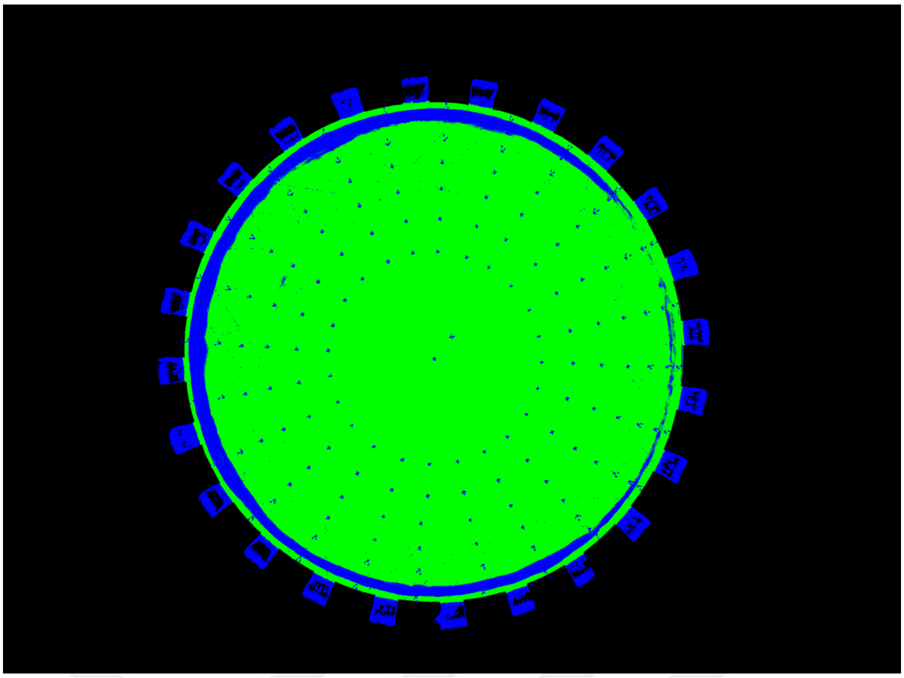

Figure 5.10 : Segmented point cloud from interior of the dome.

The distributed dots are seen in Figure 5.10 result of the hanging cables from the mosque chandelier seen in vertical view. Points labeled as non-part of the dome are given in the Figure 5.11.

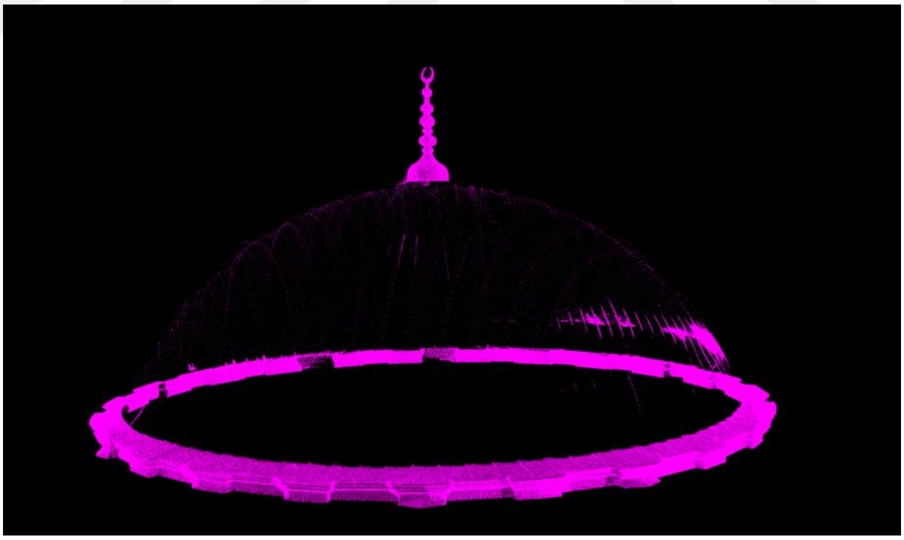

Figure 5.11 : Points as labelled not belonging to dome.

5.3.2 Decomposition of the unsegmented parts.

In order to process further deconstruction of the non-dome labeled points (Figure 5.11), Density-Based Spatial Clustering of Applications with Noise (DBSCAN) was used. DBSCAN is a machine learning clustering algorithm initially developed by (Ester et al., 1996).

DBSCAN is an unsupervised clustering technique, which does not require the number of clusters beforehand, and returns clusters and the remaining points. Thus, the user is only required to define two parameters: (a) epsilon, a value for the radius to test the distance of seed point to its neighbors, and (b) the min number of points parameter to classify whether a point is a core point of the cluster. DBSCAN implementation in this research was based on the skilearn module of python. The example results with the parameter values of epsilon = 0.05m and the minimum number of points selected as 10 are presented in the Figure 5.12 and in the Figure 5.13 demonstrating the success of detecting different cluster classes.

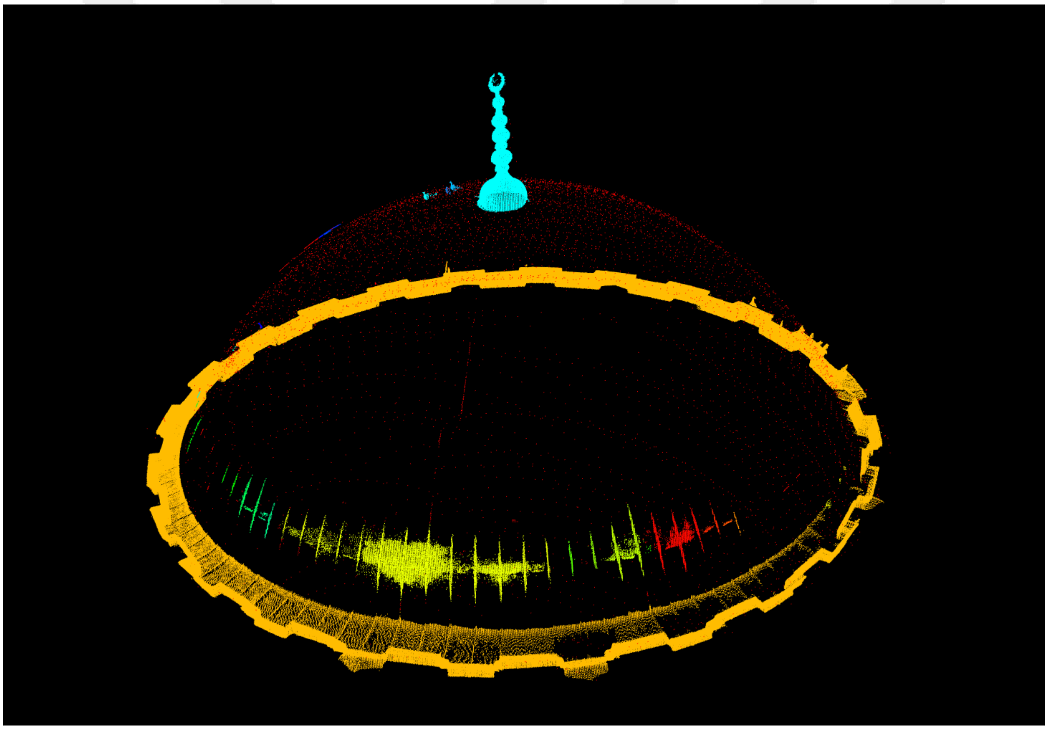

Figure 5.12 : Result of DBSCAN based clustering.

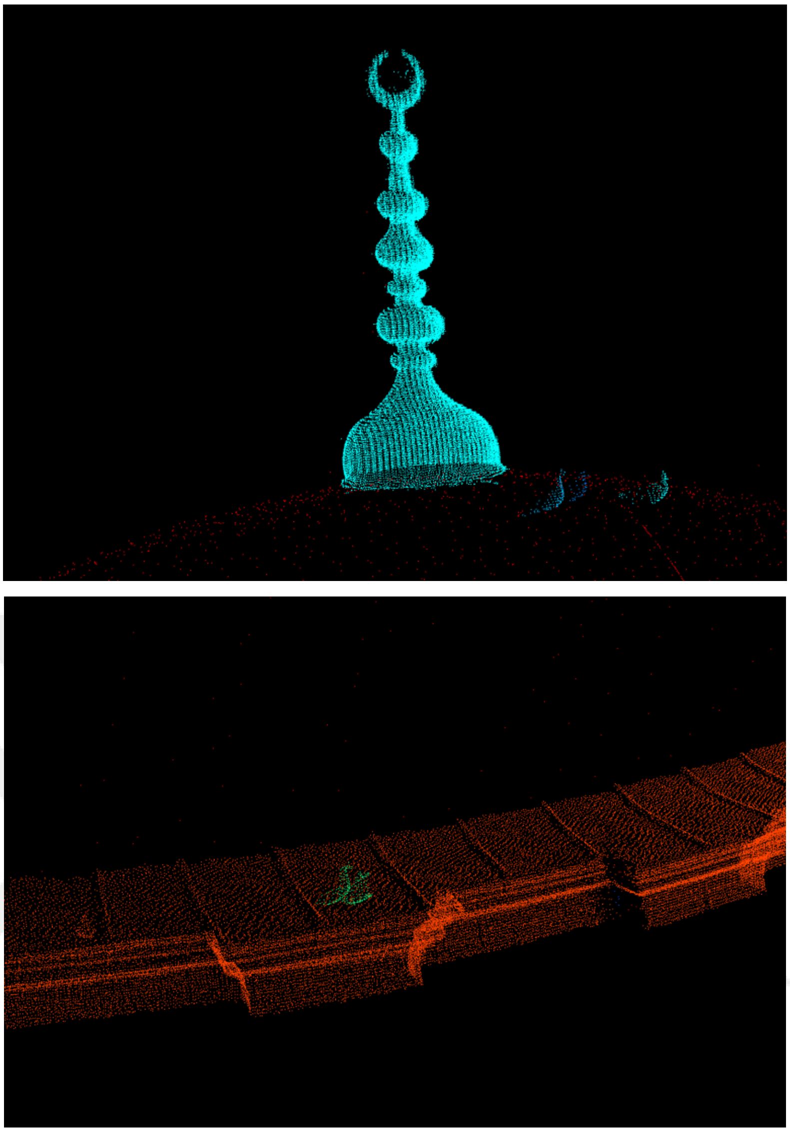

Figure 5.13 : Detail of DBSCAN clustering results.

5.3.3 Decomposition of the roof

A 3 level of dome decomposition overlayed and applied based on the principle design of the architectural knowledge as explained in the methodology section. First, an initial mosque decomposition procedural model is initialized. After the extraction of the central dome, the procedural decomposition segments for possible dome layout are based on the architectural criteria. In order to realize this, a 3D grid-like structure is projected parallel to the main walls of the mosque using the VTK unstructured grid datatype. Then, we check the symmetrical distribution of the point cloud to identify the similar dome composition in different parts. In symmetrical parameterized sibling, the dome is initially generated to tighten the parameters in search space.

Nevertheless, the user had the opportunity to make fine tunings. Based on the intersection with the point cloud and the grid, the system proposes bounding boxes for each area where the successive domes will be searched. The grid and the possible decomposition are presented in Figure 5.14 below.

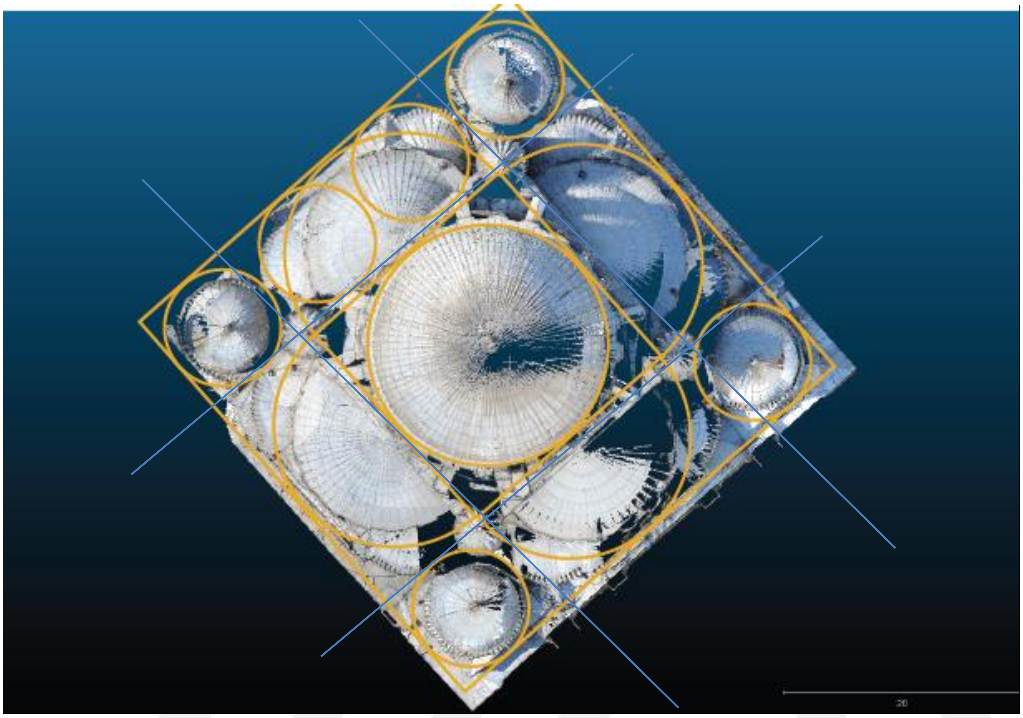

Figure 5.14 : Decomposition lines shown in blue.

In the following stage, segmentation of individual dome parts of the mosque was run for parametric model generation (Figure 5.15).

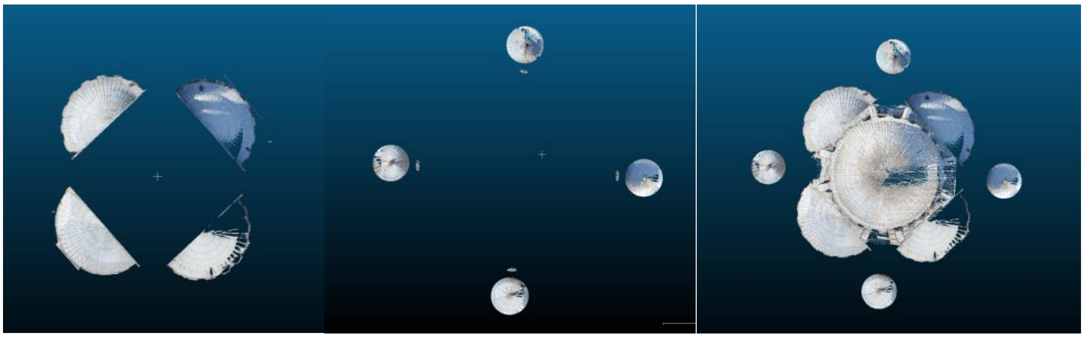

Figure 5.15 : Decomposition of the domes, the second level and third level.

In the final step, the resulting geometry can be exported using the parameters or an IFC file. The exported geometry is converted to an IFC file using FreeCAD software can be seen in Figure 5.16. FreeCAD is open-source CAD software that supports the extraction of the CAD drawings to the IFC file.

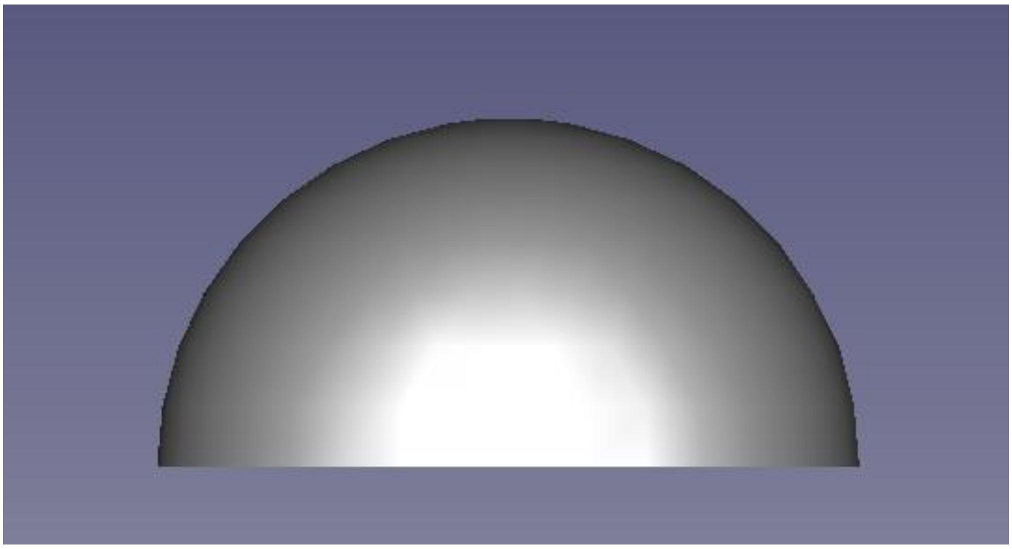

Figure 5.16 : The final output parametric dome geometry ready for BIM application.

6. RESULTS AND DISCUSSION

The visual consistency, level of geometric, semantic relations established within the case study are evaluated. We also compared to expert drawings from the point cloud with the result. In this section we give examples of results.

Our results of the iterations and the ratio of inliers detected for each dome is presented in Table 6.1.

Table 6.1 : Results of the iterations.

Dome Name	Best Iteration Sequence	Ratio of inliers %
Central Dome	8	0.85
NW Semi-dome	4	0.85
SE Semi-dome	6	0.81
SW Semi-dome	8	0.79
NE Semi-dome	8	0.81

In the Figure 6.1, the distance of each point to the parametric dome is presented. Red indicates the closest distance of points to the parametric shape.

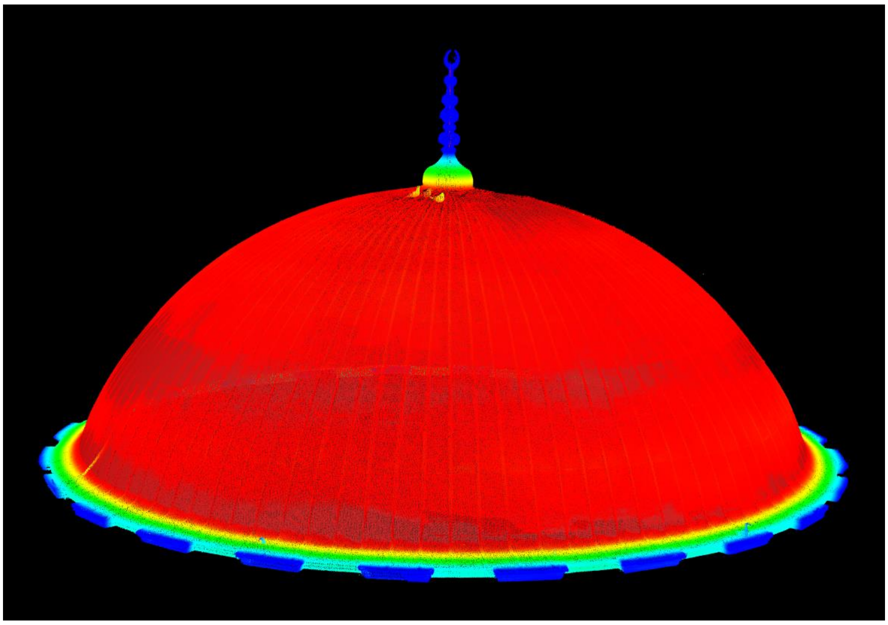

Figure 6.1 : The distance of each point to the extracted parametric dome. Red color indicates the closest, and blue the furthest points.

Finally, the cross-sections drawn by the conservation expert were compared to the produced sphere parameters. The architectural survey's overlay of the dome element with its thickness and our test result shows a close-fitting in Figure 6.2. The overall distance between the expert drawn and parametric shape was found under 3cm for this example.

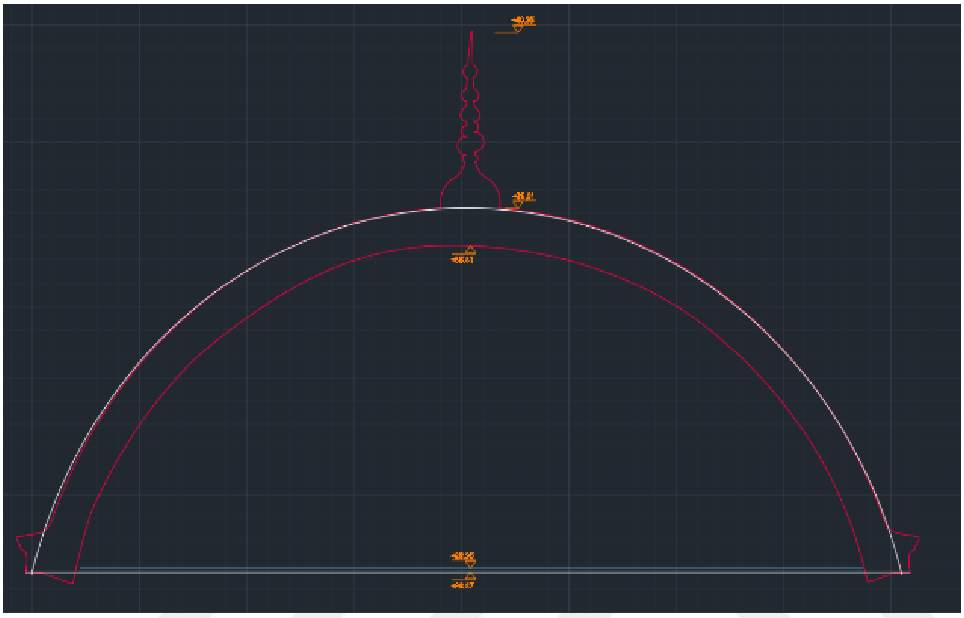

Figure 6.2 : Comparison of the Overlay of extracted Southeast Façade cross-section of the main dome (red) and the dome defined from the parameters from of methodology (white).

In the result of some of the other dome types segmentation, our output data shows a partial fit (Figure 6.3). This is because these domes are composed of a union of partially another primitive and other transition elements to the spire. Possible solutions to this issue are addressed in section 7.

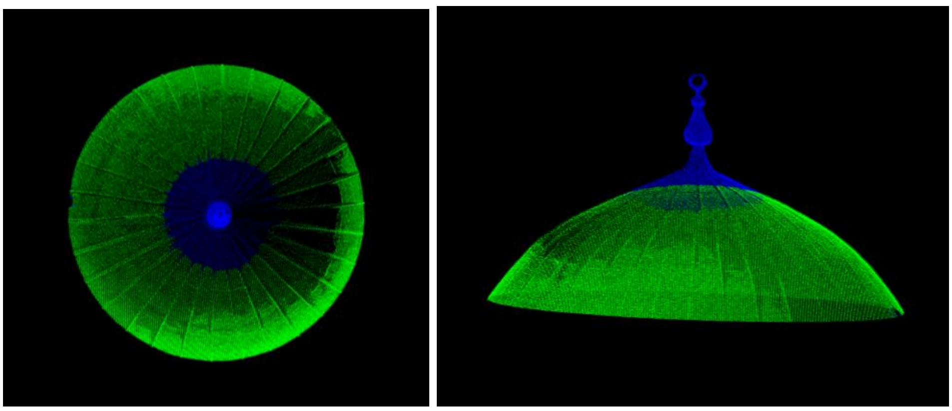

Figure 6.3 : Southeast dome segmentation result-top and side views.

7. CONCLUSION AND RECOMENDATIONS

This research investigated and demonstrated a methodology of modeling parametric elements from noisy point clouds for cultural heritage assets. In order to do this, we evaluated available architectural knowledge and made our observations to define architectural elements, rules, and semantic relations criteria database. We developed a parametric object extraction methodology using the generated criteria rule based on a knowledge base, specifically for the architectural elements of domes and windows. Then, clustering and segmentation are performed on noisy unstructured point clouds. Finally, parametric elements were extracted semi-automatically. Our algorithm uses a procedural approach based on architectural criteria rather than generating a procedural model and mapping on the point cloud. It applies directly to the point cloud to generate a heritage, site-specific model. We demonstrated the applicability of our research question and experimented on different cases from the Şehzade Mosque, one of the most significant works of Sinan. Integrating HBIM methodology with point cloud-based data processing techniques (Scan to BIM) is becoming significant for cultural heritage-related works. Because parametric elements and architectural families are one of the main components of this system, the presented method outputs provide parametric entities, and semantic information can be used as an input to these systems.

The method also guides the user for a possibility of straightforward interpretation of significant structural changes, based on significant changes in dome elements or simply craftsmanship, which can be due to natural and physical decays. However, the presented method has a number of limitations. First of all, the user needs to define the point cloud boundaries and import to the program as good, as it belongs to a single architectural element. However, this is not very easy since the two different elements' design patterns can intersect, and the definition of some of these uncertain areas is difficult on the point cloud. Therefore, a coarse selection may result in the extended running of the algorithm and wrong outputs. The parametric model only works with single models. Thus, it is likely that some elements may be a combination of different elements. As seen in the windows, the presented method makes no additional assumptions for parts of the structures, such as nearly five hundred years old weary ornamental designs with vague shapes. Thus, additional algorithms are needed to deliver solutions. One way to overcome these limitations can be to include eigenvalues. We consider this as a starting point for future work.

In the Ottoman Empire, mosque design and façade properties changed through the years; this seems to be a continuation of some common trends. Therefore, presented method can be extended in a number of ways to include new rule sets describing other variations and combinations. For example, dome structures varied in design during the following centuries. In order to fit a better model to the domes, geometrical shapes such as ellipsoid or parabolic could be applied. The presented method helps to highlight the altered parts of the structure in the eyes of the conservation expert.

The developed method can be extended to different structures as other properties are identified with algorithms such as similarity and new rules from the architectural domain. Furthermore, integrating machine learning and AI applications to extract geometric and semantic information for HBIM will be an essential step towards a fully automated solution. Also, open-source HBIM approaches and international initiatives are needed for the practical applications of HBIM.

Even though there are certain similarities in heritage structures, as seen in Sinan's mosques, applying the developed methodology and the results presented are a practical step working in the noisy point cloud using RANSAC-based methodology. The study showed few differences in cm between the expert drawings and the models extracted using the presented method. We want to extend our work to further details and local variations in dome elements and apply them to other architectural elements, including ornaments such as skirts and spires and enrich these with further semantic data.

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