An investigation on Success Factors for Scan to BIM Process

Master thesis

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Conceptual Formulation

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Introduction

Building Information Modeling (BIM) has been widely adopted within the construction industry and, project stakeholders extensively gain profit from BIM usage during the construction phase. However, this trend in Facility Management (FM) is not as anticipated. There are three main types of existing buildings in terms of creating BIM model for facility management; 1) new buildings without preexisting BIM model, 2) existing buildings with preexisting BIM model, and 3) existing buildings without preexisting BIM model. Most of the existing buildings place in the third category. FM industry could gain profit from using BIM by creating BIM model for the existing buildings.

From different methods of capturing data (image-based, range-based, and other techniques), laser scanning is the most popular method for creating models of the existing buildings (Volk et al., 2014). laser scanning can be used in three different ways within FM;1) Scan to Point Cloud 2) Scan to Dataset, and 3) Scan to BIM. Based on Volk et al. (2014) research, scan to BIM process consists of; data capture, data processing, object recognition, and BIM modeling. Based on the different characteristics of the building components (mainly Structural, Architectural, and MEP), these components were studied separately within Scan to BIM researches.

The most time consuming and labor intensive part of the scan to BIM process is object recognition and its linkage to BIM model or point cloud to BIM conversion. Within last years some solutions for point cloud to BIM conversion in forms of software have been released. However, this conversion is not fully automated and needs some manual efforts. Regards to these manual efforts, the point cloud to BIM conversion could be considered as a semi-automated process.

Some research conducted to explore the advantages and usages of laser scanning in managing the existing buildings (Mill et al. (2013), Alizadehsalehi et al. (2015)). Most of the studies addressed the technique for automating the process of creating the existing buildings BIM model by laser scanning (Tang et al. (2010), Brilakis et al. (2010), Tzedaki and Kamara (2013) Xiong et al. (2013)). Many efforts had been done to propose a semi-

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automated approach for point cloud to BIM conversion, especially for component recognition. However, appropriate efforts for exploring the success factors for this conversion have not been made and it seems essential to evaluate this conversion and propose some suggestions to improve it.

Research Questions

To bridge this gap in the knowledge, the issue could be addressed by answering the following questions:

Which success factors (SF) for Scan to BIM conversion are mentioned in previous studies?

Which tools for different steps of Scan to BIM conversion are available?

Based on experiments, using the found software within Scan to BIM process, what are practical success factors (SF) for conversion?

Methodology

To answer these questions, research is divided into two parts. First, success factors for Scan to BIM by reviewing the literature will be identified. Then regards to the literature, available tools for Scan to BIM conversion will be reviewed and the appropriate ones based on availability in the market will be selected to use in the experiment. Finally, success factors for Scan to BIM by performing two experiment will be explored in practice.

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Signature of the Supervisor

Abstract

The operations and maintenance spent about 90% of the total life cycle cost of a building. The saving in these tasks could result in a huge saving of time and cost. Since the utilization phase starts after completion of the construction, this phase is significantly affected by the construction phase. One of the most recent technologies which were introduced into the construction industry in last decade was Building Information Modeling (BIM). Beneficial use of BIM by construction practitioners encouraged the Facility Management (FM) organizations to achieve benefit from this beneficial technology. In order to gain benefit from using BIM within FM, it is essential to create the 3D model of the existing buildings. The new technologies in laser scanning have been used to overcome this barrier. For this reason, a process called Scan to BIM was established to create an accurate 3D model of the buildings using the laser scanning technologies. In recent years, many types of research were done to find the methods for converting the captured data from laser scanning machines (so called point cloud) into BIM model. However, the whole Scan to BIM process has not been studied yet. The aim of this study is to investigate this process and find out which factors should be considered in order to perform the Scan to BIM process successfully. For this reason, a comprehensive review of the literature was done through the 75 research papers from different databases. The total amount of 28 factor was found. The findings of the literature review were tested by two experiments include an HVAC plant building and an office building. Based on the experiments, three additional factors were found. The findings are concluded into four main categories to help the managers for successful completion of the Scan to BIM process.

Keywords: Building Information Modeling, BIM, Facility Management, Laser Scanning, Point Cloud, Scan to BIM

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List of Abbreviations

AEC	Architecture, Engineering, and Construction
BAS	Building Automation Systems
BIM	Building Information Modeling
CAFM	Computer Aided Facility Management
CMMS	Computerized Maintenance Management Systems
CSF	Critical Success Factors
FM	Facility Management
HVAC	Heating, Ventilation, Air Conditioning
ISO	International Organization for Standardization
LOD	Level Of Development
MEP	Mechanical, Electrical, and Plumbing
PB	Phase-Based
PS	Phased-Shift
RFID	Radio Frequency Identification
SF	Success Factors
VDC	Virtual Design Construction

1. INTRODUCTION

The operations and maintenance spent about 90% of the total life cycle cost of a building. The saving in these tasks could result in a huge saving of time and cost. Since early 1900 by introducing the management into science, the need for establishing a separate discipline for managing the buildings was found. By introduction of the computers into workplaces, this need was resulted in rising a new managerial discipline in 1960 which called Facility Management (FM).

By progress of the building science and building the multi-functional building complexes, paying attention to this filed become crucial. The extra-large multi usage buildings require the group of expert to manage their operation, perform the maintenance on a regular basis, and do the repair periodically. Nowadays, the FM include but not limited to activities within about 15 different disciplines.

Since the utilization phase is the longest phase of the life cycle of a building and spent the biggest portion of the life cycle cost, this phase and using advanced technology in this phase for increasing the efficiency of the FM become popular within the last decades. Since the utilization phase starts after completion of the construction, this phase is significantly affected by the construction phase.

1.1 Statement of the Problem

By introducing the advanced technologies into the construction industry, the practitioners start to gain profit from these technologies in terms of saving cost and time in their projects. One of the most recent technologies which were introduced into the construction industry in last decade was Building Information Modeling (BIM). Beneficial use of BIM by construction practitioners encouraged the FM organizations to achieve benefit from this beneficial technology.

Since the existing buildings form the biggest portion of the building industry and most of the existing buildings were built before the introduction of the BIM into the construction industry, most of the under operation buildings do not have a 3D model. In order to gain benefit from using BIM within FM, it is essential to create the 3D model of the buildings. The new technologies in laser scanning have been used to overcome this barrier. For this reason, a process called Scan to BIM was established to create an accurate 3D model of the buildings using the laser scanning technologies. It seems essential to assess these process in order to gain profit by increasing its efficiencies.

1.2 Aims and Objectives

In recent years, many types of research were done to find the methods for converting the captured data from laser scanning machines (so called point cloud) into BIM model. Since the laser scanning capture, the spatial geometry of the objects, the most important concern of the researchers was to find a way for converting the set of points in a point cloud which represents an object into a BIM family object. This conversion so called object detection and in the recent years, the software providers released software for this reason.

Most of the academic efforts in recent years have been focused on finding the method for this conversion. Different methods for converting architectural, structural, and Mechanical, Electrical, and Plumbing (MEP) were designed and software based on these methods are available in the market. However, the whole Scan to BIM process has not been studied yet. The aim of this study is to investigate this process and find out which factors should be considered in order to perform the Scan to BIM process successfully.

1.3 Research Questions

In order to achieve the objectives of these study the answers of the following questions should be addressed:

- Which success factors (SF) for Scan to BIM Conversion found out in previous studies?
- Which tools for point cloud to BIM conversion are available?
- What are success factors (SF) for Semi-Automated and Manual Point Cloud to BIM Conversion?

Answering these questions could help to find out the factors for finishing the Scan to BIM process successfully.

1.4 Scientific Endeavors and Achievements

To find the answer to the research questions, a comprehensive literature review should be done. For this reason, papers from most popular and well-known databases should be reviewed. The success factors from the literature must be extracted and categorized base on the consequence steps of the Scan to BIM process.

Available hardware (especially the laser scanning machines) for performing the process and their used method for capturing data should be studied. Available software in the market which is related to the process should find out and based on the available resource, the set of software for doing the Scan to BIM process completely should be used.

To test the found factors from a review of the literature, some experiments should be done. The experiments should be selected in a way to cover all the disciplines (Architecture, Structure, and MEP). Using the set of software, the Scan to BIM process be done from beginning to end and the additional success factors for the process should be explored from the experiments.

Finally, the found factors should be categorized based on their function. The functional group will help the managers in the strategic levels to understand which factors should be kept in mind for successful completion of a Scan to BIM process.

1.5 Scope of the Study

Based on the available sources, especially time and cost, about one hundred papers should be downloaded and the most recent related ones will be reviewed. For this reason, the most reliable databases should be searched. Based on the availability of the Autodesk and Trimble software, the software related to the Scan to BIM process from these software providers will be used in this study. Using the software from another software provider depend on the availability of software license and training.

For doing the experiments two building will be tested regards to the Scan to BIM process and it will be tried to partly model them based on the laser scanning data and using the point cloud. Available time will specify the Level Of Development (LOD) of the final model and the required efforts.

1.6 Thesis Guideline

In the first chapter of this study, a summary of the activities before starting the research and their results are described. A brief background of the topic, the gap in the knowledge regards to the specific topic, the objectives of this research, questions which this study will try to answer, the methods and efforts which will be used in this study, and finally the scope of the study were discussed.

In the second chapter, the theoretical overview of the related topics to this study is described. First, the background of the three main areas which involve in this study; Facility Management, Building Information Modeling, and Scan to BIM are explained. Then, the previous researches in this field were reviewed in details and finally, the problem which will be addressed in this study is stated.

Chapter three describes the used method in this study and its related considerations. First, the used method by other researchers and the possible methods for answering the research questions are introduced. Then, the used method in this study and reasons for selecting this method is presented. At the end, the borders of the study were clearly defined.

In chapter four the findings of the research are described and based on the findings the discussion is made. In the first part of this chapter, found success factors from the literature are presented and categorized in three main categories of; Before Laser Scanning, Laser Scanning, and After Laser Scanning. In the second part, the experiments are discussed in details and the additional factors which explored through the experiments are presented.

In chapter five the summary of this study is concluded. In this chapter, found success factors are categorized based on their functionality into four main categories. The barriers and issues which limited this study are presented in the next part. Finally, the recommendation for the researchers who want to continue in the direction of this study and improve its findings are made.

2. THEORY

In this chapter, first, an overview of the subject and its background is given to provide some information for improving the knowledge about the topic. Then, previous research related to the title of this study are reviewed to provide an outlook of what has been done before in this field. Finally, the gap in the knowledge and the problem which is aimed to be addressed in this study is stated.

2.1 Background Overview

This part consists of three subchapters which cover the general description, definition, and history of the fields which form the skeleton of this study. The facility management is discussed in detail from its emersion until the integration of technologies within this management discipline. Then, BIM as one of the new technologies that introduced to Architecture, Engineering, Construction and Facility Management (AEC/FM) is explained and the advantages of its usage within FM organizations are mentioned. At the end, laser scanning as the most recent advanced technology for capturing existing building's data is introduced.

2.1.1 Facility Management

This part aims to give a brief review about FM, its importance, history, organizations, standards, definitions, and functions

Importance of FM

Operation and maintenance costs are respectively about 85% and 12% of total lifecycle cost of a building. 30 to 40 percent of operation cost spends for energy consumption of the building[1]. EuroFM stated that "FM is the largest business services market in Europe". It estimates the FM market as € 640 billion with 5 to 8 percent of GDP within European countries[2]. In [3] the value of facility services within Europe was estimated about $1000 billion.

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[1] B. Hardin and D. McCool, *Bim and Construction Management: Proven Tools, Methods, and Workflows* (Wiley, 2015).
[2] K.P. Reddy, *Bim for Building Owners and Developers: Making a Business Case for Using Bim on Projects* (Wiley, 2012).
[3] J.M. Wiggins, *Facilities Manager's Desk Reference* (Wiley, 2014).

FM History

Facility Management (FM) is a new business within the private sector. Regards to the higher number and bigger size of the facilities owned by the public sector, they used to manage their facilities earlier. By growing the private sector, number and size of their facilities were increased. After this development, the needs for separate management discipline to manage the facilities were identified [4]. By arising the scientific management in early 1900, higher amounts of people were gathered to work in large office buildings. This revolution in the workplace could be considered as the start point for introducing the Facility Management (FM).

Using computers in workplaces in 1960 resulted in coining the 'Facility Management' term. The computer usage required more services within facilities so the provided services went one step more ahead than cleaning, maintenance, and repair. The energy crisis in the next decade forced the organization's managers to emphasize on reducing the costs. It accelerated the tendency for managing facilities to decrease the operation cost of the running businesses. First FM Institute was established at the end of this decade by a private office furniture manufacturer. The aim of this institute was to present FM as a new managerial field [5]. By founding the International Facility Management Association (IFMA) in 1980, this field was standardized as a separate managerial discipline. During the last decade of 20th century, the FM was known more widely. Changing the work related laws which affected the employees and contracts, and arising service providers with concentrated specialties which resulted to initiating outsourcing, were two major factor that changed the FM field significantly.[6]

By starting the 21st century, FM position was placed in organizational charts extensively. Contractual issues were addressed within Europe and North America, and technology adoption within FM was initiated in this era. In 2010s era the FM companies grew by incorporating small service providers which resulted in offering a wide range of services in the field. The FM companies expand their tasks into a more specialized sector like care home, and healthcare and pharmaceutical sectors[7]. Formerly, the FM covered building’s cleaning, maintenance, and repair. Nowadays, FM contains a

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[4] K.O. Roper and R.P. Payant, *The Facility Management Handbook* (Amacom, 2014).
[5] Wiggins, *Facilities Manager's Desk Reference*.
[6] Ibid.
[7] Ibid.

variety of disciplines (included but not limited to management of real estate, finance, changes, human resources, contracts, and health and safety as well as engineering).[8]

FM Organizations

In [9], the most significant institute in FM field are listed as follows:

- **International Facility Management Association (IFMA)** based in the USA with more than 23000 members in 85 countries.
- British Institute of Facilities Management (BIFM) based in the UK with more than 13000 members.
- **Facilities Management Association (FMA)** based in UK and acts as the representatives of companies which provide non-core business services within FM sector.
- **EuroFM** consists of about 75 organizations within more than 15 European countries
- **Global FM** is a worldwide federation of national FM organizations.

FM Standards

During the last decade, notable efforts have been done to standardize the FM tasks. The International Organization for Standardization (ISO) published two standards about FM in spring of 2017. This organization wants to publish one more standard in this field which is currently under development[10]. Publishing FM standards within Europe was started at 2016 by publishing two standards. These standards were followed by a set of 5 standards which currently are accepted by 30 different countries within Europe includes Germany (DIN) and UK (BS). The list of international and European standards in FM field is given in Table 1.[11]

FM Definition

IFMA defines FM as “A profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process, and technology”[12]. In ‘ISO 41011:2017 Facility Management — Vocabulary’ the

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[8] B. Atkin and A. Brooks, *Total Facilities Management* (Wiley, 2009).
[9] Wiggins, *Facilities Manager's Desk Reference*.
[10] B. Hardin, *Bim and Construction Management: Proven Tools, Methods, and Workflows* (Wiley, 2011).
[11] R. Deutsch, *Bim and Integrated Design: Strategies for Architectural Practice* (Wiley, 2011).
[12] "Fmpedia Wiki," International Facility Management Association, http://community.ifma.org/fmpedia/w/fmpedia/facility-management-1.

International Organization for Standardization defines FM as "Organizational function which integrates people, place, and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business." [13]

Table 1 FM Standards

International	ISO/DIS 41001 Facility Management - Management systems - Requirements with guidance for use
	ISO 41011:2017 Facility Management - Vocabulary
	ISO 41012:2017 Facility Management - Guidance on strategic sourcing and the development of agreements
European	EN 15221-1:2006 Facility Management - Part 1: Terms and definitions
	EN 15221-2:2006 Facility Management - Part 2: Guidance on how to prepare Facility Management agreements
	EN 15221-3:2011 Facility Management - Part 3: Guidance on quality in Facility Management
	EN 15221-4:2011 Facility Management - Part 4: Taxonomy, Classification, and Structures in Facility Management
	EN 15221-5:2011 Facility Management - Part 5: Guidance on Facility Management processes
	EN 15221-6:2011 Facility Management - Part 6: Area and Space Measurement in Facility Management
	EN 15221-7:2012 Facility Management - Part 7: Guidelines for Performance Benchmarking

Based on European Committee for Standardization (CEN) "Facilities management is the integration of processes within an organization to maintain and develop the agreed services which support and improve the effectiveness of its primary activities (Figure 1)"[14]. According to these definitions, the most important factors which most of the definitions emphasize on them are; People, Place, and Process (Figure 2).

FM during building Life Cycle

Since the facility management has significant influence in different phases of the project, it should be integrated with other management disciplines from the beginning of the project. Although the planning phase is shorter than construction and operation phase in terms of time, the decisions which made during the planning phase are applied to the life cycle of the facility. Since these decisions affect the FM, it will be

[13] International Organization for Standardization, "Iso 41011:2017 Facility Management — Vocabulary," (International Organization for Standardization, 2107).

[14] "Facilities Management Introduction," The British Institute of Facilities Management (BIFM), http://www.bifm.org.uk/bifm/about/facilities/.

beneficial to involve the FM company or experts within planning phase.[15]

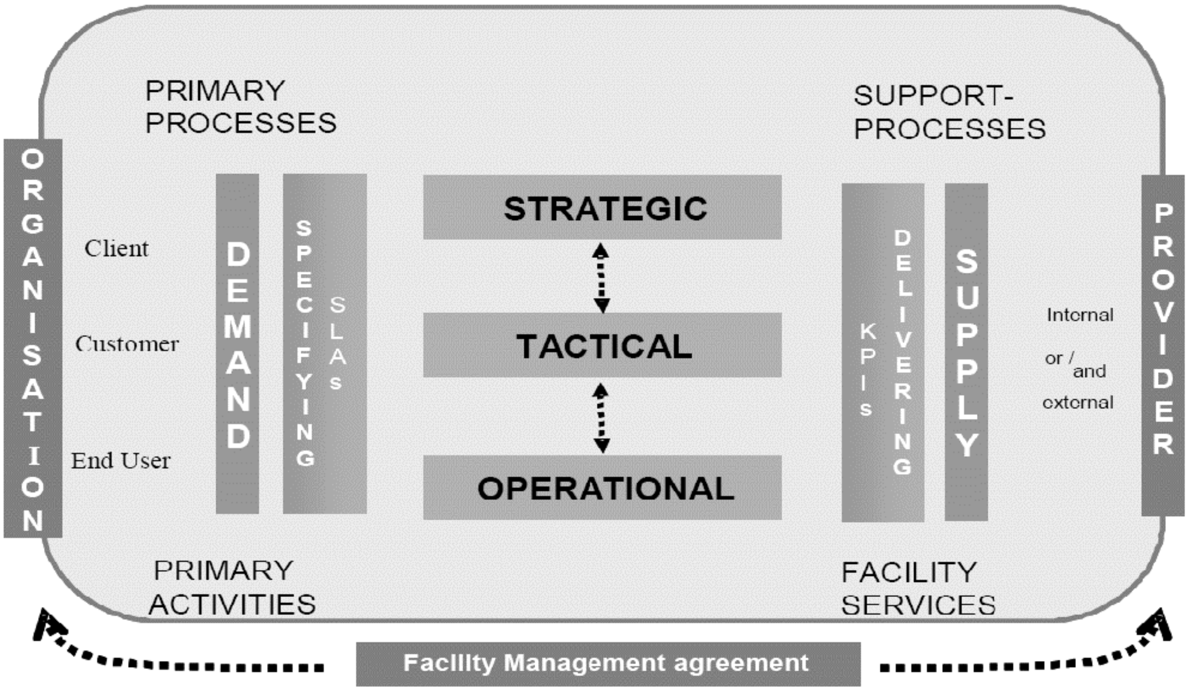

Figure 1 FM Model [16]

During the construction phase, changing the original design is inevitable and the change order during this phase happens time to time. Since by finishing the construction phase the drawing and specifications should be transferred to the FM organization for use in operation and maintenance phase, it is crucial that the as-built drawings be prepared with accuracy. If it does not happen, providing reliable as-built data could be very expensive for the owner.[17]

The operation phase is the most significant period within the life cycle of a building in terms of time and cost. Since the FM organization is responsible for daily operation of the building during operation phase, this phase is most affected by the FM organization. During this period changes are small and are limited to those which resulted from wear and tear and daily activities within the building. By developing the scope of FM in last decade and the need for outsourcing some services to gain benefit from specialized experts, the coordination between internal and external practitioners becomes a new challenge for FM organizations.

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[15] H.P. Wiendahl, J. Reichardt, and P. Nyhuis, *Handbook Factory Planning and Design* (Springer Berlin Heidelberg, 2015).
[16] German Institute for Standardization DIN, "Din En 15221-5:2011 Facility Management - Part 5: Guidance on Facility Management Processes," (Beuth, 2011).
[17] Wiendahl, Reichardt, and Nyhuis, *Handbook Factory Planning and Design*.

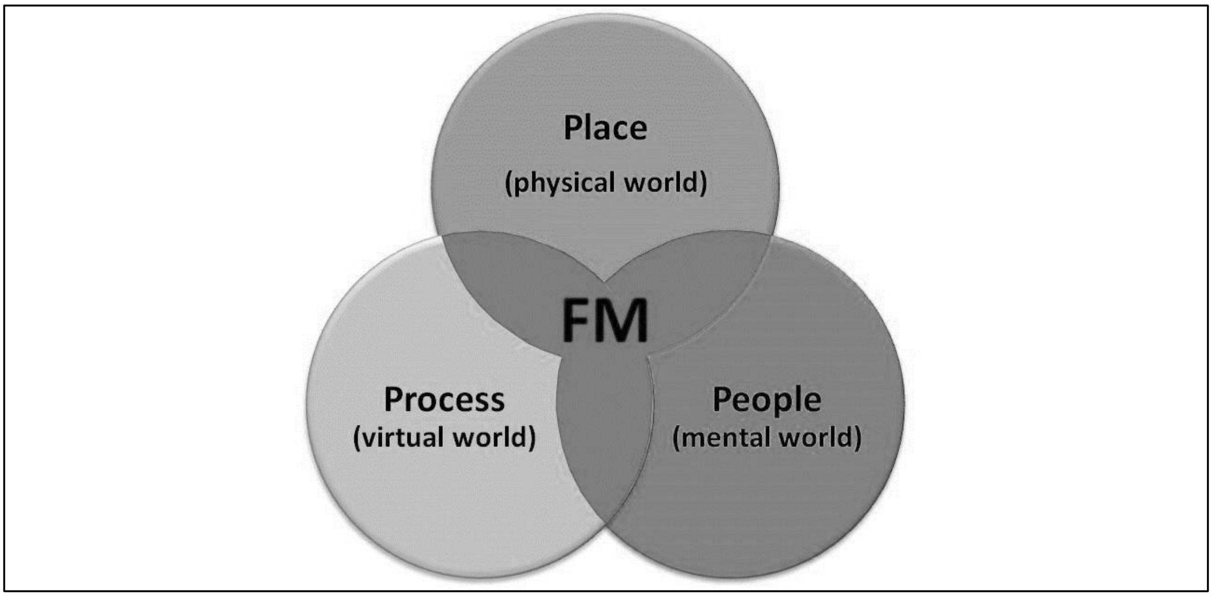

Figure 2 'People, Process and Place' model [18]

After certain years of operating, the building could be renovated or developed. The former happens when the building required refurbishment and it is decided to operate the building for the same usage as before. The latter occurs when for some reasons it does not make sense to continue the previous usage of the building and it is necessary to develop the building for another usage based on new needs and demands. The life cycle of building elements differs from each other based on their discipline. For IT and telecommunication, it is about 5 years, and structural elements could be used 50-70 years. These phases are somehow similar to planning phase, but the current situation of the building should be kept in mind. Considering FM organizations point of view, one of the most significant issues which should consider after renovation or development of the building is to update the as-built documents (2D drawings or 3D models).[19]

When the functional life cycle of the building is finished, it is expected to transfer the ownership of the building. In that time, whether the new owner wants to change the usage of the building or keep using it for the previous usage, the FM documents and records could considerably increase the value of the building. Even if the life cycle of the building is finished and the renovation and development of building be not economic, in the time of demolition of the building, information of FM organization could be worth to calculate the salvage value of the building.[20]

[18] Reddy, *Bim for Building Owners and Developers: Making a Business Case for Using Bim on Projects*.
[19] Wiendahl, Reichardt, and Nyhuis, *Handbook Factory Planning and Design*.
[20] Ibid.

Functions of FM

Nowadays, FM includes a vast range of activities from different disciplines. In [21], commonly performed functions of FM are listed as followings:

1) "Management of the Organization
2) Facility Planning and Forecasting
3) Lease Administration
4) Space Planning, Allocation, and Management
5) Architectural/Engineering Planning and Design
6) Workplace Planning, Allocation, and Management
7) Budgeting, Accounting, and Economic Justification
8) Real Estate Acquisition and Disposal
9) Sustainability
10) Construction Project Management
11) Operations, Maintenance, and Repair
12) Technology Management
13) Facility Emergency Management
14) Security and Life-Safety Management
15) General Administrative Services."

Technologies for FM

During the last 25 years, the usage of technology, especially IT and software, within FM sector is growing progressively. Nowadays, plenty of computer applications is available which could be facilitated managing the facilities. Selecting the appropriate software should be done carefully by keeping the needs of the FM organization in mind. Computerized Maintenance Management Systems (CMMS) is focusing on processes and procedures within FM organization. According to [22] "CMMS are software that is used to schedule and record operation and preventive/planned maintenance activities associated with facility equipment. The CMMS can generate and prioritize work orders and schedules for staff to support "trouble" calls and to perform periodic/planned equipment maintenance." It contains a number of works have done, material and which used and the date of actions. Computer-Aided Facilities Management (CAFM) refers

[21] Roper and Payant, *The Facility Management Handbook*.
[22] Don Sapp, "Computerized Maintenance Management Systems (Cmms)," https://www.wbdg.org/facilities-operations-maintenance/computerized-maintenance-management-systems-cmms.

to create and use IT-based systems for FM sector. Regards to [23] "CAFM software provides the facility manager with the administrative tools and the ability to track, manage, report, and plan facilities operations. A typical CAFM system is defined as a combination of Computer-Aided Design (CAD) and/or relational database software with specific abilities for FM." The CAFM system could contain information about the people, spaces, and access to them, and financial information of spaces e.g. the leasing, incomes, and tenants.

"Building Automation Systems (BAS) are computerized distributed control systems for intelligent buildings" [24]. It covers all energy consuming elements of building including lighting systems, Mechanical, Electrical, Plumbing (MEP) systems, fire protection systems, heating, ventilation, and air-conditioning (HVAC) systems, etc. it is mainly used for monitoring the performance of this systems and decreasing the energy consumption by controlling the temperature and lighting of building. They use to optimize the building efficiency and improving the sustainability. Based on [25] these mentioned computer-based FM systems could be more advantageous by integrating their databases and interfaces with the most recent technology in the field of Architecture, Engineering, and Construction (AEC) so-called Building Information Modeling (BIM) (Figure 3).

2.1.2 Building Information Modeling (BIM)

Definition

In [26] BIM is defined as "Building Information Modeling is the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility."

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[23] James R. Watson and Russ Watson, "Computer-Aided Facilities Management (Cafm)," https://www.wbdg.org/facilities-operations-maintenance/computer-aided-facilities-management-cafm.
[24] R. Issa et al., *Building Information Modeling: Applications and Practices* (American Society of Civil Engineers, 2015).
[25] Ibid.
[26] J. Reinhardt and Associated General Contractors of America, *The Contractors' Guide to Bim* (Associated General Contractors of America, 2008).

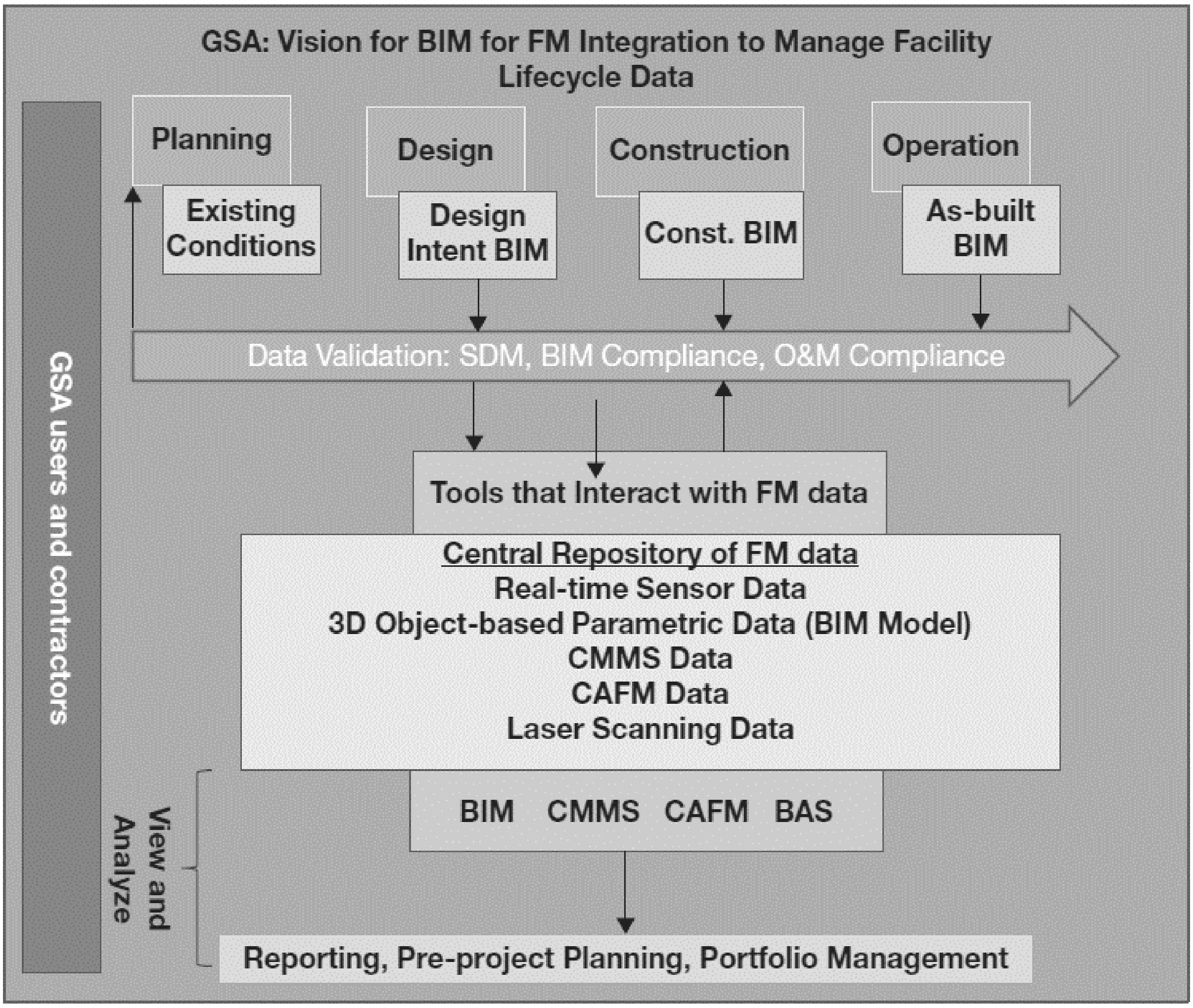

Figure 3 Integrating BIM with FM systems [27]

Based on [28] "Building Information Modeling: Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms, and Building Information Model: Is the DIGITAL REPRESENTATION of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onwards."

BIM for Owners

By finishing the construction phase information of building should be transferred to the owner. Traditionally, geometries of buildings elements in form of as-built drawings were

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[27] P. Teicholz, *Bim for Facility Managers* (Wiley, 2013).
[28] National Institute of Building Sciences, "National Bim Standard-United States Version 3," (Washington, DC2015).

submitted to the owner at the commissioning phase. 3D as-built models contain the required information for the owner in form of 3D model which is more understandable for the owners with low knowledge about buildings. 3D as-built models could reduce the efforts in commissioning and increase the accuracy of information [29]. Specifications are another type of information about the building which includes but not limited to; material description, warranties, user guides, and installation manuals. Normally this information is provided by different sources from the practitioners who work in different disciplines. Two major problems are; gathering huge amount of information from different resources, and linking this separated and uncategorized information together for future use. This problem could be resulted in the loss of essential information, wasting time to find the information and difficulties in finding required data in needed time which could be led to additional expenses to maintenance and operation costs.[30]

considering both forms of information, the as-built model could be updated continuously within the life cycle of the building by FM organization which will provide more reliable information on the current status of the building based on its most recent changes. After completing the construction phase, owners could use BIM in commissioning phase for compliance with design (quality assurance), transfer the as-built data, testing, and hand over information to FM organization. BIM also could be used for managing the facility, maintenance planning and control, scheduling and budgeting for repairs, crowd simulation, emergency and evacuation planning, and real-time control of building systems [31]. In [32] the advantages of BIM for owners are listed as follows:

- “Increase in staff efficiency to get to information (time)
- Maintenance of equipment to warranty standards (risk profile and expense)
- Proper documentation of commissioning issues (fire stopping, accessibility)
- Limited amount of wasteful printing (costs)
- Ability to back up critical digital and facility data that could be lost (risk profile)
- Information embedded or linked to the model to avoid unnecessary waste
- Less chance for facility downtime as a result of improper maintenance

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[29] Teicholz, *Bim for Facility Managers*.
[30] Ibid.
[31] Ibid.
[32] Hardin and McCool, *Bim and Construction Management: Proven Tools, Methods, and Workflows*.

- More efficient repair response
- Improved client/occupant satisfaction”

BIM for FM

Regards to a vast area of FM services, using new technologies like BIM within FM sector is complicated and could be performed at different levels. Since BIM provide beneficial information about physical assets, FM sector follows AEC sector in adopting BIM. Of course, BIM model is not replaced with a whole range of information which is used by FM organization, but it will facilitate using this information especially information of building. Since the FM organization and its practitioners are not as complete as AEC practitioners familiar with building drawings and specifications, BIM could provide a better understanding of people who involved in FM sector. BIM could be used for energy analysis and sustainability during the life cycle of the building. It can help FM organization in terms of managing inventories, furniture, and equipment, and to improve the energy efficiency of the building as well as the security management. FM organization could gain profit from using BIM for space planning. Since BIM provide accurate geometry of spaces and the objects in them, it is very useful tool for measuring the spaces and checking rules requirements. Recently some real-time data analysis software are realized which are a further step in building automation.[33]

During the last decades, serious efforts have been made to adopt BIM within FM sector, however, there are still some challenges in using BIM in FM. The current BIM software developed to be used for design and mostly have been divided into Architectural, Structural, and MEP disciplines. Based on the different characteristics and requirements of FM sectors, neither current BIM software provides full support to FM sector, nor developing separate BIM software for using in FM makes sense based on economic and interoperability issues. Integrating BIM within FM companies requires a comprehensive well-defined strategy. Most of the FM companies have their own sources of information in forms of drawings, specifications, daily reports, etc. which need planned process to convert to BIM model. Nowadays, BIM software providers keep the interoperability issues in mind. This issue should be addressed through the FM-based BIM software to be able to interact with wide range of FM related

[33] Teicholz, *Bim for Facility Managers*.

applications. Based on the average duration of design and construction phases in building life cycle, BIM software providers realize new version annually or every two years. According to the marketing matters, it is impossible to downgrade the BIM models to the earlier version, which will be resulted to needs to buying the new version. Software providers also do not provide support services for products more than 5 years for the same reason. Regards to the longer duration of operation and maintenance phases which are main phases that FM sector involves, the cost of BIM software and upgrade them are considerable and could affect the trend of adopting BIM within FM sector.

Currently, there are plenty of FM applications which each of them contain a huge amount of information. Large scale FM companies need to use more than of them since because of the wide range of their activities and services there is no one comprehensive software which could cover all of their requirements. In most of the cases, information of these applications has overlap. It should be considered that BIM must use to overcome some barriers by integrating some information in itself, not to add another complicated software to previous ones. According to this issue, level and method of linking BIM model with FM databases could be carefully taken into account [34]. Although the BIM model contains a huge amount of useful information about the building, some of this information is not used in daily activities of FM organization and some essential information are missing from BIM model. Another issue is that how much in detail information are required by FM organization. In most of the cases, FM organization does not need as in detailed information as construction practitioners. Based on this problem defining the level of detail (or Level Of Development) for BIM model seems essential.[35]

Level Of Development (LOD)

According to [36] "The Level of Development (LOD) descriptions identify the specific minimum content requirements and associated Authorized Uses for each Model Element at five main progressively detailed levels (and one sub level) of completeness (Figure 4):

- **LOD 100**, The Model Element may be graphically represented in the Model with

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[34] Ibid.
[35] Ibid.
[36] The American Institute of Architects, "Aia Document G202™–2013," (2013).

a symbol or other generic representation but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e., cost per square foot, the tonnage of HVAC, etc.) can be derived from other Model Elements.

- **LOD 200**, The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.

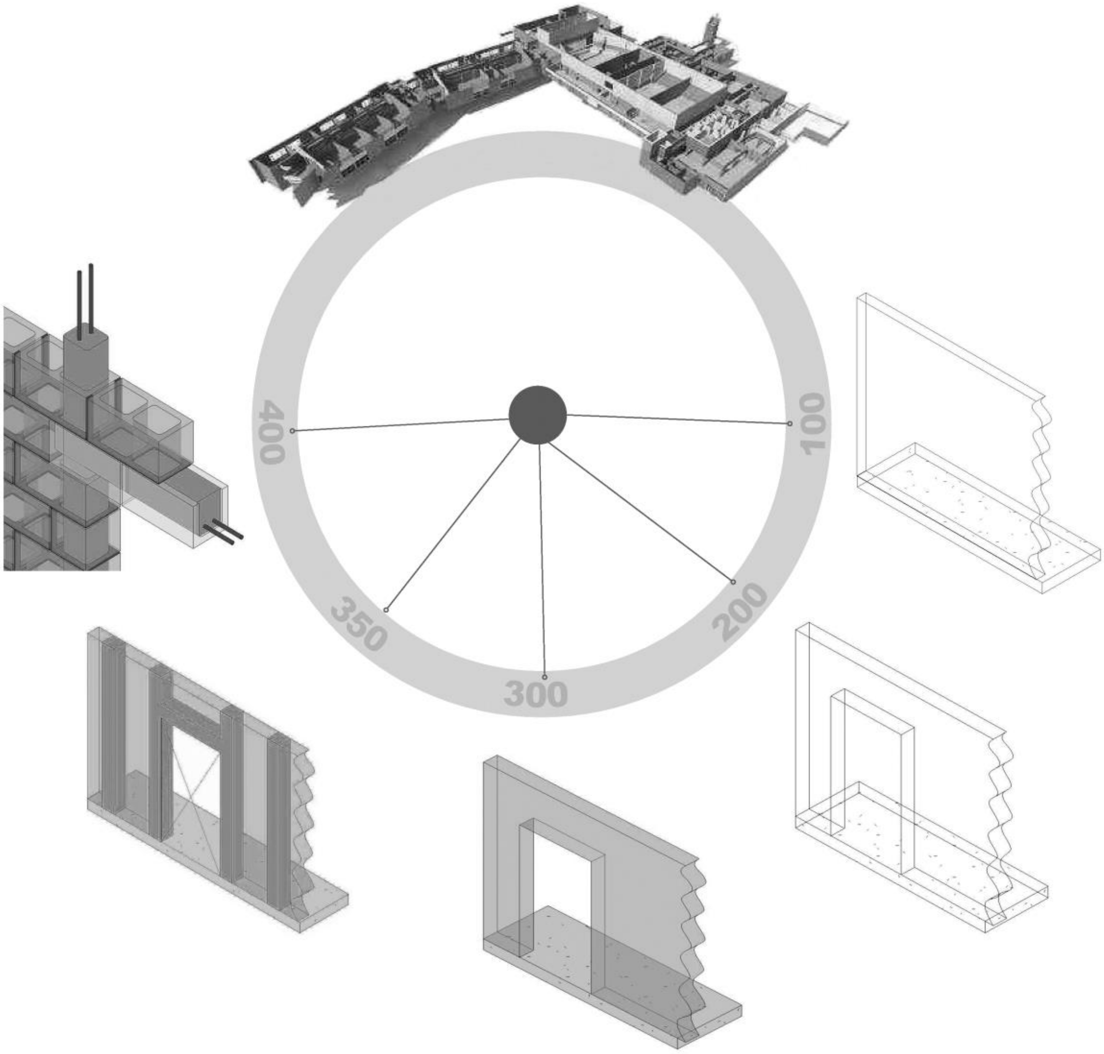

Figure 4 Level of Development[37]

- **LOD 300**, The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location,

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[37] Jan Reinhardt and Jim Bedrick, "Level of Development Specification Version: 2014," (BIMForum, 2014).

and orientation. Non-graphic information may also be attached to the Model Element.

- **LOD 350**, The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element (LOD 350 was developed by the BIMForum working group).[38]
- **LOD 400**, The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.
- **LOD 500**, The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements."

Creating BIM model

In terms of creating BIM model, buildings are divided into two main categories; 1) new buildings and 2) existing buildings (Figure 5).

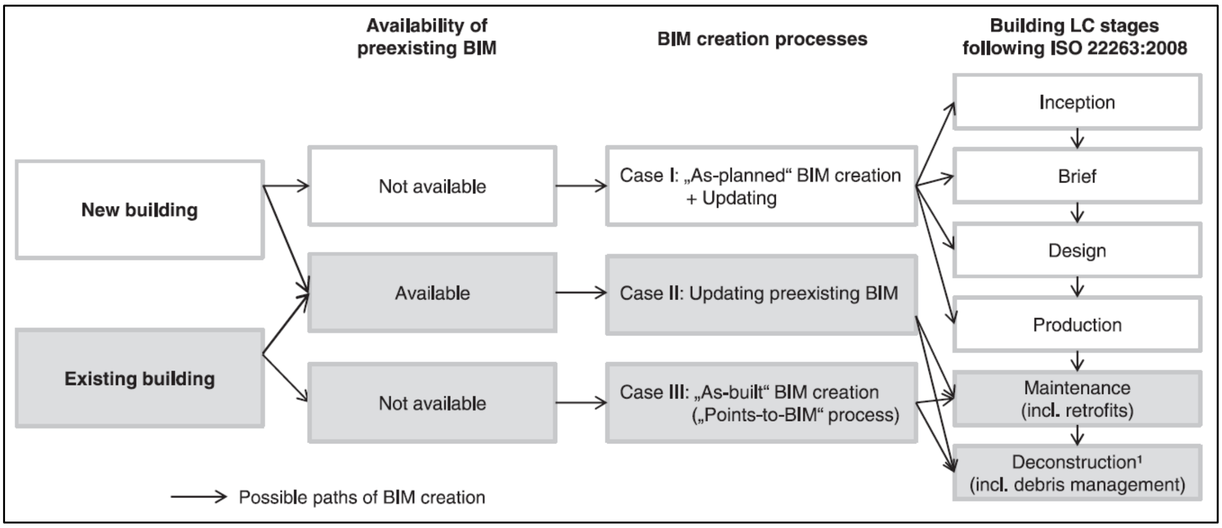

Figure 5 BIM model creation processes in new or existing buildings depending on available, pre-existing BIM and life cycle stages [39]

Each of these types of buildings is subdivided into two subcategories in terms of the existence of pre-existing BIM model. There are two approaches for creating BIM model

[38] Jan Reinhardt and Jim Bedrick, "Level of Development Specification," (BIMForum, 2016).
[39] Rebekka Volk, Julian Stengel, and Frank Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs," *Automation in Construction* 38 (2014).

for new buildings. The first one is to include the BIM model creation within the design contract. In this case, the designer is responsible for creating as-design BIM model in the design phase. This model could be used during the construction phase, and be updated base on the change orders during this phase. At the end of the construction phase, this model should be updated to as-built model for further uses. The second approach is used for the new buildings without as-built BIM model. In this approach construction management organization or third party is hired to neither update the existed as-design BIM model base on the latest changes and the current status of the building, or create the BIM model from the beginning base on the as-built drawings.[40]

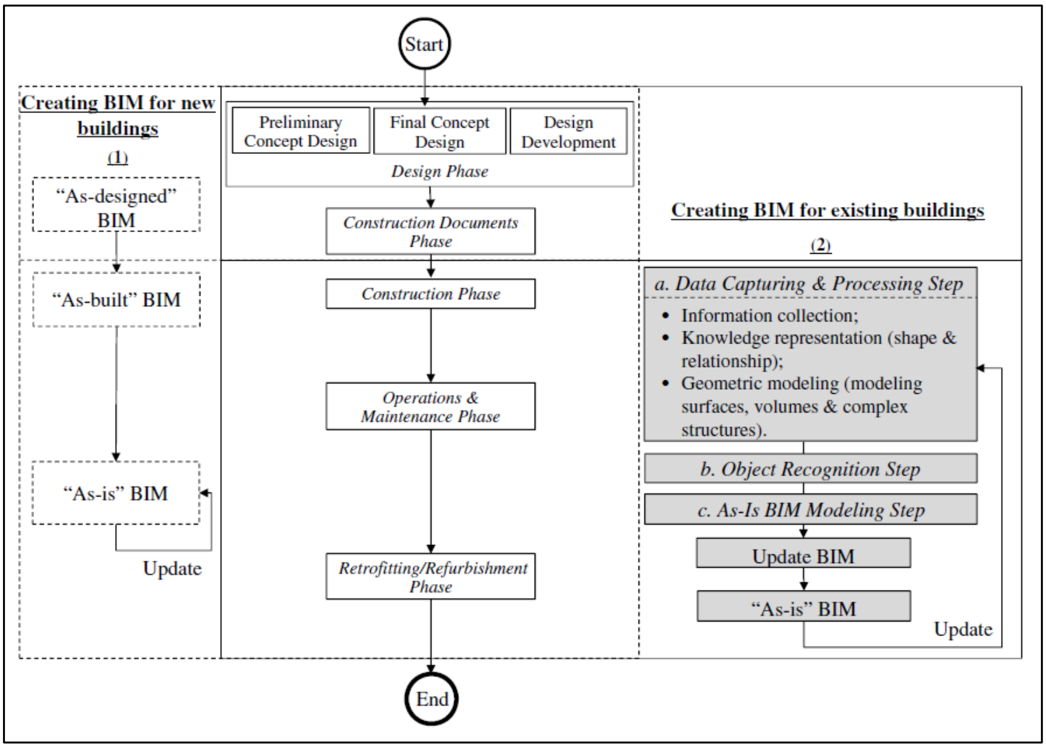

Figure 6 Comparison of BIM for existing buildings and new buildings[41]

Since the existing building with as-design BIM model is rarely found, the most challenging cases in terms of creating BIM model are existing buildings especially the old ones. In these cases, there are no as-design or as-built drawings, and if there are, they are not accurate and reliable. The situation of the specification and other information of buildings are more critical in these cases. This information should be extracted from information of design, maintenance, and renovation phases. It is very time-consuming and labor intensive to find the related information extract them and

[40] Hardin and McCool, *Bim and Construction Management: Proven Tools, Methods, and Workflows*.
[41] Qiuchen Lu and Sanghoon Lee, "Image-Based Technologies for Constructing as-Is Building Information Models for Existing Buildings," *Journal of Computing in Civil Engineering* 31, no. 4 (2017).

use them for BIM model creation (Figure 6) [42]. According to [43] more than 80 percent of residential buildings in Europe was built before 1990 and not only do not have as-design or as-built BIM model but also do not have original drawings in CAD format. To equip information of these buildings with BIM model (Case III in Figure 5), employing the process so-called 'Point-to-BIM' or Scan-to-BIM' is inevitable

2.1.3 Scan to BIM

As formerly discussed, the process of generating BIM model is different in new buildings and existing buildings. Even for the existing building, this process depends on the availability of BIM-based information. Figure 4, illustrates the BIM modeling process for different types of buildings. As it can obviously in Figure 7, for new buildings the process include the updating of as-design BIM model based on the latest changes during the construction phase to generate the as-built BIM model. For the existing building, it rarely happens that they have pre-existing BIM model. By the way, in this case, the BIM model should be updated based on the current situation of building by using the as-built drawings (if they exist) and recorded documents of operation, maintenance, and renovation of the building. Since most of the existing buildings are not placed in this two cases, most of the buildings belong to the third group which is existing buildings without any previous BIM records.

To generate a BIM model out of an existing building, first, the geometries of building elements should be captured to form the object. Then this objects should be equipped with semantic property and attribute information to create a BIM family object. An accurate, reliable technique which can automate this process to decrease the required time and cost for creating BIM model, could extremely facilitate the FM tasks by improving the documentation and visualization. As mentioned before, most of the buildings belong to the third case which generating their BIM model should be done toward the scan to BIM process. As it is shown in Figure 4, this process consists of four main subprocesses that are described in details in the following parts.

Based on [44] "The current state of the Scan-to-BIM procedure can be described as the

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[42] Ibid.
[43] Ibid.
[44] Vasiliki Tzedaki and John M. Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model," in *AEI 2013 : Building Solutions for Architectural Engineering* (State College, Pennsylvania, United States: American Society of Civil Engineers, 2013).

spatial information of a facility is scanned and raw point clouds are created. Additional supportive devices like cameras and Radio Frequency Identifications (RFID) capture facility's semantic information like material, price etc. The raw point clouds are registered in a common coordinate system and a unique point cloud is obtained. The registered point cloud is segmented and geometry is attached on surfaces or volumes. Finally, semantic information is attached, objects' attributes and objects' relationships are established and a BIM model of the scanned facility is created."

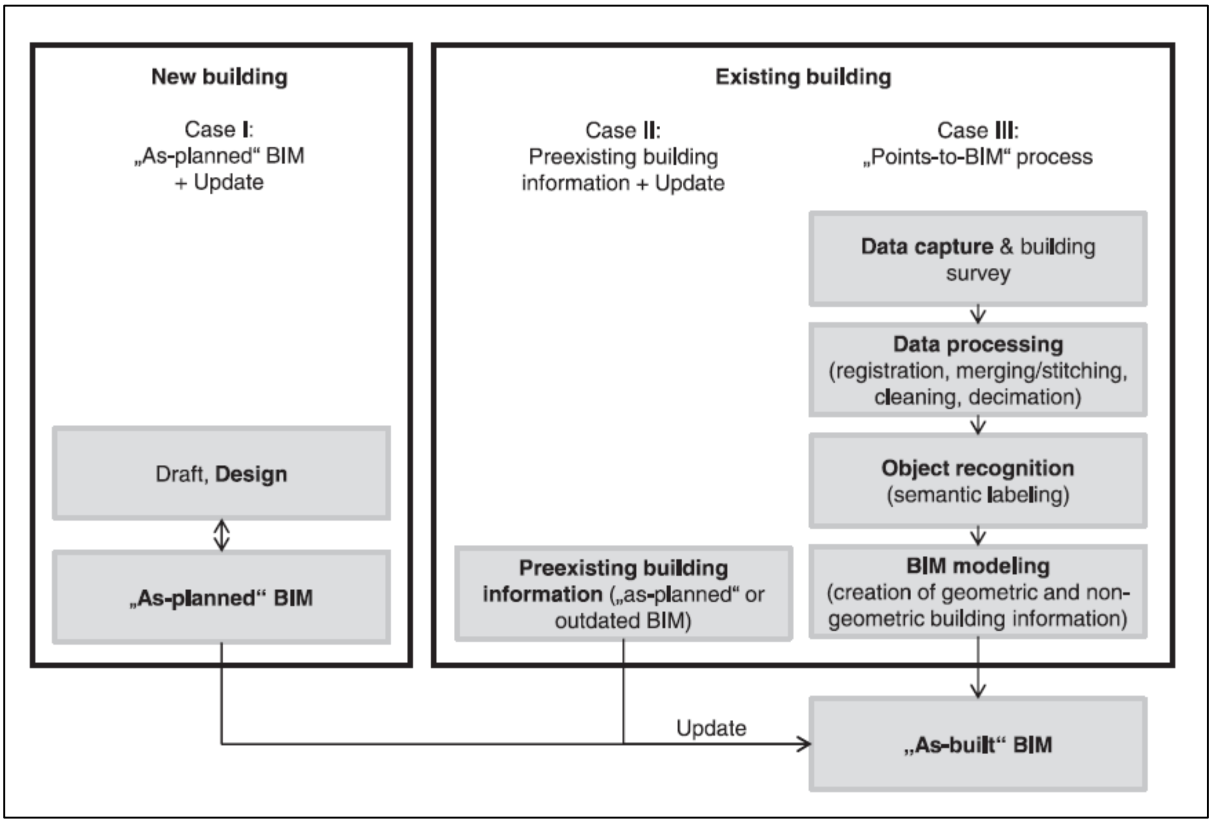

Figure 7 BIM creation process for new and existing building[45]

Data capture

The first step in the scan to BIM process is data capture. The aim of scan to BIM and the desired usage of the model determines the LOD which directly affects the selection of data capturing technique and its quality. Since the captured data is the basis of scan to BIM process, it has a significant effect on the next level in terms of quality of the model and required time and efforts to create the model [46]. Data capturing is performed by using the variety of techniques which are categorized into contact techniques and

[45] Volk, Stengel, and Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs."

[46] Pingbo Tang et al., "Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds: A Review of Related Techniques," ibid.19, no. 7 (2010).

non-contact techniques. Figure 8 shows this to categories and their sub-categories. Non-contact techniques are categorized under the image-based, range-based, and other techniques clusters. Contact techniques are divided into manual and other techniques.

During the last years, fewer efforts had been made on developing other techniques. Tagging techniques have two major problems, first, RFID and barcodes are mostly installed on elements and equipment in new buildings rather than existing buildings. Secondly, installing these tags in existing buildings is labor intensive and because of high dependency to interoperability is significantly subjective. In pre-existing information technique, all available information on buildings in forms of drawings, specifications, operation and maintenance records, and photos are collected to use in next steps for creating BIM model. According to the huge amount of data, difficulties in extracting useful information, and unreliability and inaccuracy of this information, this technique is not a trustworthy one.

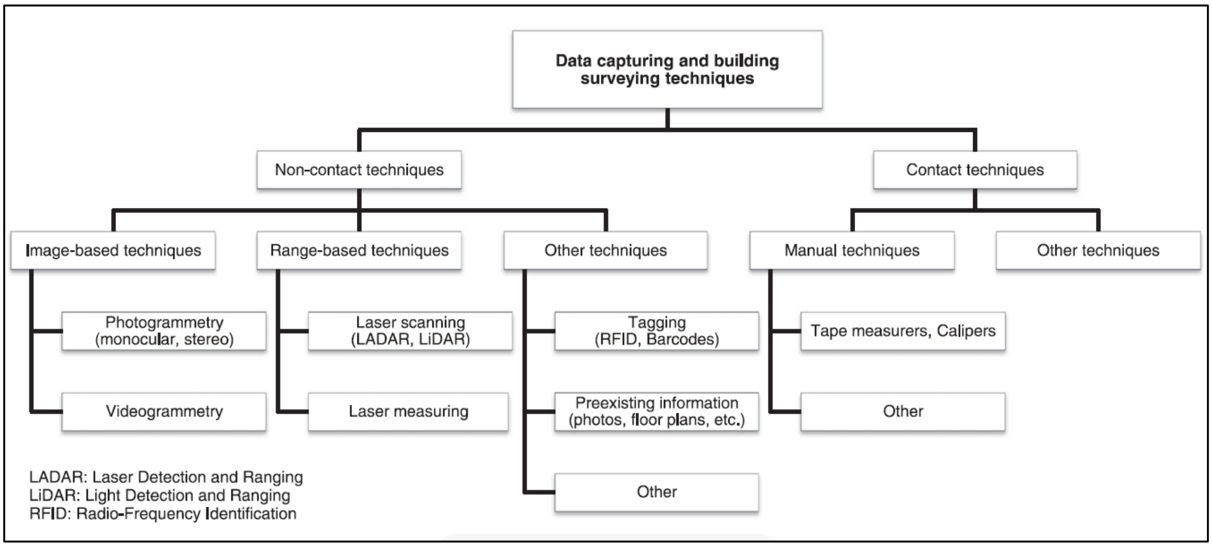

Figure 8 Data capturing techniques [47]

Image-based technique captures the color of objects spatially. Range-based technique extracts spatial information of the object based on their reflection. Currently, the range-based technique is popular, even though they have some disadvantages like expensive equipment and deficiencies in capturing transparent and reflective objects. As it will be discussed later, this technique requires additional efforts to process

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[47] Rebekka Volk, Julian Stengel, and Frank Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs," ibid.38 (2014).

captured information, recognize them as BIM object and finally convert them to BIM family. Based on [48] “Laser scanning is an emerging technology that can serve to accurately capture the physical geometries of existing buildings in data files called point clouds”. During the last years, many companies introduced laser scanning machines (e.g. Faro, Leica, Riegel, Topcon, Trimble, Zoller & Frohlich).[49] Based on the popularity of this method, many software providers released a new generation of software which can recognize the surfaces within point cloud and convert them into BIM objects. Laser scanning could capture all the visible information of a variety of building elements from wall surfaces and windows shapes to pipes HVAC equipment in form of as-is point cloud.

Previously, researchers had focused on capturing the only geometry of building elements. Regards to the considerable significance of semantic properties of elements in creating BIM model, currently, most of the research concentrate on them to improve the LOD of captured data to enhance the quality of BIM model. The researcher is laboriously working on developing automated solutions for converting captured data into BIM model. This conversion is known as “Scan to BIM” process. Based on the capability of non-contact techniques which is limited to capturing only the visible objects, some academic endeavors are started to integrate some technologies like radars, radiography, magnetic particle inspection, sonars or electromagnetic waves to include the information of invisible objects like Structural elements into BIM model.

Data processing

The reason for laser scanning and the way which BIM model will be used, determine the LOD, the type of data capturing, the size of data, type of processing and its required time and effort. The main aim of data processing is to prepare the raw captured data for further usage based on needs and objectives (e.g. segmenting the building elements, define meshes, or recognizing an object with aim of exporting them into as BIM family) [50]. The first step of data processing is called “Registration”. In this step captured data from different locations (scanning stations) are integrated into one coordinate system with one origin. After the registration, all the data are included into

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[48] Teicholz, *Bim for Facility Managers*.
[49] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies," in *Computing in Civil and Building Engineering* (2014).
[50] Volk, Stengel, and Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs."

a single file which called “point cloud”. The registration process could be done automatically by employing software like Trimble Realworks or be done in a semi-automatic manner with software like Autodesk ReCap.

In semi-automated registration, at the beginning, two captured data are integrated by selecting three common points from each station manually. The process will be continued by selecting the common points of this integrated file with next station. The process continues until all the stations are integrated into a single file. In comparison with the automate registration, this process is more time to consume and labor intensive, but with higher accuracy [51]. According to [52] “Point cloud data is made of discrete point spatial coordinates (x, y, z) plus a point intensity value, therefore, a point cloud model only contains coordinate information.” Since point clouds include only the geometry of objects, to gain maximum profit from BIM model, the conversion should not only include the creating geometric information of elements, but also the semantic information which equips the BIM model.

Next step is to clean up the point cloud. In this step, the unneeded and useless captured information and clutter, which are called “Noise”, are cleaned from the point cloud. This information could include people, passing or parked cars in the street, reflections, etc. Depending on a number of noises in the point cloud, the point cloud cleaning could be an exhausting process. One of the most important consideration during the data processing is its time. The processing time could be varied extremely depending on different factors. The quality of captured data and their file size is one of the factors which significantly affect the processing time. Based on the type of usage which is considered for point cloud, the accuracy of laser scanning machine could be set to a higher level which will be resulted in bigger file size and time-consuming data processing step. Another factor is LOD, this factor is also influenced by the point cloud usage and more clean point cloud with higher LOD requires more time for data processing. The size of the building which has a direct effect on the number of laser scanning stations is also a considerable factor which influences the data processing

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[51] Pingbo Tang et al., "Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds: A Review of Related Techniques," ibid.19, no. 7 (2010).
[52] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."

time.[53]

As previously discussed, based on the aim of laser scanning and the further usage, the scanned data could be used in three different approaches. The first approach is “Scan to Point cloud”. In this approach, the resulted point cloud will be segmented into building elements and meshes will be defined for further usage. In [54] the process of using point cloud in factory buildings of VOLVO company is described which used for managing the assembly line and machinery. Scan to BIM as another approach in using scanned data. This approach is continued after data processing which is described in the next parts of this study. Recently, some efforts have been made to link the point cloud with the FM databases like CAFM and CMMS. This approach which is known as Scan to Dataset is under developing to derive benefit from advantages of point cloud without spending time and effort for converting it to BIM model.

Object recognition

After processing the captured data and creating the point cloud, the building elements should be converted to BIM family objects. During this step which is called object recognition, the points which represent the geometry of the building elements should integrate with semantic information of related object to provide the characteristics and the functionalities which are expected from the element [55]. In [56] the terms ‘detection’, ‘recognition’, and ‘identification’ are defined as follows:

- Detection: an object is present. This means that some specific features are found in the data (e.g. circular cross-sections).
- Recognition: the type of object can be discerned. This means that the analysis of the features enables discerning objects of a specific type (e.g. pipes with circular cross-sections).
- Identification: a specific object can be discerned. This means that each recognized object can be matched to a specific object in a known list (e.g. a

[53] Volk, Stengel, and Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs."
[54] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."
[55] Tang et al., "Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds: A Review of Related Techniques."
[56] Frédéric Bosché et al., "The Value of Integrating Scan-to-Bim and Scan-Vs-Bim Techniques for Construction Monitoring Using Laser Scanning and Bim: The Case of Cylindrical Mep Components," ibid.49 (2015).

recognized pipe is discerned as being a certain pipe present in the project BIM model).

In this step, the objects should be identified and their deficiencies like clutter, uncaptured parts are manipulated. Based on [57] "Methods and tools for object recognition differ due to geometric complexity of the building, required LOD, and applied capturing technique, data format, or processing time." As illustrated in Figure 9, object recognition methods are divided into three main categories; data-driven approaches, model-driven approaches, and other methods. In the first approach, the extracted information from a point cloud is used. Four different methods could be employed in this approach, they are; feature-based, shape-based, material-based, and statistical matching methods. In model-driven approach, which captured data are compared with the knowledge or contextual information to find the matching, a predefined structure is the basis of the conversion. Other approaches are rarely used and are not popular among neither researcher nor professionals. Some of the researchers are trying to integrate data-driven and model-driven approaches into one method to eliminate the shortages of each approach.

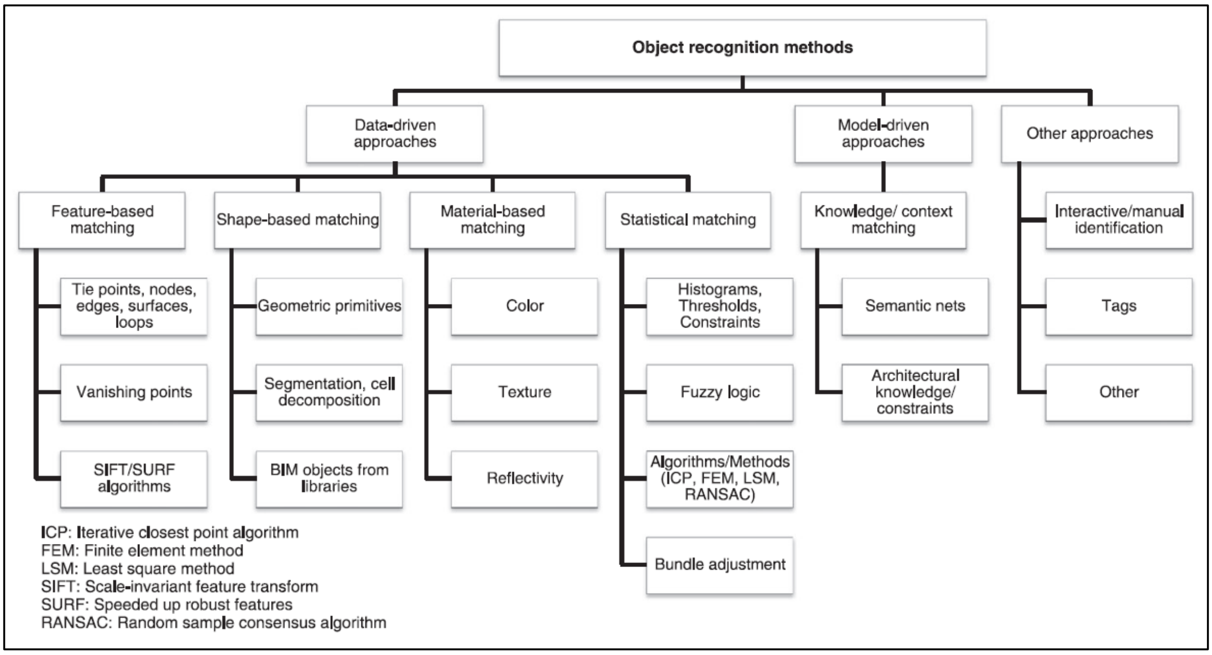

Figure 9 Object recognition methods

As it is mentioned before the laser scanning only captures the geometry of the objects and their specification and additional information is not included in the point cloud.

[57] Rebekka Volk, Julian Stengel, and Frank Schultmann, "Building Information Modeling (Bim) for Existing Buildings — Literature Review and Future Needs," ibid.38 (2014).

Adding the specification of the components like material (name, number, code, etc.) and dates (Installation, guarantee period, periodic checking, etc.) should be done manually. Two steps for extracting BIM model from point cloud are mentioned in [58] as: identifying collections of points that belong to each surface, and fitting geometry (meshes, primitives, NURBS, subdivision) to them. This study stated the challenges for automated segmentation as follows:

- **"Density**: Point cloud models exhibit locally variable densities based on orientation and distance from the capture device. Furthermore, occlusions from surface irregularities and adjacent objects produce regions with missing data.
- **Surface Roughness**: the physical texture of common surfaces can range from smooth (steel, marble) to very irregular (grass, crushed stone). Because a given scene can contain a wide range of surface roughness, no priors about noise levels can be reliably used.
- **Curvature**: surfaces can be flat, single curved, double curved, or have undulations at multiple scales, making boundaries hard to define.
- **Clutter**: a scene can be made up of multiple objects in close proximity, making feature detection difficult.
- **Abstraction**: 3D modeling is inherently a process of abstraction. This required that some decisions have to be made by the user. In consequence, automation needs to balance flexibility with the ease of use."

Based on [59] "There are various commercial solutions (e.g., ClearEdge3D®, Kubit®, Geomagic®, Leica Cyclone®, Bentley Decartes®, LFM®, etc.) available to automate some of the feature recognition and modelling steps but they are currently limited to simple geometric shapes and objects (e.g., rectangular shaped windows and doors; straight circular pipes)."

2.2 Previous works

In [60], a new method for overcoming the obstacle of occlusion in point cloud is

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[58] Dimitrov Andrey and Golparvar-Fard Mani, "Robust Context Free Segmentation of Unordered 3d Point Cloud Models," *Construction Research Congress* (2014).
[59] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."
[60] H. Masuda and Ichiro Tanaka, "As-Built 3d Modeling of Large Facilities Based on Interactive Feature Editing," *Computer-Aided Design and Applications* 7, no. 3 (2010).

presented. The proposed method used the segmentation and meshes to model the missing part. For testing the method, a sample system was implemented in two different cases. A method is proposed in [61], to solve the occlusion problem in the point cloud of the industrial plants which resulted from the existence of a large number of pipes close to each other within small space. Normally, there are no enough spaces in these facilities which restrict the options for locating the laser scanning machine as well. The proposed method separately processes several datasets which are captured from a different location. A method for automating the recognition of building from point cloud with aim of creating BIM model for energy analysis use is presented in [62].

The proposed an algorithm for recognizing the building envelope and the validate it by testing the algorithm for a residential house. Their algorithm recognizes the building envelope as an individual object which can be used for energy simulation. The researcher proposed four different techniques for detecting unneeded objects from the point cloud. The methods are developed for different scenarios to cover all possible situation which could be occurred. The techniques are compared by using them for several datasets from different stations. The techniques are integrated to a software which enables the user to select the appropriate techniques based on the situation[63]. In [64], a new method for segmenting the façade of the building based on its planar properties is proposed. The proposed method was tested by studying a single case.

In [65], a case was studied to develop an as-built BIM by using photos and point cloud data that was captured continuously during the construction phase. To overcome the problem of occlusion, they repeated the scanning several time to improve the efficiency of BIM model. In the cases that it is impossible to use the captured data for achieving the most efficient BIM model, they used the as-design drawings to support the Scan to

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[61] Yousuke Kawauchi et al., "An Integrated Processing Method for Multiple Large-Scale Point-Clouds Captured from Different Viewpoints," ibid.8, no. 4 (2011).
[62] Wang Chao and Cho Yong, "Automated 3d Building Envelope Recognition from Point Clouds for Energy Analysis," *Construction Research Congress* (2012).
[63] M. J. González et al., "Automatic Detection of Unstructured Elements in 3d Scanned Scenes," *Automation in Construction* 26 (2012).
[64] Joaquín Martínez et al., "Automatic Processing of Terrestrial Laser Scanning Data of Building Façades," ibid.22.
[65] Liu Xuesong, Eybpoosh Matineh, and Akinci Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera," *Construction Research Congress* (2012).

BIM process. To evaluate the as-built BIM model, in [66] a method was presented to compare the point cloud with extracted as-built BIM model. The deviation between geometries of objects in the point cloud and as-built BIM model could drive from errors within different steps of Scan to BIM process. The presented method tried to identify the errors and their source to make it possible to remove it. The method was validated through a case study. In [67], a method was presented to extract the pipeline from scanned data automatically. The pipeline consisted of straight and the shape pipes and elbows. The results show the efficiency of proposed method for low quality, noisy, and diverse density point cloud.

In [68], the researchers try to prove that the standard deviation of distance measuring error by laser scanner machines is normally distributed. Their assumption was confirmed through two experiments consist of a planar single color surface. The researchers tried to introduce a method for automated conversion of point cloud to BIM. Using the proposed algorithm, the elements of building indoor environment (e.g. walls, floor, ceiling, etc.) are recognized. This method is useful even in the situation that clutter and occlusion exist within point cloud. The method was evaluated through studying case of a building with high cluttered scan data[69]. In [70], the researchers tried to model the Scan to BIM process. They described the Scan to BIM process and its challenges generally and divided the process into sub-steps. They found out the problem related to Scan to BIM process as; data format, algorithms, and predefined values. Based on the time limitation they did not validate their data and postponed it to future works. A method for capturing building data by laser scanner machine and creating BIM model as a part of the modeling process is introduced in form of a case study in [71]. The possibility of detecting façade damages by using laser scanning and

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[66] Engin Burak Anil et al., "Deviation Analysis Method for the Assessment of the Quality of the as-Is Building Information Models Generated from Point Cloud Data," *Automation in Construction* 35 (2013).
[67] Joohyuk Lee et al., "Skeleton-Based 3d Reconstruction of as-Built Pipelines from Laser-Scan Data," ibid.
[68] Hiroshi Masuda, Ichiro Tanaka, and Masakazu Enomoto, "Reliable Surface Extraction from Point-Clouds Using Scanner-Dependent Parameters," *Computer-Aided Design and Applications* 10, no. 2 (2013).
[69] Xuehan Xiong et al., "Automatic Creation of Semantically Rich 3d Building Models from Laser Scanner Data," *Automation in Construction* 31 (2013).
[70] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[71] Tarvo Mill, Aivars Alt, and Roode Liias, "Combined 3d Building Surveying Techniques – Terrestrial Laser Scanning (Tls) and Total Station Surveying for Bim Data Management Purposes," *Journal of Civil Engineering and Management* 19, no. sup1 (2013).

generate the BIM model is studied.

A new system was set up in [72] to evaluate the construction progress by using laser scanning. The daily laser scanning was done to compare the as-is situation with the as-design model and a Java program was developed to measure the completion percentage. Since this system was only tested in laboratory condition, studying the cases for validating the finding is necessary. In [73], an algorithm was developed for recognizing the pipes within the point cloud and convert them to BIM object. A single case was studied to validate the algorithm and resulted in accuracy which ranges from few millimeters to centimeters. To control the flatness of the surfaces, in [74], the researchers presented a method to segment the on-site scanned data of surfaces by comparing them with their corresponding object in BIM model. The method used two different standard flatness control techniques. The proposed method was tested through two concrete slabs and validated that, it is advantageous in comparison with the traditional methods.

In [75] the new method for segmenting the point cloud is developed. By proposed method, only one parameter requires to be set by the user in order to segment the point cloud. They performed an experiment on two point clouds. First a corridor with plenty of pipes and the second point cloud of an outdoor space of building with existing people and cars in the street. Scan to BIM process is in detail described in [76], and a single case was studied for testing the proposed system. The system aimed to track the MEP components within construction to retrieve the as-built model. In this study, the on-site MEP components were studied, which was challenging because of the differences of the on-site fabricated MEP components and how they designed (as-design). In [77], it is tried to define an algorithm for cleaning the point cloud of a retaining wall in a highway. The developed algorithm was analyzed and validated by testing it

[72] Chengyi Zhang and David Arditi, "Automated Progress Control Using Laser Scanning Technology," *Automation in Construction* 36 (2013).
[73] Mahmoud Fouad Ahmed, Carl T. Haas, and Ralph Haas, "Automatic Detection of Cylindrical Objects in Built Facilities," *Journal of Computing in Civil Engineering* 28, no. 3 (2014).
[74] Frédéric Bosché and Emeline Guenet, "Automating Surface Flatness Control Using Terrestrial Laser Scanning and Building Information Models," *Automation in Construction* 44 (2014).
[75] Andrey and Mani, "Robust Context Free Segmentation of Unordered 3d Point Cloud Models."
[76] Bosché Frédéric et al., "Tracking the Built Status of Mep Works: Assessing the Value of a Scan-Vs-Bim System," *Journal of Computing in Civil Engineering* 28, no. 4 (2014).
[77] Oskouie Pedram, Becerik-Gerber Burcin, and Soibelman Lucio, "Automated Cleaning of Point Clouds for Highway Retaining Wall Condition Assessment," *Computing in Civil and Building Engineering* (2014).

on a different set of data. The researcher aimed to substitute this algorithm as an automated point cloud cleaning method with the manual method of cleaning the point cloud which is time-consuming and labor intensive.

The current approaches in using point cloud in BIM during the different phases of building life cycle is discussed in [78] by studying two cases. They studied the conversion of point cloud into BIM model and found out its barriers. They concluded that automated conversion of point cloud to BIM model could be resulted in saving the notable amount of time and efforts. The researchers were combined two methods to compare as-design and as-built MEP components. The method was validated by studying a case which was a real construction project. This method could recognize the pipes that are not built in the design place and extract the completion progress based on the recognized object[79]. To overcome the challenges of automated 3D modeling, a new method was introduced in [80], for segmentation of unordered point clouds. Using this method, only one parameter should be set for performing the segmentation. The method was tested by seven point clouds and its usefulness for point clouds with different density and clutter was validated. To improve the visual appearance of the point cloud, a rendering method was presented in [81]. The method was tested through three cases which captured by different data capturing methods and the results showed that that the new method has considerable advantages in comparison with traditionally mesh-based methods.

The researchers proposed a method for extracting polygonal surfaces from point cloud with high density and large size. The method was tested in six experiments and the results showed that it is able to recognize the surface in practical time[82]. In [83], a new method for creating a semantic model of furnished offices and the interior home was

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[78] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."
[79] Bosché et al., "The Value of Integrating Scan-to-Bim and Scan-Vs-Bim Techniques for Construction Monitoring Using Laser Scanning and Bim: The Case of Cylindrical Mep Components."
[80] Andrey Dimitrov and Mani Golparvar-Fard, "Segmentation of Building Point Cloud Models Including Detailed Architectural/Structural Features and Mep Systems," ibid.51.
[81] Hiroaki Date, Takashi Maeno, and Satoshi Kanai, "A Rendering Method of Laser Scanned Point Clouds of Large Scale Environments by Adaptive Graphic Primitive Selection," *Computer-Aided Design and Applications* 11, no. 6 (2014).
[82] Hiroshi Masuda et al., "Reconstruction of Polygonal Faces from Large-Scale Point-Clouds of Engineering Plants," ibid.12, no. 5 (2015).
[83] Enrique Valero, Antonio Adán, and Frédéric Bosché, "Semantic 3d Reconstruction of Furnished Interiors Using Laser Scanning and Rfid Technology," *Journal of Computing in Civil Engineering* 30, no. 4 (2016).

developed by using boundaries of elements which not only consider the geometry of objects but also their connections. The researcher used the Radio Frequency Identification (RFID) to detect the furniture. The attached tags to the furniture then are used to extracting geometric data from FM database. These data are used for object recognition and modeling of objects. A research was conducted to develop a method for extracting BIM model from unorganized point cloud for using in energy simulation. In this method, the point cloud is downsized initially, then data is processed and finally, the objects are recognized. The method was tested by three different point cloud and its efficiency was validated [84]. An automated method for recognizing the pipes from a point cloud of an industrial plant in [85] is studied. The study has proposed a method which processes and segments the point cloud, extracts the pipes and finally, classifies them. The studied case validated the proposed method and discover that it could be very helpful.

The researcher developed another framework for recognizing the planar elements like walls, floors, and ceilings in the point cloud which aimed to automate the segmentation. In this framework, first the planar surfaces are recognized, then based on the properties like height, density, and relation with other surfaces, the recognized surfaces are categorized as objects. They test the framework in registered point cloud of an office building which resulted in segmenting almost all the planar elements of point cloud correctly[86]. The point cloud related literature is deeply reviewed in [87] with focus on the cleaning the point cloud. They also developed their own framework for cleaning the point cloud of infrastructures. This framework, first removes the unneeded part, then fill the holes in the surfaces base on the neighbor condition and, finally balance the density of point cloud. They tested their algorithm on ten cases to validate their findings. Different methods which are currently used for object recognition are discussed in [88]. Besides describing these six approaches in detail, in this study an

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[84] Chao Wang, Yong K. Cho, and Changwan Kim, "Automatic Bim Component Extraction from Point Clouds of Existing Buildings for Sustainability Applications," *Automation in Construction* 56 (2015).
[85] Hyojoo Son, Changmin Kim, and Changwan Kim, "Fully Automated as-Built 3d Pipeline Extraction Method from Laser-Scanned Data Based on Curvature Computation," *Journal of Computing in Civil Engineering* 29, no. 4 (2015).
[86] Anagnostopoulos Ioannis et al., "Detection of Walls, Floors, and Ceilings in Point Cloud Data," *Construction Research Congress* (2016).
[87] Rashidi Abbas and Brilakis Ioannis, "Point Cloud Data Cleaning and Refining for 3d as-Built Modeling of Built Infrastructure," *Construction Research Congress* (2016).
[88] Te Gao et al., "Evaluation of Different Features for Matching Point Clouds to Building Information Models," *Journal of Computing in Civil Engineering* 30, no. 1 (2016).

experimental analysis was also done to performance evaluation of the different approaches in recognizing pipes and duct from the point cloud and convert them to BIM objects.

For recognizing the indoor objects of the building like walls and windows, a method was proposed in [89]. This method consists of two parts, first, the walls are recognized according to their boundaries, then windows as hollow parts within walls are detected and separated. The study was tested in two indoor spaces includes a seminar room and a corridor, and the results validated the accuracy of the proposed method by confidence level of 90%. In [90], through a multi-objective research, the knowledge of construction management practitioners about BIM and laser scanning was evaluated and their deficiencies and advantages were proposed. This research also studied the demand for laser scanning within the construction industry. They performed a questionnaire survey among the personnel of construction management companies which showed that they have a high level of knowledge about BIM, but the laser scanning knowledge was in lower level among the participants. A segmented point cloud was used in [91] to add labels to recognized objects within point cloud. Wo types of the label were used in this study. Semantic labels to recognize the object type (e.g. wall, floor, ceiling, etc.) and geometric labels to determine the shape of the object (e.g. horizontal, vertical, etc.).

A method for automated creation of BIM model from scanned data is presented in [92]. This study focused on the pipelines and consists of three parts. First, the location of the pipeline is detected, then the pipeline is segmented into its parts, and finally generating the BIM model of the pipeline. The method was tested in two industrial plants and validated the usefulness of the method for generating the BIM model of pipelines in industrial plants. A method was proposed in [93] to find the collisions between

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[89] Jaehoon Jung et al., "Automated 3d Wireframe Modeling of Indoor Structures from Point Clouds Using Constrained Least-Squares Adjustment for as-Built Bim," ibid., no. 4.

[90] Alomari Kasim, Gambatese John, and J. Olsen Michael, "Role of Bim and 3d Laser Scanning on Job Sites from the Perspective of Construction Project Management Personnel," *Construction Research Congress* (2016).

[91] Perez-Perez Yeritza, Golparvar-Fard Mani, and El-Rayes Khaled, "Semantic and Geometric Labeling for Enhanced 3d Point Cloud Segmentation," ibid.

[92] Hyojoo Son and Changwan Kim, "Automatic Segmentation and 3d Modeling of Pipelines into Constituent Parts from Laser-Scan Data of the Built Environment," *Automation in Construction* 68 (2016).

[93] Takeru Niwa and Hiroshi Masuda, "Interactive Collision Detection for Engineering Plants Based on Large-Scale Point-Clouds," *Computer-Aided Design and Applications* 13, no. 4 (2016).

BIM model and a point cloud of engineering plants. The experiments showed the efficiency of presented method in calculating the collisions of large scale point clouds of engineering plants. In [94], an improvement to an existing method for automated detection of the cylinder object from a point cloud is proposed. The method was tested by some point clouds and validated the advantages of the new method in creating the model of pipes. To recognizing structural elements from the point cloud and convert them to BIM objects automatically, in [95], a method was presented. The presented could detect the cross section of the structural elements. The method successfully detected the majority of cross section and structural elements within two steel frames with different shapes and sizes.

2.3 Problem Statement

Based on the review of previous works, most of the efforts have focused on introducing the efficient algorithm which not only requires less user effort and performs the object recognition automatically but also could recognize the objects more efficiently and with higher accuracy. Previously, the researches were conducted by focusing on the specific usages of Scan to BIM processes like its usage for modeling pipes or planar surfaces, however, the whole process has not been studied yet.

Based on the availability of different software packages in the market which each one could be used in the single step of Scan to BIM process, studying the whole process by using a set of various software seems essential. While the steps of the process have been investigated deeply by the researchers, the whole process from beginning to end has not been considered in academia. To bridge this gap and investigate the whole process and interoperability between software that used in each step of the process, this study aims to find out the most significant consideration for performing Scan to BIM process from FM point of view.

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[94] Ashok Kumar Patil et al., "An Adaptive Approach for the Reconstruction and Modeling of as-Built 3d Pipelines from Point Clouds," *Automation in Construction* 75 (2017).
[95] Debra F. Laefer and Linh Truong-Hong, "Toward Automatic Generation of 3d Steel Structures for Building Information Modelling," ibid.74.

3. METHODOLOGY

In this chapter, used methods for conducting research and answering the research questions are described. First, a brief review of the different research methods, especially those which were employed in previous related works, is presented. Then, based on the nature of this study, the appropriate method for answering the research questions are proposed. Afterward, the used method is described in details by presenting the used resources, their characteristics, and specifications. At the end, the scope of the work or delimitation of the study is presented to give a description of the boundaries of this academic endeavor.

3.1 Introduction

As it was mentioned in the last chapter, most of the previous researches are concentrated on presenting new methods for automating the Scan to BIM process. For this reason, after proposing the algorithm, it was tested practically by doing some experiments. Since the Scan to BIM process is introduced to academia within last ten years and it has not been widely used in industry, conducting the surveys in forms of questionnaire and interview is problematic.

Regards to above-mentioned issues, the only way to gathering information in this field is to review the literature and extract the useful information from previous related works. In Architecture, Engineering, and construction industry the field of using laser scanning, especially Scan to BIM, is introduced recently (10 to 15 years) and it is still under the development. Scan to BIM rarely has been used practically within the industry and in the real projects, most of the efforts are made within academia and the research projects.

Since Scan to BIM is a fast growing topic and it is improving day by day, industry practitioners are waiting for the good establishment of this method and assuring about its advantages to start using it within their projects. The software providers are updating their product in short periods based on the new findings of recently published research to improve the software and reduce their deficiencies. The incompleteness of the software and is under development, beside the high amount of required time and cost for using Scan to BIM, is another reason that companies have not started to use it and do not want to bear the risk of using a newly introduced, under development method.

3.2 Methods

Based on the nature of this study and research questions, and reviewing the previous related works and their methods, using the Critical Success Factors (CSF) approach could lead to answering the research questions. Based on [96] “Critical Success Factor has been widely adopted by researchers as a top-down methodology for examining factors affecting technological change. The CSF approach is an effective way of identifying a few manageable but vital factors from a large number of factors.”

Different methods have been used in form of CSF approach by the researcher. These methods mostly include the literature review, questionnaire survey, and interview as qualitative methods. The variety of quantitative methods has been employed to analyze and validate the qualitative findings of the above-mentioned methods as well.

The most popular method is to find the Success Factor (SF) from reviewing the literature or conducting interview firstly. Then try to find the CFSs and validate the finding by a questionnaire survey. In most of the cases, close end questions with answers in form of Likert Scale are used. In this method, the SFs are listed and the participants are asked to rank the significance level of the factor from 1 to 7 (or from 0 to 6). The number 1 means not important at all, 4 means neither unimportant nor essential, 7 means extremely essential.

As it was mentioned before, there are a handful of experts in the field of Scan to BIM and these experts are scattered all around the world. Most of these people are the researchers who have done academic endeavors in this field. In addition, these people are focusing on different aspects of the Scan to BIM process from different point of views. It is very difficult to find someone who has experience about the whole process from the beginning to the end.

The Scan to BIM has been seldom used within the industry and the practitioners are monitoring the academic progress of this process closely to be assured about its

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[96] Meng-Han Tsai, Mony Mom, and Shang-Hsien Hsieh, "Developing Critical Success Factors for the Assessment of Bim Technology Adoption: Part I. Methodology and Survey," *Journal of the Chinese Institute of Engineers* 37, no. 7 (2014).

advantages before start to use it. According to above-mentioned problem, it is somehow impossible to conduct a survey in forms of interview or questionnaire to find the research questions, even if it is possible, it does not fit within the scope of this study in terms of time and effort limitations. These considerations limit the available methods for this study to reviewing the literature and performing the experiment.

Based on the possible methods, it was decided to review the literature comprehensively to find the SFs for Scan to BIM process from previous related works. At the same time, looking for available and recently-used software in related works within the Scan to BIM process to find the best combination of a set of software which fit for this study. Finally, perform two experiments using the best-fitted software to validate the found SFs and find out the additional SFs which are not mentioned in previous studies.

3.2.1 Review of Literature

Performing the literature review was begun with finding the related works in March 2017. For this reason, the total amount of 94 Papers was downloaded based on the related keywords (Laser Scan, Point Cloud, Scan to BIM). Five papers which had been published before 2006 were immediately deleted from the database. Figure 10 shows the number of found papers based on the keyword and publication year.

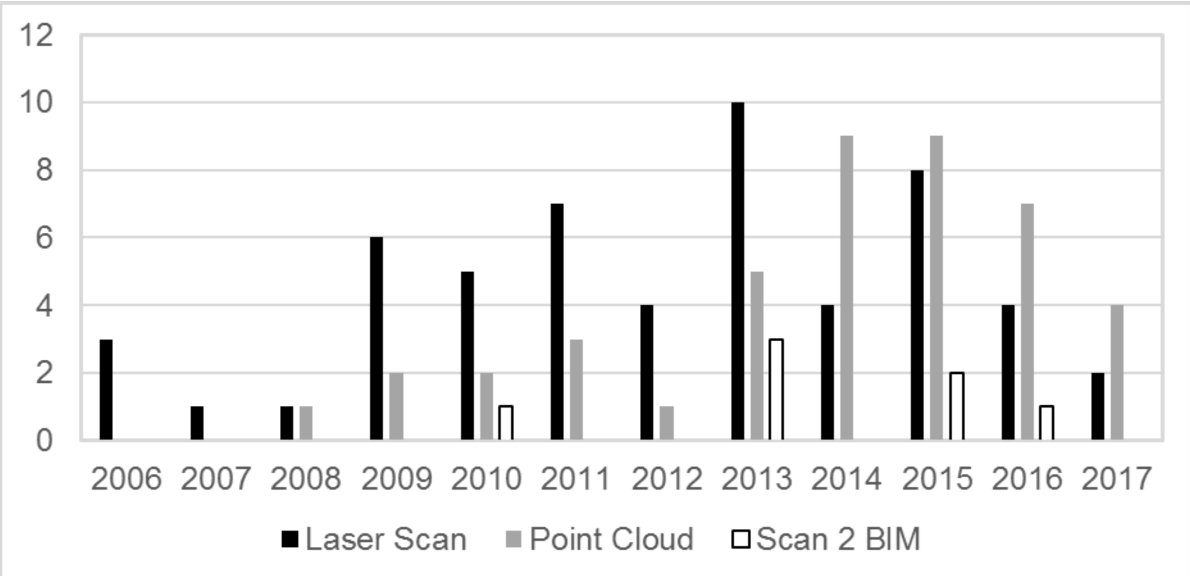

Figure 10 Number of found papers based on the keyword and publication year

As it can be obviously seen, the trend of publishing papers in all three fields shows that the number of published papers was started to grow from 2009. the trend of publishing the papers are somehow the same, although the numbers are different. According to the trend of the publication, the topics become popular among researcher from 2010.

It should be noted that there were some papers which have more than one of the keywords, so it is expected that the sum of the numbers of papers in Figure 10 is more than total amount of papers. In terms of using the keywords, papers with keyword ‘Laser Scan’ placed at the top with the total amount of 55 papers, then the keyword ‘Point Cloud’ was with 43 papers. Only 7 papers included the ‘Scan to BIM’, which shows that this topic has not been studied deeply yet.

Figure 11 illustrates the number of found papers in terms of publication year. Base on the distribution of papers within different years, and the decision about reviewing the recent publication, it was decided to eliminate the papers which had been published before 2010. So the number of papers which have been reviewed was 75. As it is depicted in figure 11, the pick of published papers was in the period of 2013 until 2015.

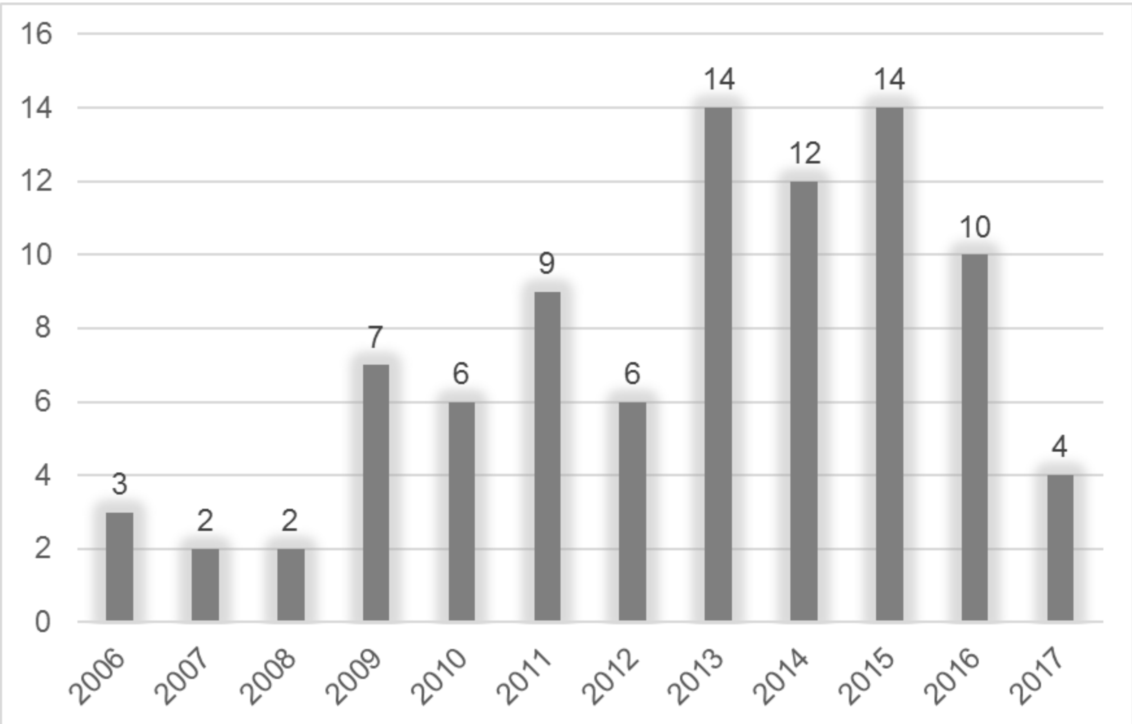

Figure 11 Number of papers in terms of publication year

Considering the time delay between introducing a new method by researcher and releasing the final product from industry, nowadays, after 2 years from popularity period of this topic in academia, there is a wide range of software for facilitating and automating can to BIM process available in the market. It should be noted that the papers are downloaded in March 2017, so the number above this year presents the number of found papers in the first quarter of the year.

Figure 12 depicts the number of downloaded papers from different databases. Most of the papers were downloaded from ASCE (American Society of Civil Engineers) and ScienceDirect databases. Since these two databases contain most of the journals in the fields of Architecture, Engineering, and Construction (AEC) and Facility Management (FM), these numbers are not unexpected.

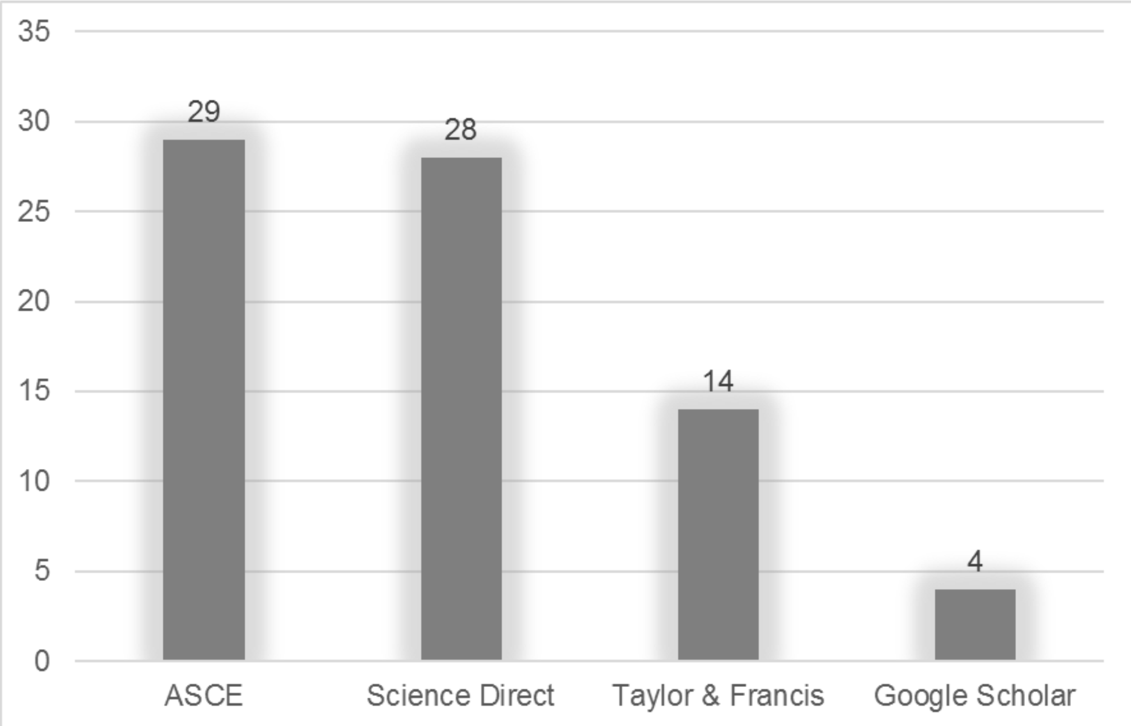

Figure 12 Number of found Papers in terms of Database

19 journals and proceeding from 3 databases were investigated to find out the related papers about the topic of this research. The scope of some of the journals and proceedings are more related to the topic, so it is predictable that the number of found papers in terms of journals and proceeding is distributed uniformly.

Figure 13 illustrates the number of found papers which are categorized in terms of the journals and proceeding they belong to. As it can be observed, the journal of ‘Automation in Construction’ has the highest number of papers among found papers. This journal is one of the most valuable journals in the field of AEC/FM in terms of impact factor and is published monthly. Volume 72 of this journal which was published in December 2016 contains 410 pages and has included 40 papers. Based on its frequency and size, the high number of found papers from this journal could be interpreted and is reasonable.

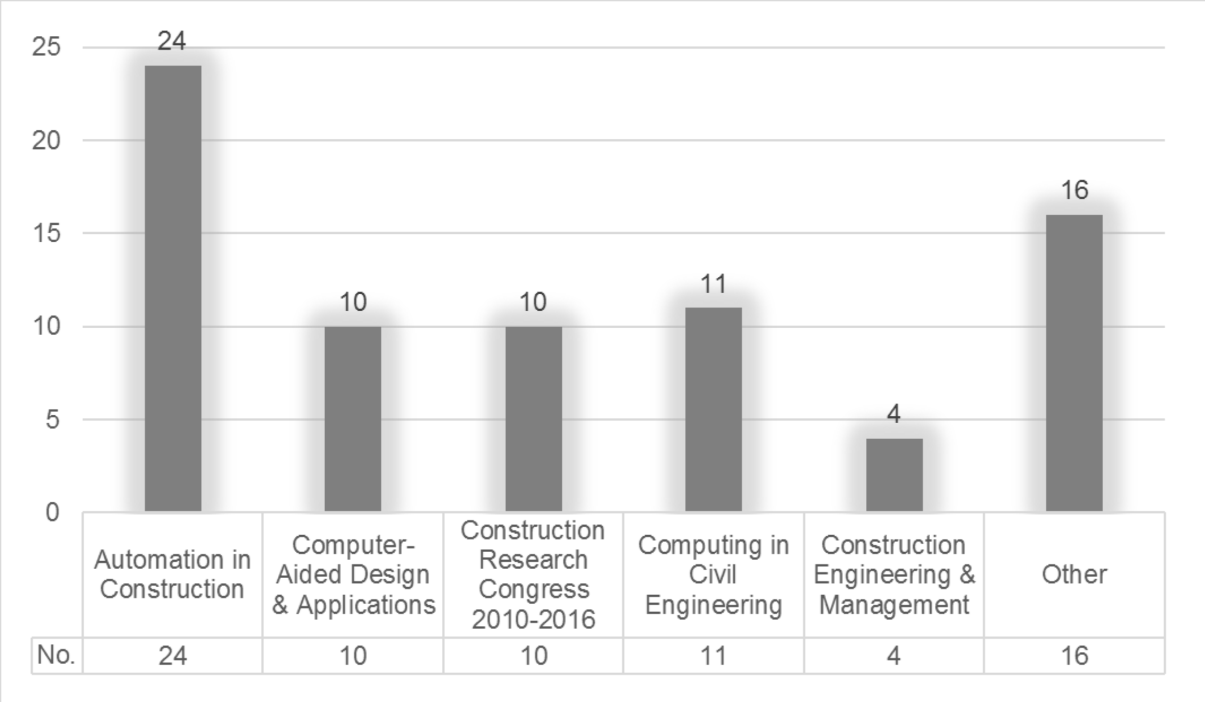

Figure 13 Top 5 Journals (In terms of number of found papers) and Other

After the ‘Automation in Construction’ journal of ‘Computing in Civil Engineering’ from ASCE is in the second place with 11 papers. Proceeding of ‘Construction Research Congress’ from ASCE and journal of ‘Computer-Aided Design & Application’ from Taylor & Francis” are placed in next position with 10 papers equally. Journal of the ‘Construction Engineering & Management’ from ASCE is at the end of the list with 4 papers. 16 other papers belong to journals which each of them has less than 2 papers through the found papers.

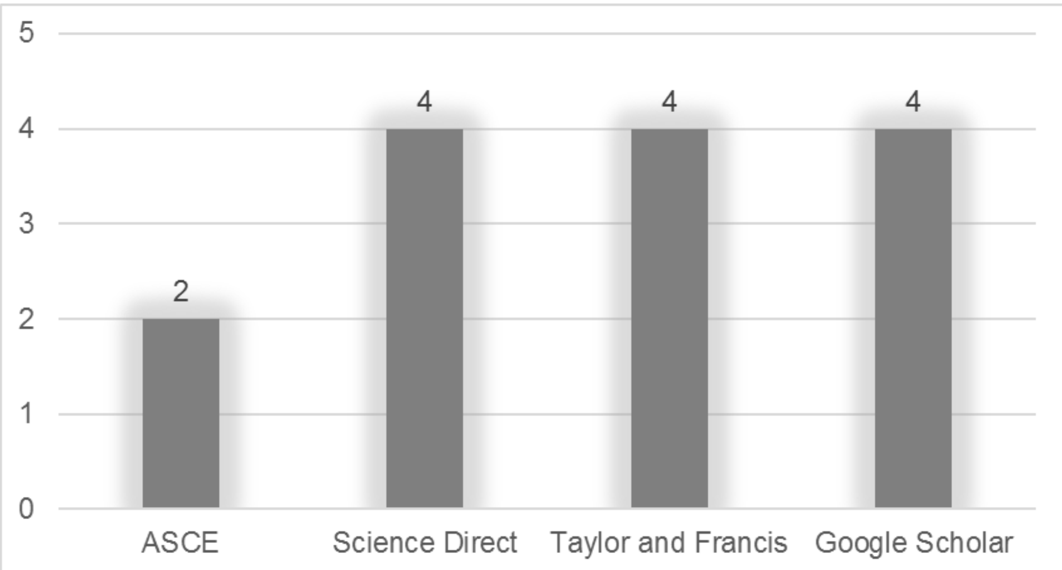

Figure 14 Number of Papers do NOT belong to top 5 journals

Figure 14 shows the number of papers which do not belong to top 5 journals in terms of highest number of found papers. Among these remaining papers, 4 papers belong to each of ScienceDirect, Taylor & Francis, and 'Google Scholar' databases and ASCE database have only 2 papers.

Table 2 Information of reviewed papers

Database	Journal	Number of papers	Publication Year (Number)
ASCE	AEI 2013	1	2013
	AEI 2015	1	2015
	Computing in Civil and Building Engineering	2	2014 (2)
	Construction Research Congress 2010	1	2010
	Construction Research Congress 2012	3	2012
	Construction Research Congress 2014	3	2014
	Construction Research Congress 2016	4	2016
	Journal of Computing in Civil Engineering	10	2011 (3), 2013 (1), 2014 (3), 2015 (3)
	Journal of Construction Engineering and Management	4	2010 (1), 2011 (2), 2016 (1)
	Total	29	
Science Direct	Automation in Construction	24	2010 (1), 2011 (1), 2012 (2), 2013 (6), 2014 (2), 2015 (7), 2016 (2), 2017 (3)
	Computer-Aided Design	1	2013
	Computers in Industry	1	2013
	Construction and Building Material	1	2011
	Simulation Modelling Practice and Theory	1	2015
	Total	28	
Taylor & Francis	Architectural Engineering and Design Management	1	2012
	Computer-Aided Design and Applications	10	2010 (2), 2011 (1), 2013 (1), 2014 (2), 2015 (1), 2016 (2), 2017 (1)
	International Journal of Construction Education and Research	1	2015
	Journal of Civil Engineering and Management	1	2013
	Survey Review	1	2016
	Total	14	
Other	Google Scholar	4	2010 (1), 2011 (1), 2013 (2)
	Total	4	
Total		**75**	

In Table 2, the names of whole journals which the papers are downloaded from them are listed. The papers are categorized based on their databases and number of downloaded papers from journals are written in the next column. Last column (right) shows the publication year of the found papers. In the case of existing more than one paper with same publication year from the single journal, the number of papers in each year is mentioned in the parentheses. The sum of the number of found papers from each database and the number of found papers are listed as well.

3.2.2 Experiment

To practically test the results and findings of the literature review, two experiments were performed. It was tried to select the cases with different characteristics, usage, and specification. For this reason, a medium size building which accommodates the heating systems and a large scale office building was chosen. These buildings contain a wide range of components include structural, architectural, and MEP. In this part, first, the buildings are briefly described, then used technological tools include hardware and software are presented.

GASAG

The GASAG building, which is placed in the HTW University of Applied Science, is a rectangular steel structure building which heating system of neighbor buildings are placed in it. The total area of the building is 560m^2 and it has 8m height. It is built as a small scale industrial building with high height columns which are designed in sides and no column in the middle. There are thick brick walls between the columns as exterior walls and slabs are reinforced concrete.

The building is covered big parts of university buildings heating systems. It has uncovered structure (steel beams and columns, and concrete slabs), small architectural part (rooms with doors and windows, corridors and staircase, etc.), and a wide range of MEP components (pipes, ducts, cables, and equipment). This variety of elements from different disciplines and the uncovered situation of them, make this building an appropriate case for performing the experiment.

The west side of the building is divided into two level and some small rooms as offices are built at the higher level. The lower level spaces are used as storage rooms. There are two staircases in the building. One in the east side which is accessible through main interior space of the building, and another one which is to the west and connects the office spaces into a small entrance door. There are two steel corridors in the higher level in south side and center of the building, they provide access to MEP components in a higher level.

Verbändehaus

Verbändehaus is an office building consists of an l-shaped building in the east and a c-shaped building in the west which were connected to each other by two sets of double elevators. Two parts of building form a big rectangular with the office spaces around and an empty space in the center which forms an atrium. Each of c-shaped and l-shaped buildings has 8 floors with total areas of about 550m^2. The c-shaped building has 8 floors and one underground floor, and the l-shaped building has 9 floors and one underground floor as well. The atrium has 350m^2 areas and it is covered by a glass roof at the top.

The structure of the building is reinforced concrete and the façade is built with precast concrete walls which contain windows within themselves. Each part of the building has two staircases and two sets of double elevator connect two parts to each other with bridges which are placed in front of the elevators.

Since the structure of the building is somehow completely hidden (Except the columns) it was impossible to capture structural related information by laser scanning. The scanning of the MEP systems was also limited to the equipment which is located at the roof top. The aim of using this building was testing a large scale building and try to model its architectural elements by using Scan to BIM process.

Hardware

In this part, an overview of the hardware which is used for this study is explained. Used hardware was a Trimble brand laser scanning machine and a super computer. Their usage and specifications are described in the following headings.

Based on the number of the laser scanning stations and size of the point cloud, laptops or normal PCs are unable to handle the process in the reasonable time. To overcome this issue, a supercomputer was used. The computer was equipped with 6 Intel core-i7 processor to accelerate the processing and reduce the time.

Based on [97], "terrestrial laser scanners can be divided into three basic groups:

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[97] Mill, Alt, and Liias, "Combined 3d Building Surveying Techniques – Terrestrial Laser Scanning (Tls) and Total Station Surveying for Bim Data Management Purposes."

- triangulation,
- time of flight (TOF), and
- phase-shift (PS) or phase-based (PB).

Triangulation laser scanners shine a laser pattern onto the object and use a camera to look for the location of the laser's projection onto the object. The pattern projector and the object being measured are configured in a triangle, hence the name triangulation scanner. Triangulation laser scanners are used in applications generally requiring an operating range that is less than 25 m.

TOF laser scanners compute distances by measuring the time frame between sending a short laser pulse and receiving its reflection from an object. Since the laser pulse travels at a constant speed, the speed of light, the distance between the scanner and the object can be determined. TOF laser scanners can determine up to 50,000 points per second up to a distance of over 1 km from the scanner.

PB laser scanners avoid using high precision clocks by modulating the power of the laser beam. The emitted (incoherent) light is modulated in amplitude and fired onto a surface. The scattered reflection is collected and a circuit measures the phase difference between the sent and received waveforms, hence a time delay. This method allows faster measuring, up to 1,000,000 points/s. Because of the laser power required to modulate the beam to certain frequencies, the range of these scanners are limited to approximately between 25 and 80 m."

A Trimble TX8 laser scanning machine (Figure 15) was available and surveying team was familiar with this machine and had some experiences in using it. Since the laser scanning machines are expensive and it takes time for surveying team to become familiar with them, using the available laser scanning machine was the only possible option.

Based on the Trimble company assertion, this laser scanning machine could measure 1 million points per second. They offer this product for capturing a detailed scan of existing site conditions. It provides a high-density point cloud by covering 360 x 317 degree. It means that only 43 degrees are not covered by this laser scanning machine. This inefficiency is common in all types of laser scanning machines with different ranges, but it does not result in a deficiency in the point cloud. It only leads to an uncaptured circle hole under the scanner which could be covered by datasets from other stations.

Figure 15 Trimble TX8 laser scanning machine[98]

The Trimble TX8 laser scanning machine provides 5 different levels for data capturing (Table 3). The capturing time is three minutes which is based on the basic quality level of the laser scanning machine. It can precisely capture data from 120 m which could be extended up to 340 m by an optional upgrading. It has a touch screen to facilitate its usage and set the level of data capturing into the desired level. It is also possible to define the scan area in the case that it aims to capture some specific spaces or parts. The machine works with non-visible, safe to use laser and enables to capture data in bright sunlight.

The laser beam diameter of the machine is 6, 10, and 34 mm respectively for 10, 30, and 100 m. Based on the machine specifications, it could be used for:

- Preconstruction as-built
- Building Information Modeling (BIM)
- Virtual Design Construction (VDC)
- Quality control during construction
- Comparing design intent to as-built conditions

Table 3 Levels of data capturing[99]

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[98] "Trimble Tx8," Trimble Navigation Limited, http://mep.trimble.com/sites/mep.trimble.com/files/marketing_material/MEP_TX8_LR.pdf.
[99] Ibid.

Scan Parameters	Preview	Level 1	Level 2	Level 3	Extended[1]
Max range	120 m	120 m	120 m	120 m	340 m
Scan duration (minutes)[3]	01:00	02:00	03:00	10:00	20:00
Point spacing at 10 m	15.1 mm	———	———	———	———
Point spacing at 30 m	———	22.6 mm	11.3 mm	5.7 mm	———
Point spacing at 300 m	———	———	———	———	75.4 mm
Mirror rotating speed	60 rps	60 rps	60 rps	30 rps	16 rps
Number of points	8.7 Mpts	34 Mpts	138 Mpts	555 Mpts	312 Mpts

Software

In this part, some available software in the market related to the Scan to BIM process which has been used in this study is reviewed. The selection of the software base on the different considerations like their efficiency and experience in the field, popularity, and possibility to get their license. The software is presented according to the sequence of their usage within the process.

Trimble Realworks, After finishing the laser scanning on-site, the memory stick was taken out of the laser scanning machine and data were transformed to the PC. Then the files are opened within Realworks for performing the further actions. Realworks had been used in this study for two purposes; data format conversion from TZF to E57, and automated registration. The usage of the Realworks is described later under the experiment headings.

Autodesk ReCap, ReCap is the product of Autodesk company which is one of the most popular and well-known software providers in the field of design. Since the Autodesk owns the most used software for building 3D modeling (Revit), they released ReCap to support their software package in the field of laser scanning and point cloud usage.

ClearEdge3D Edgewise, According to [100], “Several commercially available software programs have been developed to assist the current manual process of 3D modeling (e.g., Leica CloudWorx by Leica Geosystems, AutoCAD Plant 3D by Autodesk, and

[100] Son and Kim, "Automatic Segmentation and 3d Modeling of Pipelines into Constituent Parts from Laser-Scan Data of the Built Environment."

EdgeWise Plant by ClearEdge3D, all of which were introduced in 2014). These programs are user-friendly tools for the 3D modeling of the pipelines, provide several features for manipulation of laser-scan data in the form of 3D point clouds acquired from the built environment, and have the capability to create and modify pipeline models to help and guide users in what would otherwise be a repetitive, tedious, and time-consuming modeling process. For example, a recent version (i.e., 4.0) of the EdgeWise Plant software includes a variety of features for executing detection of the straight portion of a pipeline and for fitting cylindrical shapes to it."

The ClearEdge3D company was established to offer object recognition software on 2006, they released their first software on 2009. Their first software had been focused on recognizing the pipes and MEP components from point clouds. Progressively they introduced supplementary software to complete their software package. Currently, they offer a software package so called Edgewise Building Suite. The package consists of pipes, ducts, structure, and building elements (Walls, levels, and windows) recognition.

"Based on [101], "The ClearEdge3D software suite probably constitutes the state-of-the-art in commercial solution for automated extraction of pipes, in particular". "ClearEdge3D commercializes the EdgeWise 5.0 software package that features functionalities for (semi-) automatically extracting structural components like walls, windows, doors from TLS point clouds and exporting them in a BIM model format."[102]

"Trimble Realworks and ClearEdge3D are designed to automatically create a 3D model by manually segmenting the point cloud and choose the corresponding catalogs for each segment of point cloud (Table 4)."[103]

Revit, By finishing the object recognition in Edgewise, the recognized objects should be exported. The exported file from Edgewise is then imported to Revit 2015 by the Edgewise plugin which was added to Revit automatically after installing the Edgewise on the PC. Since the Revit models are planned to be used in the further researches, it was decided not to use the latest available version of the Revit (2017). This decision was made because it is impossible to downgrade the Revit models. Even when the

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[101] Frédéric et al., "Tracking the Built Status of Mep Works: Assessing the Value of a Scan-Vs-Bim System."
[102] Enrique Valero, Antonio Adán, and Frédéric Bosché, "Semantic 3d Reconstruction of Furnished Interiors Using Laser Scanning and Rfid Technology," ibid.30 (2016).
[103] Wang, Cho, and Kim, "Automatic Bim Component Extraction from Point Clouds of Existing Buildings for Sustainability Applications."

lower version Revit model is opened by the higher version, before opening the file the software gives a message that for opening the older version file into newer version software, it is necessary to upgrade the file. The upgraded file could not be opened by lower version anymore.

Table 4 Realworks vs Edgewise[104]

Software	Advantages	Limitations
Trimble Realworks	• Combine 3D scanning, imaging and position data • Semi-automatically modeling pipes	• Need manual point cloud segmentation and modeling object category selection
ClearEdge3D Edgewise	• Semi-automated feature extraction • Deep integration with Revit, PDMS, AutoCAD, and other platforms • Designed for various applications	• Need manually segmenting point cloud and selecting object category for object modeling

3.3 Delimitations

According to the characteristics of Scan to BIM process which is mentioned in the first part of this chapter, it is necessary to define the scope of the work and boundaries of academic endeavors for this research. Since base on the availability of the resources (especially time and knowledgeable experts in the field), it was impossible to validate the SFs and found out the CSFs, it was decided that this study focused on the exploring SFs. For this reason, a comprehensive literature review was performed and the findings were tested within two experiment. The number of the cases for conducting the experiments were selected based on the available human resources. The hardware and software for performing the experiments were chosen from available tools within the university and its research institutes.

[104] Ibid.

4. RESULTS AND DISCUSSIONS

In this chapter first, the found SFs for performing the Scan to BIM process from previous works are described. As it was discussed in the methodology chapter, the variety of research papers was reviewed and the related SFs were extracted which are presented in the first part of this chapter. Then, the experiments which were used to test the found SFs from literature, and on the other hand, find out the SFs which was not mentioned in previous studies, are described in details.

4.1 Success Factors from Literature

This part describes the found SFs of Scan to BIM process from FM point of view. The SFs are listed and a brief description for each of them is provided for better understanding the factor. The SFs are categorized sequentially in three categories; Before Laser Scanning, Laser Scanning, and After Laser Scanning.

4.1.1 Before Laser Scanning

Well defined requirement or LOD

Since defining the requirements and objectives of the project have a direct and significant influence on the whole Scan to BIM process, it is very critical to have clear and well understood LOD before starting the process [105]. Choosing the LOD should be done based on the requirement and desired usage of the point cloud. As it was previously discussed, the point cloud could be used for a variety of reasons.[106]

Even when it is planned to use the point cloud for generating BIM model by Scan to BIM process, the usage of the BIM model could be different and consequently, the LOD could be different. As it will be discussed in the next part of this study, the LOD has a direct effect on the file size and density of point cloud. Since the density and size of point cloud could influence the whole time and cost of the process, selecting the

[105] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[106] Randall Tristan, "Construction Engineering Requirements for Integrating Laser Scanning Technology and Building Information Modeling," *Journal of Construction Engineering and Management* 137, no. 10 (2011).

appropriate LOD should be performed by considering all effective factors.[107]

list of objects to be scanned

In most of the cases, it is not necessary to capture data from the whole facility and only some specific parts are required to be captured. To save time on-site and reduce the required effort, it is valuable to have a well-prepared list of object which should be scanned. Numbering the objects in the list and specify their location in the 2D drawings by writing down the corresponded number could prevent the misunderstandings and errors.[108]

In the case of progressive or multiple scanning, a list of object to be scanned could be checked to find out the necessity of repeating the scanning of the specific object in the next scanning. In most of the cases, it is impossible to scan all the desired objects within first scanning. It could result from the existence of occlusion, the problem with accessibility, low quality, and unaccepted dataset, or any other unexpected problems during the scanning.[109]

Selecting appropriate laser scanning method and machine

After defining the objective, visiting the site and listing the target objects, the appropriate method for capturing data should be specified. As it was mentioned before, there are different types of data capturing method which could be used. In the case of deciding to use the laser scanning, the suitable laser scanning machine which could fulfill the requirement should be selected. In most of the cases because of the high cost of the laser scanning machines, companies buy a laser scanning machine and use it for all the scanning projects. [110]

Before buying the laser scanning machine, it could be advantageous if a group of experts which will be involved in laser scanning process have a discussion about the alternatives for laser scanning machine and select the most appropriate one considering the future projects. Even if the decision on selecting the manufacturer and

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[107] B. Riveiro et al., "Terrestrial Laser Scanning and Limit Analysis of Masonry Arch Bridges," *Construction and Building Materials* 25, no. 4 (2011).
[108] Duane Gleason, "Laser Scanning for an Integrated Bim," in *Lake Constance 5D-Conference 2013* (Constance, Germany2013).
[109] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[110] Tristan, "Construction Engineering Requirements for Integrating Laser Scanning Technology and Building Information Modeling."

the model of the laser scanning machine had been made base on the opinion of the experts, it does not guarantee the appropriateness of the laser scanning machine for all further scanning.

In most of the cases, this step is ignored since there is only one laser scanning machine available in the company. Hiring a surveying company or group could solve this problem since they are expert in this field and most probably they offer a wide range of methods and laser scanning machines. On the other hand, hiring some people out of the company could result in a discontinuity in the Scan to BIM process.

Selecting the method and laser scanning machine should be done by considering the variety of factors like desired precision and accuracy based on the required LOD. In [111], the factors which influence the selection of laser scanning machine are listed as; “range accuracy, useful range, the field of view, resolution, scanning speed, and georeferencing and registration method.”

Availability of as-design drawings

The existence of original as-design drawings could be very helpful as a reference to refer to it in cases of uncertainty and conflicts. The as-design information about levels and grids and invisible elements of the building like structural elements could be very helpful for initiating the modeling process and modeling the uncaptured objects.[112]

The as-design drawings could be used for extracting the specification of the objects, like model name and number of MEP components, type of used material, their manufacturer, supplier and product name and number, information about production like date and place of production, operation and maintenance information like date of last checking and next checking, etc.[113]

Availability of as-built drawings

Since in most of the cases the as-design drawings are altered during the construction phase, the as-built drawings are more reliable and comply the current status of building more than as-design drawings.

Considering the MEP components which most of the time are hidden above the

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[111] Ibid.
[112] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[113] Wang Chao and K. Cho Yong, "Automatic as-Is 3d Building Models Creation from Unorganized Point Clouds," in *Construction Research Congress 2014* (Atlanta, Georgia: ASCE, 2014).

ceilings, in most of the cases it is impossible to scan these components and they should be assumed or in the most optimistic situation modeled based on the as-built drawings. The problem is that the as-built drawings are mostly inaccurate since they have a high deviation in terms of location and dimension in comparison with the actual situation.[114]

Availability of shop drawings for prefabricated components

Prefabricated components, machinery, and equipment do not normally include in the BIM software families and need to be model separately. Modeling the geometries of these elements could be time-consuming and labor intensive based on the desired LOD. Semantic information of these type of elements could be very important since some different machines from the same series could have completely same geometry but different specifications and functionality which are very critical for the specialists. Availability of shop drawings for these types of elements could be very beneficial to eliminate described problems.[115]

Having a basis for planning laser scanning stations

In most of the cases, the planning for laser scanning is done in accordance with the experience of the team. In [116], it is stated that "in the field, even experienced users would not be able to conduct a comprehensive evaluation of a job site, select optimal scanning locations, and suggest the settings of scanners that can minimize the data collection time while ensuring the data qualities."

After setting the project objectives and making a decision about the expected usage of the captured data, scanning plan should be prepared. To determine the location of laser scanning machine for capturing the building information, several issues should be considered[117]. The desired usage of captured data, the complexity of building and its shapes, the LOD, and priority in capturing specific object are some example of these considerations. Obviously, locating the laser scanning machine in the places which could increase the covered area by the machine could be very important, since it will

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[114] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[115] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[116] Tang Pingbo and Alaswad Fahd Saleh, "Sensor Modeling of Laser Scanners for Automated Scan Planning on Construction Jobsites," *Construction Research Congress 2012* (2012).
[117] Gleason, "Laser Scanning for an Integrated Bim."

lead to reducing the number of scanning and time accordingly.[118]

Location of scanning stations

One of the most important factors during the laser scanning is the location of laser scanning machine. As discussed before, it is very useful to plan for the scanning and define the location of laser scanning machine[119]. Another factor which should be taken into account regards to laser scanning station when scanning indoor especially the MEP components is to place the laser scanning machine in the positions which could cover all the pipes at least in two datasets.[120]

A single scan in the best situation could scan only half of a pipe, this issue could be problematic in the case of scanning the pipes which are adjoined the planar surfaces like walls, floors, and roofs. This issue is more critical when only part of the pipes is visible[121]. In the case of scanning the industrial plant, both mentioned limitation (lack of flexibility for location of laser scanning machine and lack of possibility to perform multiple scans) are existed and make the process complicated. [122]

For scanning the indoor environments which normally include a large number of mobile inventories like desks, chairs, and other furniture, the location of the laser the scanning machine could be a critical factor [123]. The furniture is usually not included in the available 2D drawings which take into account for the laser scanning planning and even if they are included, their situation is not as same as the furnishing 2D drawing because of their movable nature. According to this issue, in most of the cases, the predefined location of laser scanning machine changes on-site to cover possible space.[124]

The location of the laser scanning station should be defined based on the possibility to

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[118] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[119] Laefer and Truong-Hong, "Toward Automatic Generation of 3d Steel Structures for Building Information Modelling."
[120] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[121] Son, Kim, and Kim, "Fully Automated as-Built 3d Pipeline Extraction Method from Laser-Scanned Data Based on Curvature Computation."
[122] Kawauchi et al., "An Integrated Processing Method for Multiple Large-Scale Point-Clouds Captured from Different Viewpoints."
[123] Valero, Adán, and Bosché, "Semantic 3d Reconstruction of Furnished Interiors Using Laser Scanning and Rfid Technology."
[124] Jaehoon Jung et al., "Automated 3d Wireframe Modeling of Indoor Structures from Point Clouds Using Constrained Least-Squares Adjustment for as-Built Bim," ibid.

capture the target object in the best way. In some case there are some immovable objects which cover the target object, the resulted occlusion could be eliminated by changing the location of laser scanning station. Determining the location of laser scanning station should be done in the way which reduces the number of stations and increases the captured area[125].

Number of scanning stations

Obviously, it is impossible to capture all information of building's object by a single scan, so several scans are needed. The number of scans depends on the complexity of building and its shapes, the required LOD, and the desired accuracy of the point cloud[126]. Increasing the number of scanning stations could increase the overlapping between datasets which is resulted in higher quality, on the other hand, it could lead to increasing the cost of data capturing step as well.[127]

In the case of scanning the indoor environment, one of the most significant issues are the furniture and inventories inside the building, these objects are the main reason for producing occlusion. For scanning indoor environment, the number of scanning station could be influenced by the amount of the furniture which covers the target objects. The number of scan stations directly influences the quality of point cloud, on the other hand increasing the number of stations extend the required time and effort within the whole Scan to BIM process and make the data size bigger [128]. Regards to all mentioned considerations the decision on the number of laser scanning stations should be made, the optimum number could increase the quality and not result in wasting time and workforce.[129]

4.1.2 Laser Scanning

Possibility of exposure to laser

Occlusion is one of the biggest issues in Scan to BIM process especially in the case of scanning the MEP objects (e.g. pipes and ducts), which are normally placed in the

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[125] Riveiro et al., "Terrestrial Laser Scanning and Limit Analysis of Masonry Arch Bridges."
[126] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[127] Laefer and Truong-Hong, "Toward Automatic Generation of 3d Steel Structures for Building Information Modelling."
[128] Tristan, "Construction Engineering Requirements for Integrating Laser Scanning Technology and Building Information Modeling."
[129] B. Giel and R. R. A. Issa, "Using Laser Scanning to Access the Accuracy of as-Built Bim," *Computing in Civil Engineering (2011)* (2011).

high level from the floor. The situation of these elements makes it impossible the higher part of them even with the several scanning. In the worse cases, these elements are partly (or fully in the worst cases) covered by architectural elements like ceilings[130]. This problem is more critical in the industrial plants which there are a huge amount of pipes close to each other within a small space.[131]

The occlusion could also happen in outdoor laser scanning like the bridges over the rivers. Based on the characteristics of this structures, it is impossible to scan the lower part of them because it is very difficult to locate the laser scanning machine below the bridges.[132]

The most complicated case in scanning the building elements occurs for structural elements. In most of the cases, the structural elements like beams and columns are covered by the architectural elements like walls and ceilings and they could not be exposed to the laser. Even in the case which the structural elements are not hidden, based on their neighborhood situation (slabs are placed above the beams and walls are placed next to columns) it is impossible to cover all sides of the structural elements by laser scanner machines. [133]

Using Targets during scanning/type of targets/location of targets

Different types of targets could be used during the laser scanning which could be very helpful during the processing step. The targets are used to identify the common points from two datasets in registration step. Although using the targets speeds up the registration step, on the other hand, placing the targets on the desired surface could be a time-consuming procedure during on-site data capturing step. Increasing the number of targets resulted in more accurate point cloud with higher accuracy, but the optimum number of targets should be determined by considering the required time and effort for placing them as well.[134]

Different types of the targets are available, three of them are illustrated in Figure 16.

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[130] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."
[131] Kawauchi et al., "An Integrated Processing Method for Multiple Large-Scale Point-Clouds Captured from Different Viewpoints."
[132] B. Riveiro, M. J. DeJong, and B. Conde, "Automated Processing of Large Point Clouds for Structural Health Monitoring of Masonry Arch Bridges," *Automation in Construction* 72 (2016).
[133] Debra F. Laefer and Linh Truong-Hong, "Toward Automatic Generation of 3d Steel Structures for Building Information Modelling," ibid.74 (2017).
[134] Gleason, "Laser Scanning for an Integrated Bim."

The paper targets are normally used on the planar surfaces and are easy to use. It should be kept in mind that these targets must be exposed perpendicular to the laser, otherwise, they cause errors. Even small movement of the targets between to scanning could result in inaccuracy. For corners and the turning points, the paddle targets are more suitable.[135] Paddle targets should manually be rotated by team members. Using sphere targets could avoid this problem since they appear the same from every point around. In [136], it is suggested that targets are not placed in the same height and they should be scattered uniformly in the scanning space. The optimum form of scattering the targets are in a way that they are placed in different Cartesian coordinates (xy, xz, yz).

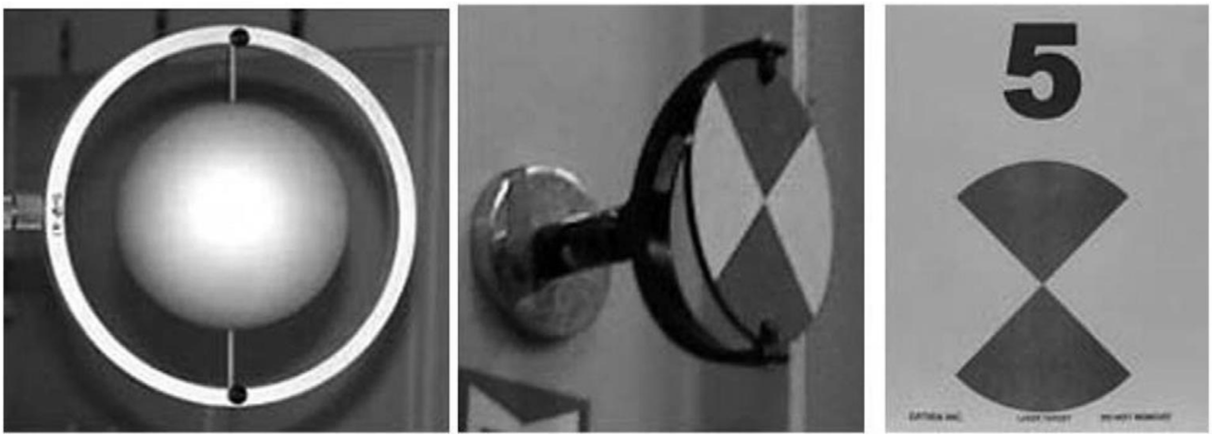

Figure 16 Sphere paddle, and paper targets[137]

Distance of laser scanning machine from target object

The available laser scanning machines in the market differ from covered distance. Making a decision about the distance of the laser scanning machine from the desired elements should be performed by considering the covered distance of the machine, expected LOD, and the possibility of capturing as big as possible part of the object.[138]

It should be noted that locating the laser scanning machine in the nearest point to the target object is not advantageous in all cases. When an unneeded object locates between the laser scanning machine and the target object, it will result in the occlusion

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[135] Hamid Hajian and Burcin Becerik-Gerber, "Scan to Bim: Factors Affecting Operational and Computational Errors and Productivity Loss," in *27th International Symposium on Automation and Robotics in Construction (ISARC 2010)* (Bratislava, Slovakia2010).
[136] Burcin Becerik-Gerber et al., "Assessment of Target Types and Layouts in 3d Laser Scanning for Registration Accuracy," *Automation in Construction* 20, no. 5 (2011).
[137] Ibid.
[138] Chao and Yong, "Automated 3d Building Envelope Recognition from Point Clouds for Energy Analysis."

and its shadow produces a gap or a hole within the target object. The closer the laser scanning machine to unneeded object, the bigger its shadow and the hole within the target object. In this case, if it is impossible to locate the laser scanning machine next to an unneeded object, the only solution is to move the laser scanning machine far away from the unneeded object to increase the size of resulted hole within the target object.[139]

According to angular coverage of the laser scanning machine, increasing the distance of the laser scanning machine from the target object could increase the covered area which could be captured. On the other hand, a high distance of the laser scanning machine from the target object could be resulted in decreasing the accuracy of the point cloud. Regards to these issues, the optimum distance of the laser scanning machine from target object should be determined.

Quality of laser scanning file or Density (number of point per unit)

Available laser scanning machines in the market have different levels. These levels provide a wide range of ‘Density’ (number of a point per unit) which is mentioned as quality level. Obviously, the higher number of points in a single unit of the point cloud, the bigger size and higher quality of point cloud. The problem which caused by high density scanned data is reducing the required time for registering and processing and need for the high-performance computers. The quality or density level should be chosen based on the desired LOD.[140]

The low density of point cloud could also be problematic. The object with low density could be detected as noise in cleaning step and be removed or during the object recognition step, they could be ignored and not be detected.[141]

Less crowded time and Less crowded scanning group to reduce the noise

One of the most effective factors in producing the noise are moving objects especially the people. In both cases of indoor and outdoor laser scanning, the time of laser scanning could significantly reduce the number of noises caused by the people. Since the laser scanning does not require the daylight, making a decision on doing the laser scanning in the nonworking hours (for indoor laser scanning) and less crowded hour

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[139] Riveiro et al., "Terrestrial Laser Scanning and Limit Analysis of Masonry Arch Bridges."
[140] Andrey and Mani, "Robust Context Free Segmentation of Unordered 3d Point Cloud Models."
[141] Giel and Issa, "Using Laser Scanning to Access the Accuracy of as-Built Bim."

(for outdoor laser scanning), could be very helpful. Although doing laser scanning during in non-working hour could not be possible or increase the cost of the scanning process.[142]

Taking photo or recording movie from building

In most of the cases the people who are involved in data processing, object recognition, and modeling steps do not participate in laser scanning. This causes the lack of visual understanding about the building and its elements. Taking a photo from building and captured object or recording video could overcome this barrier. The photo could be attached to the point cloud and BIM model in the next steps to improve the visualization of the model.[143]

Since it is difficult to include whole captured space in a photo the number of the photo could increase enormously if there is no defined procedure for taking a photo. Another problem is naming the photos to eliminate the misunderstanding and confusing which photo belongs to which part of the building. Some laser scanning machine manufacturers equipped their machines with the functionality of taking a photo to avoid the above-mentioned problem. [144]

Taking a photo from the laser scanning station could be useful since the photos provide the colorful, high-resolution view of the captured object. The photos provide a better understanding of the captured environment[145]. On the other hand, in the case of taking a photo from the same location, the situation of the target object in occluded areas will not also visible in the photos. For taking a photo from the target object, both mentioned cases should be considered.[146]

Using same scanning level in all stations

As it is mentioned before, the laser scanning machines have different quality levels. By increasing the level, the scanning process could be done several times which is resulted in increasing the density of scanned data (higher amount of points in a single

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[142] Dimitrov and Golparvar-Fard, "Segmentation of Building Point Cloud Models Including Detailed Architectural/Structural Features and Mep Systems."
[143] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[144] Tristan, "Construction Engineering Requirements for Integrating Laser Scanning Technology and Building Information Modeling."
[145] Giel and Issa, "Using Laser Scanning to Access the Accuracy of as-Built Bim."
[146] Riveiro et al., "Terrestrial Laser Scanning and Limit Analysis of Masonry Arch Bridges."

unit), growing the size of scans, and extending the scanning time [147]. Regards to the density of resulted point cloud, capturing data by using different level in different stations could result in unbalance distribution of objects density. This difference in density could result in non-uniform results of object recognition software for similar objects.[148]

Using multi color scan to differentiate objects based on color

The laser scanning machines are able to identify the RGB (Red, Green, Blue) colors. This functionality could be useful for the better understanding of the environment and improving the visual perception of the point cloud.[149]

Using RFID tags for the mobile objects

At the same time with the laser scanning process, the RFID tags could be attached to the mobile objects like furniture. These tags are scanned and will be available through the point cloud and could be used by linking the point cloud to the FM database for extracting the geometric and semantic information of objects. Linking the mobile object from point cloud to their profile in the FM database could extremely save the required time for modeling these elements.[150]

4.1.3 After Laser Scanning

Accuracy of as-design drawings

Since in the most of the cases the buildings are built before introducing the CAD technology to building industry, the original drawings are made with hand by the craftsman and are not accurate or do not comply with the current status of the building.[151]

Accuracy of as-built drawings

The as-built drawings are seldom updated during the operation and maintenance phase, so when talks about the as-built drawings, in most of the cases they represent the status of building after finishing the construction phase rather than the current

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[147] Abbas and Ioannis, "Point Cloud Data Cleaning and Refining for 3d as-Built Modeling of Built Infrastructure."
[148] Lee et al., "Skeleton-Based 3d Reconstruction of as-Built Pipelines from Laser-Scan Data."
[149] Gleason, "Laser Scanning for an Integrated Bim."
[150] Valero, Adán, and Bosché, "Semantic 3d Reconstruction of Furnished Interiors Using Laser Scanning and Rfid Technology."
[151] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."

status of the building based on the applied changes and alteration during operation and maintenance phase.[152]

Existence of Standards and family libraries comply with the As-built components

“Each combination of points representing different types of building components must be manually replaced by objects from a standard library of components. Lastly, a more detailed set of attributes must be attached to each object to reflect the level of as-built detail needed ”[153]. The availability of the object family in Revit related to the real element could be very helpful. In the case that there is no Revit family object corresponding to the real object, the accuracy of the model could be reduced.

Downsizing the point cloud

Even the file that is resulted from the lowest level of laser scanning, contains millions of points[154]. Ideally, the scanning level should be defined base on the desired LOD. Downsizing the point cloud as much as possible, could speed up the process and lead to notable time saving [155] Since the point cloud which produced from integrating several scanned data has a huge size which decelerates the whole Scan to BIM process.[156]

Based on the size of the point cloud and current software which used within Scan to BIM process the high-performance computers are required.[157] Some efforts have been done to adopt some techniques to enable using the normal PCs and laptops in different steps of the process. One of the proposed solutions is slicing the point cloud and use the separate slices for object recognition.[158]

Another problem which could be solved by downsizing the point cloud is, balancing the density of points. In the registration step, different datasets (scans) are merged by overlapping the common objects and spaces.[159] As a result of merging, the overlapped

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[152] Ibid.
[153] Giel and Issa, "Using Laser Scanning to Access the Accuracy of as-Built Bim."
[154] Masuda and Tanaka, "As-Built 3d Modeling of Large Facilities Based on Interactive Feature Editing."
[155] Abbas and Ioannis, "Point Cloud Data Cleaning and Refining for 3d as-Built Modeling of Built Infrastructure."
[156] chul Jung et al., "Automated 3d Wireframe Modeling of Indoor Structures from Point Clouds Using Constrained Least-Squares Adjustment for as-Built Bim."
[157] Riveiro, DeJong, and Conde, "Automated Processing of Large Point Clouds for Structural Health Monitoring of Masonry Arch Bridges."
[158] Ahmed, Haas, and Haas, "Automatic Detection of Cylindrical Objects in Built Facilities."
[159] Son and Kim, "Automatic Segmentation and 3d Modeling of Pipelines into Constituent Parts from Laser-Scan Data of the Built Environment."

parts have a higher density than uncommon parts. Downsizing the point cloud could reduce the density of the common parts and lead to more balanced density.[160]

As it can be obviously seen in Figure 17, the left part shows the registered point cloud which the overlapping caused the high density in common areas (blue parts). The right part shows the downsized point cloud with more balanced density. Even by downsizing the point cloud the density will not be completely uniform and still some parts have a higher density than others, which can be seen in the bottom of the downsized point cloud.

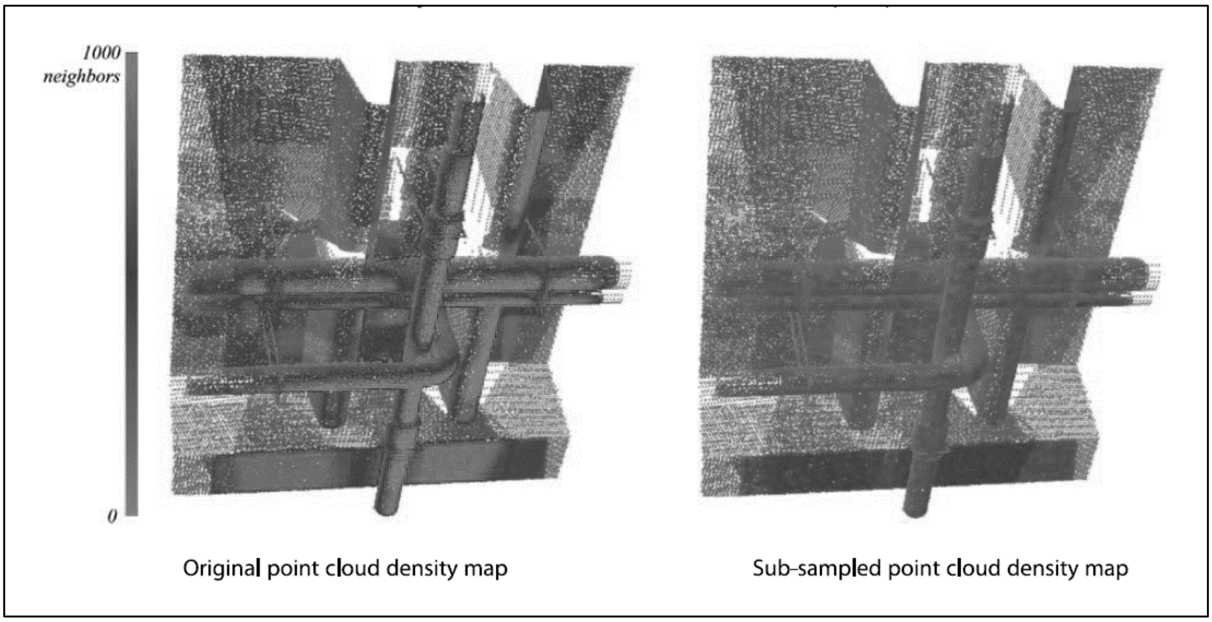

Figure 17 Registered point cloud density before (left) and after (right) downsizing[161]

Excellent user's skills

Based on the complexity of the process and considerable effect of users on the outcome of the Scan to BIM process, the level of user's skill could significantly affect the results of the process.[162] It is proven that even the highly skilled users extracting completely different results from the same data, which validate the claim that users have the highest influence on the Scan to BIM process.[163]

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[160] Son, Kim, and Kim, "Fully Automated as-Built 3d Pipeline Extraction Method from Laser-Scanned Data Based on Curvature Computation."
[161] Dimitrov and Golparvar-Fard, "Segmentation of Building Point Cloud Models Including Detailed Architectural/Structural Features and Mep Systems."
[162] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[163] chul Jung et al., "Automated 3d Wireframe Modeling of Indoor Structures from Point Clouds Using Constrained Least-Squares Adjustment for as-Built Bim."

Interoperability between used software

According to characteristics of Scan to BIM process, the data format is a critical issue during this process. First, the captured raw data format is exchanged after registration, then it is exchanged again to import into object recognition software, and finally, it is converted into BIM software readable format.[164]

Point cloud cleaning and noise removal, undesired objects

Point cloud cleaning is very important part of data processing step during the Scan to BIM process[165]. Since the resulted cleaned point cloud is used in the object recognition step, the tidiness and being free of noises is very important for the point cloud.[166] The noises and clutter could be resulted in misinterpreting the objects, recognizing noises as unreal objects, extending the object recognition time, and increasing the required effort considerably.[167]

The registration could be resulted in producing the noise within point cloud. Since the coordinates of the same point could vary in different datasets, the integrating datasets to produce the point could in registration step cause the variation in the spatial coordinates of the objects.[168]

Figure 18 illustrates a number of noises produced by registration. The imperfect correspondence between datasets is the cause of this noises. The blue parts represent the higher amount of noise. As in can be obviously seen, the location of laser scanning machine (light green circles) appears due to the lower amount of noise.

The other problematic objects in terms of producing the noises are transparent and reflective objects [169]. These objects include mirrors, windows, and highly reflective metals. These objects could result in two major type of problem. First, no corresponded point to this item, second and worse case, is locating the object in the false spatial

[164] Tzedaki and Kamara, "Capturing as-Built Information for a Bim Environment Using 3d Laser Scanner: A Process Model."
[165] Patil et al., "An Adaptive Approach for the Reconstruction and Modeling of as-Built 3d Pipelines from Point Clouds."
[166] Jung et al., "Automated 3d Wireframe Modeling of Indoor Structures from Point Clouds Using Constrained Least-Squares Adjustment for as-Built Bim."
[167] Pedram, Burcin, and Lucio, "Automated Cleaning of Point Clouds for Highway Retaining Wall Condition Assessment."
[168] P. Tang et al., "Efficient and Effective Quality Assessment of as-Is Building Information Models and 3d Laser-Scanned Data," in *Computing in Civil Engineering 2011* (2011).
[169] Masuda and Tanaka, "As-Built 3d Modeling of Large Facilities Based on Interactive Feature Editing."

coordinate.[170]

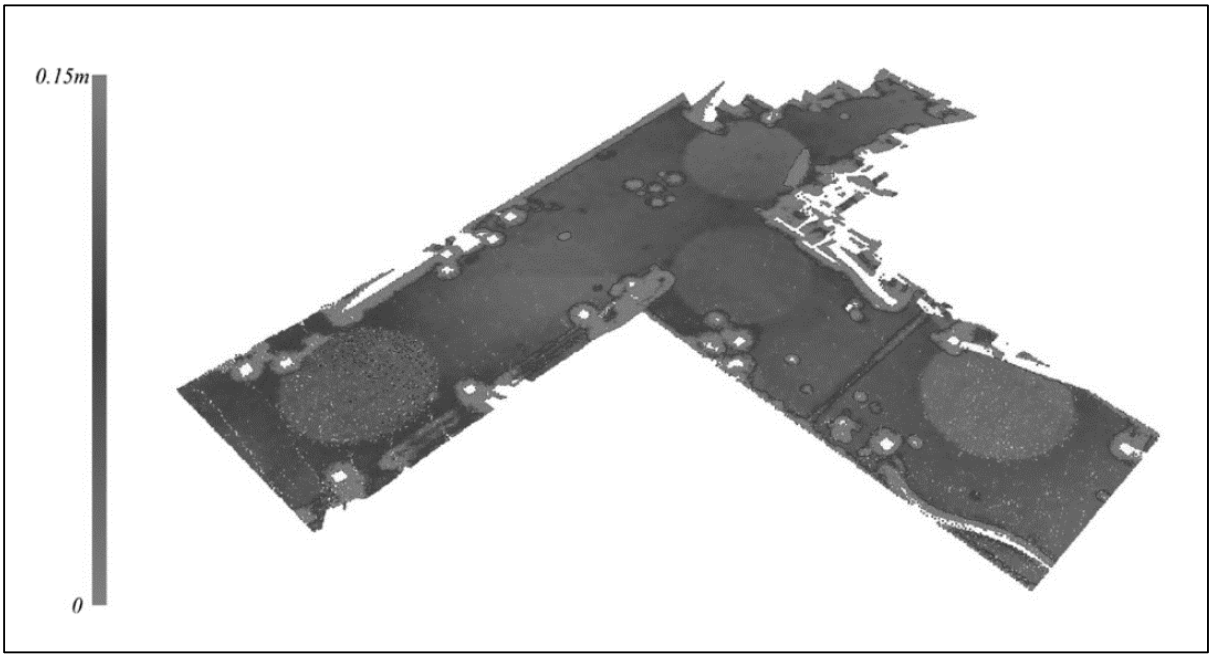

Figure 18 Noises produced after registration[171]

Segmentation of the point clouds

According to [172] “Segmentation is the process of grouping the point clouds from the laser-scanned data into subsets that logically belong to an individual object surface or region.” This step could be very advantageous for the object detection step. Some recently released registration software is equipped with this function which offers faster segmentation step but, with lower accuracy[173]. The segmentation could be used in the cases which only some parts of the building or some specific objects are required to be modeled. In this case, the desired objects could be segmented and used in the object recognition step.[174]

Another advantage of segmentation is a possibility to work on the segmented part separately which avoid the problem of data size, speed up the process, and make it possible to use the laptops [175].

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[170] Dimitrov and Golparvar-Fard, "Segmentation of Building Point Cloud Models Including Detailed Architectural/Structural Features and Mep Systems."
[171] Ibid.
[172] Ashok Kumar Patil et al., "An Adaptive Approach for the Reconstruction and Modeling of as-Built 3d Pipelines from Point Clouds," ibid.75 (2017).
[173] Gleason, "Laser Scanning for an Integrated Bim."
[174] Andrey and Mani, "Robust Context Free Segmentation of Unordered 3d Point Cloud Models."
[175] Masuda and Tanaka, "As-Built 3d Modeling of Large Facilities Based on Interactive Feature Editing."

Systematic Data Management

One of the notable problems of using Scan to BIM for managing extra-large building complexes is data management. These buildings require more scanning stations and more frequent scanning based on the shortest period of time between the alteration in different parts of buildings. Increasing the number and scanning stations and dates of laser scanning results in rising huge amount of data which is very difficult to manage to maintain and analyze.[176]

Possibility to scan not accepted stations once again

One of the problems which could occur in the Scan to BIM process is that the captured data does not fulfill the requirement and does not satisfy the expectation. It might happen because of occlusion resulted from covering the desired object by some temporary or permanent elements or any other unexpected situations or unacceptable quality of captured data. Whatever be the cause of the captured data inefficiency, the possibility to repeat the scanning could be the best for overcoming this obstacle.[177]

Another case which requires progressive and multiple scanning is the installation of new MEP equipment. When the replacement of old MEP components with the new system occurs, the components occluded each other progressively and scanning at the end of replacement could not capture all the details properly. In these cases, it is suggested that the scanning is simultaneous with installation in several phases done to make it possible to capture the maximum possible amount of components.[178]

4.2 Experimental results

In this part, the Scan to BIM process which practically applied for two buildings is described. The buildings and used hardware and software were presented in the methodology chapter. In this part, the process is discussed in details, considering the SFs which were found from literature. The Scan to BIM process was used in three different ways to explore all the factors which could influence the process by using a

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[176] T. Qu et al., "Challenges and Trends of Implementation of 3d Point Cloud Technologies in Building Information Modeling (Bim): Case Studies."
[177] Xuesong, Matineh, and Burcu, "Developing as-Built Building Information Model Using Construction Process History Captured by a Laser Scanner and a Camera."
[178] Yeung Jamie et al., "Comparison of Methods Used for Detecting Unknown Structural Elements in Three-Dimensional Point Clouds," *Construction Research Congress 2014* (2014).

different combination of the software.

At the end, some SFs which were explored during the experiments and have not been previously mentioned in the related works are briefly described.

4.2.1 GASAG

The specifications of the building were discussed in the methodology part. Since the Scan to BIM process was used as an experiment to test the found SFs through review of the literature, there were no defined LOD for the project. The requirement of the project also was not defined in details. Since it was the first practical effort of the group for capturing the information of the building, it was tried to test different options during this experiment.

The aim of the project was to scan the whole building externally and internally include the existing components, especially MEP pipes, ducts, and equipment (figure 19). The southeast interior corner of the building which contained some HVAC ducts, pipes, and machines, was selected for performing the modeling in detail. So the higher scanning level was selected for the stations which were related to this part of the building.

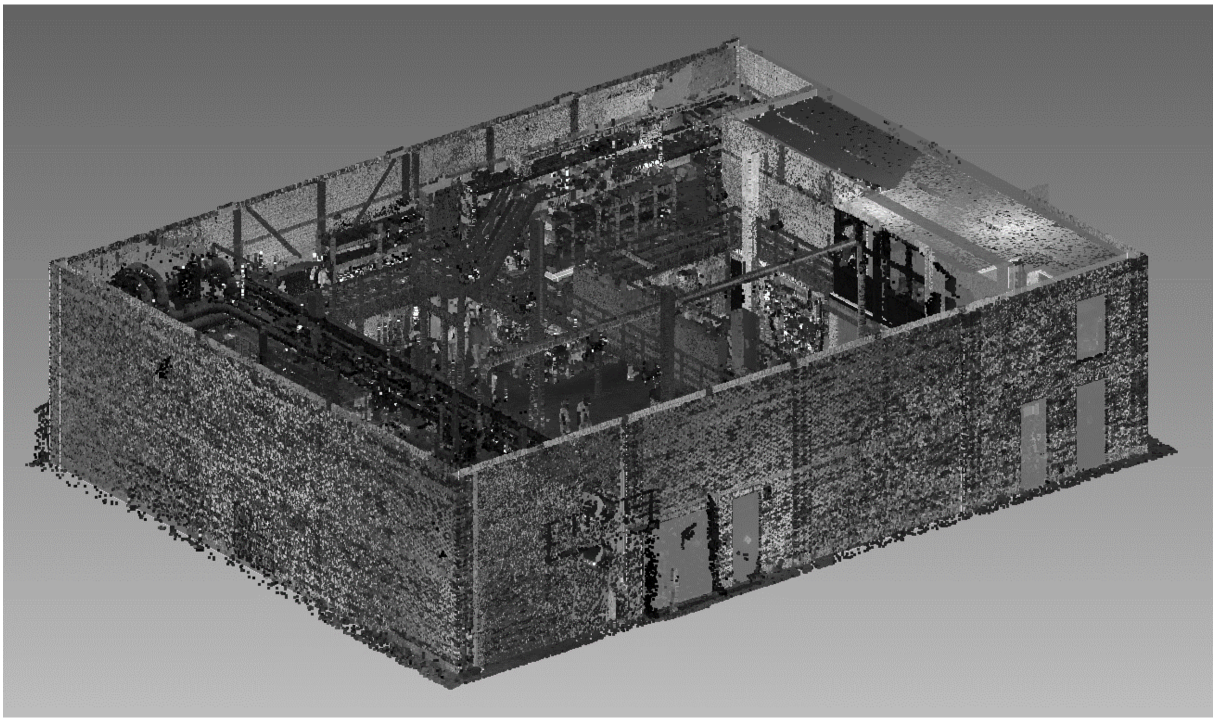

Figure 19 GASAG point cloud and the detected walls

The method which was used for this project and the type of machine were mandated by the availability of the resources. Based on the availability of the Trimble TX8 laser scanning machine, this terrestrial laser scanning machine was used. The available drawings of the building were dated in 1996 and were used for planning the stations and afterward as a reference for the modeling when the captured data were insufficient. The shop drawings of the MEP components were not available and the labels on the machines were used for identifying the brand and model of the machines.

The laser scanning stations are planned base on the theoretical knowledge of the group. It was tried to scan the whole building and its components with a minimum possible number of the stations to reduce the time and efforts for data capturing. Location of the stations was selected based on the shape of the building and visibility of the target objects. The total number of 27 scans were performed externally and internally. The external scans were done in the north, east, and south side of the building and on the roof as well. Since in the west side there was a shared wall between the GASAG building and next building, it was impossible to capture data from the west side.

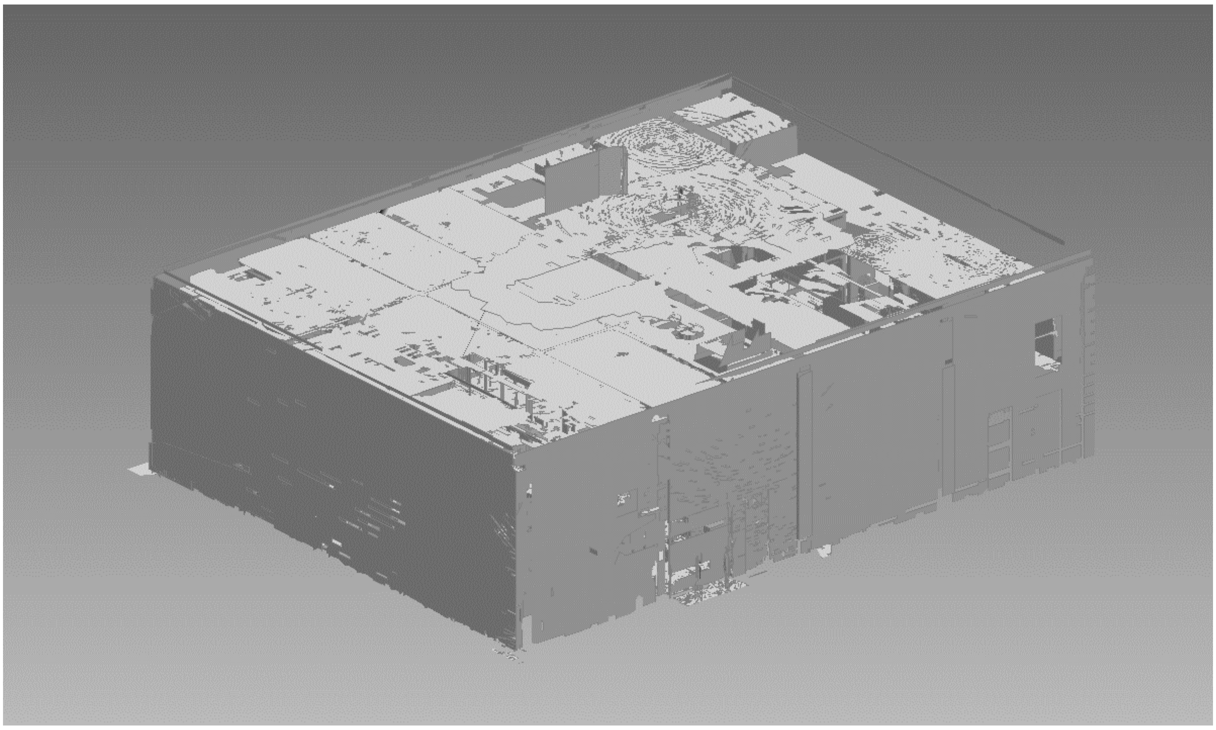

Figure 20 Detected surfaces by EdgeWise from GASAG

The external part of the building was scanned low amount of occlusion since the around of the building was not very crowded. Unlike the external part, the Inside of the building was occluded by the different types of stuff. The stored components and materials, the cabinets and regales, and the pipes and ducts were some examples of the object which produced occlusion.

Since it was aimed to reduce the scanning time as much as possible, no target was used during the laser scanning. Since the building is located on the university campus, it was possible to scan the exterior part from a low distance. Regards to the interior, the existence of a high number of objects inside the building reduced the flexibility of performing laser scanning in terms of distance from target objects and location of the stations.

The wide range of laser scanning levels was used in this project. The purpose was to test all different levels which provided by the laser scanning machine. As it was mentioned before, for three stations which mainly scanned the interior southwest corner of the building the high level was selected to capture this part of the building in more details.

Since it was the first laser scanning and the project was part of a multiple-phase project which was planned to perform between two universities, there were more than 5 persons in the scanning projects. The amount of the people and their inattention for standing between the laser scanning machine and the target objects resulted in producing a high amount of noise in the registered point cloud.

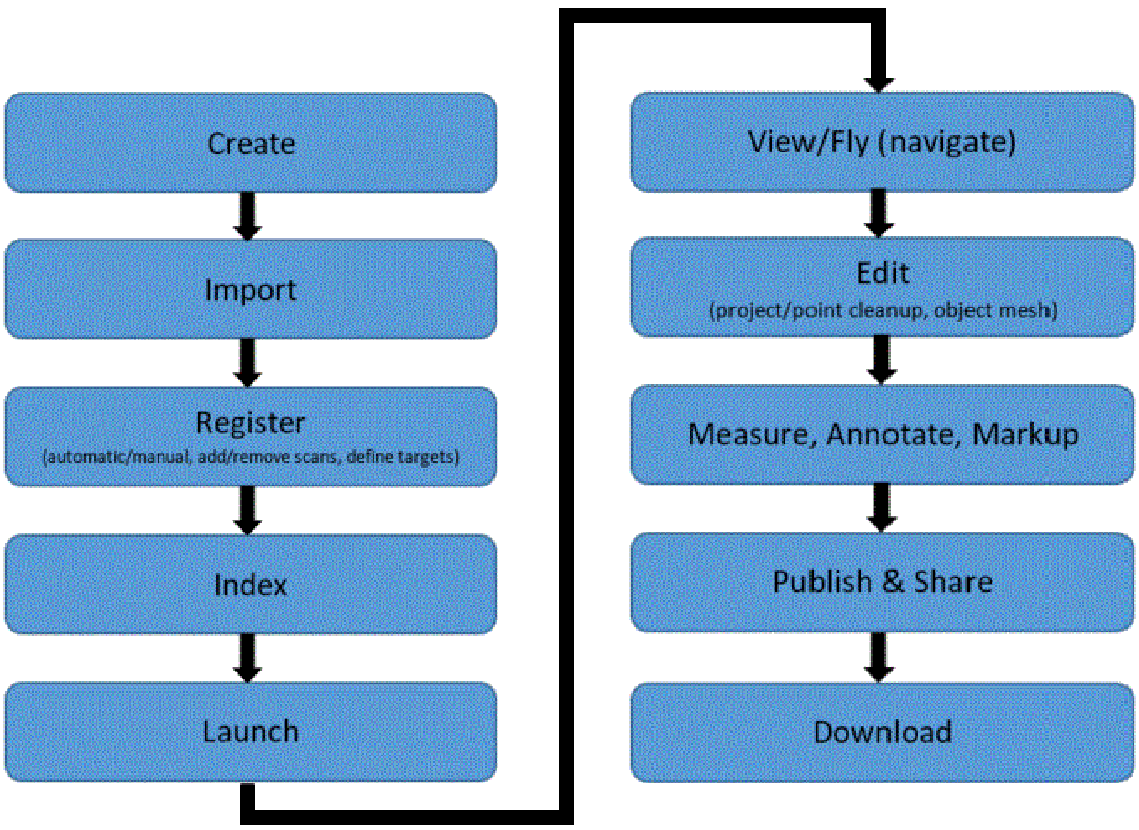

Figure 21 Scan Project Workflow in ReCap

During the laser scanning, no photo was taken, but there are some photos available which had been taken in the first visit of the group from the building. The problem was that the photos were not taken from the laser scanning stations viewpoint. Taking a photo from laser scanning station point of view is easier to manage, provide a better understanding of the scanned objects, and make it possible to attach the photos into point cloud file.

By finishing the laser scanning, the raw data was transformed from the laser scanning machine memory stick into a super computer. Then the raw data was opened by Realworks and was converted from TZF format to E57. Since in the GASAG project the datasets were planned to be registered by Autodesk ReCap and ReCap is not able to open the TZF format files, the files had been converted into an E57 format which is known the format for ReCap. Creating point cloud in ReCap consists of three steps; Importing, Registering, and indexing (Figure 21).

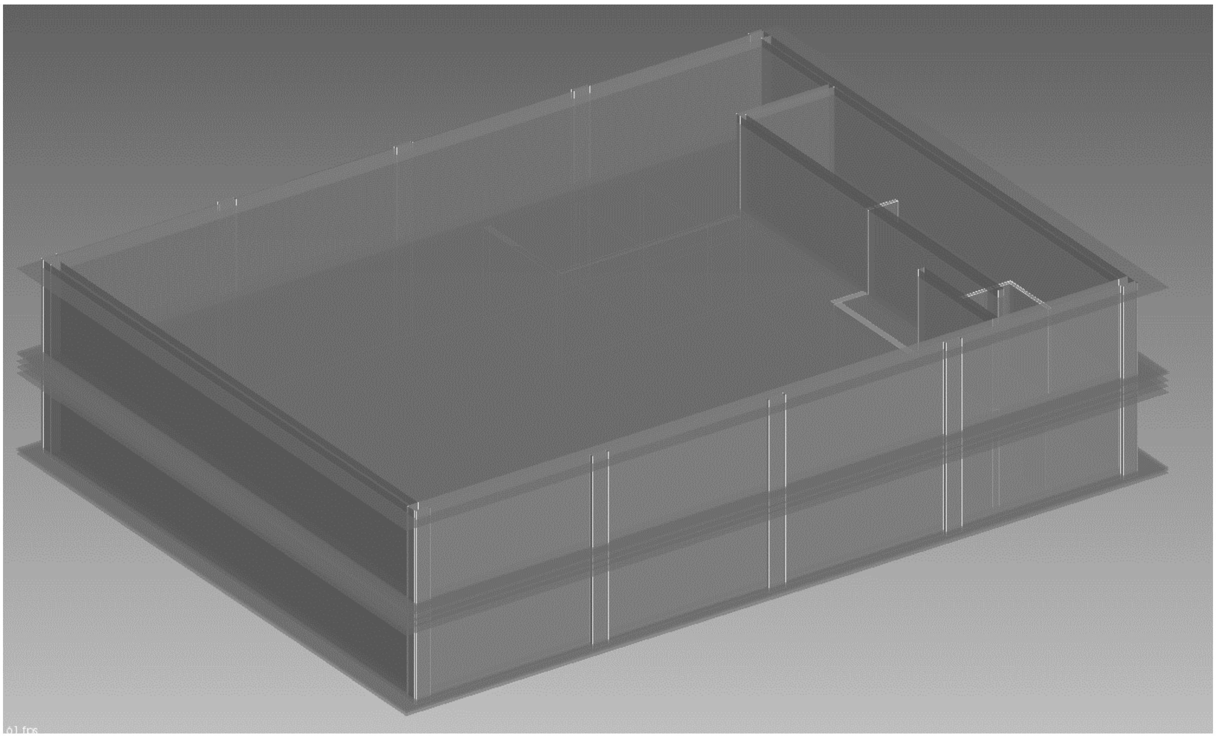

Figure 22 Defined levels for GASAG

After selecting the E57 files from open command, the scan setting window appears. From this window, it is possible to set the noise filtering and coordination system. Increasing the level of noise filtering will reduce the density of the point cloud and it is possible to lose some small size objects or those which were not captured completely. Set the coordination system will be helpful in the next steps of the Scan to BIM process and is very useful based on the interoperability issues. Since there was not any previous knowledge about the setting, no change had been made in scan setting.

Based on the number of stations and quality of datasets, the process of opening E57 by ReCap was very time-consuming. Opening the 27 E57 files took about 12 hours. Based on the long required time, the opening/importing and exporting process had been mainly performed at the end of working hour. For this reason, the system was running during the non-working hour to save the time.

After importing the files into ReCap the registration step was started. First, it was tried to register the datasets by auto registration function. The results were completely occluded and crashed and it seemed that the software could not overlap them appropriately. Since the auto registration results were not acceptable, this step had done manually. There are different methods for manual registration.

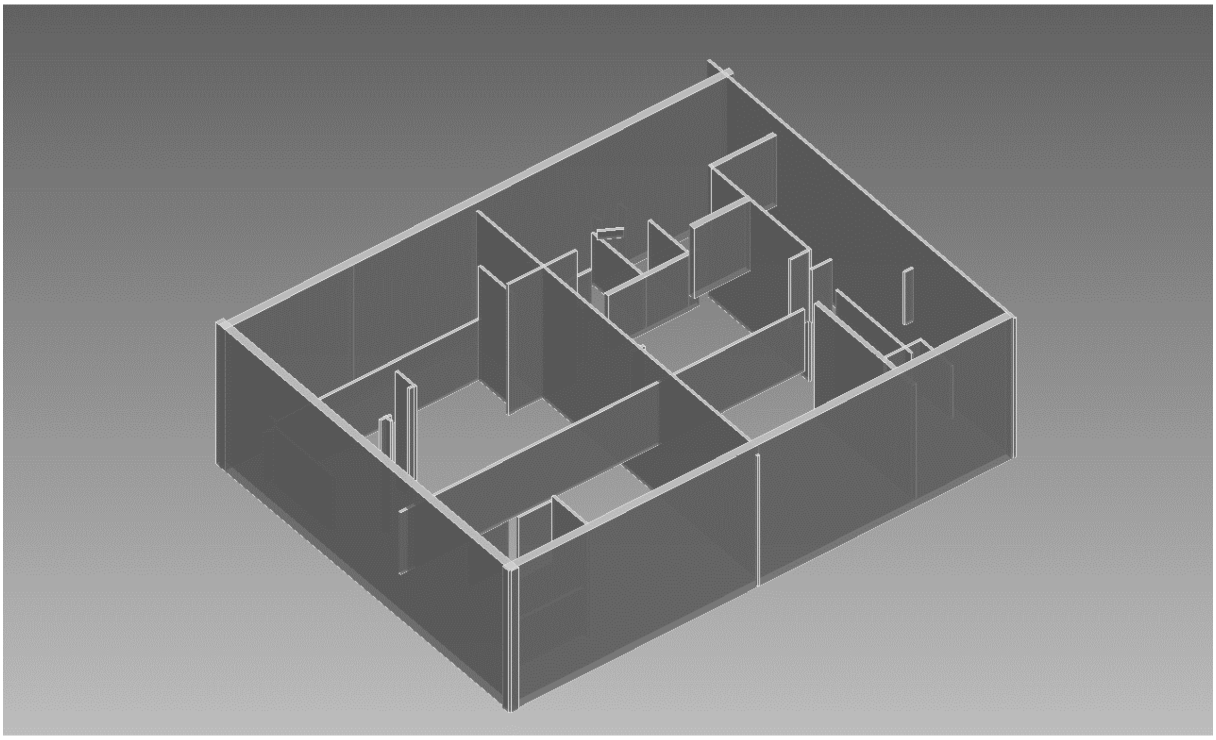

Figure 23 Detected walls by EdgeWise from GASAG

Based on using a target on data capturing time, the registration could be done by matching the targets or finding three common points in datasets. For this reason, the datasets were overlapped with each other one by one. First, two datasets with overlapping were selected, three common points from two datasets were determined, and they are registered. After overlapping each two datasets some specifications of overlapped point cloud are shown to provide the quality and accuracy of registration. These features include percentages of overlap, balance, and points smaller than 6 mm.

Then another dataset was selected and the common points between this dataset and previously registered datasets were determined. This process was continued until the last dataset were overlapped, then by a single click, the next step which is indexing was performed which also took about 12 hours. One of the biggest disadvantages of the ReCap is that it is impossible to save the project before finishing the indexing. Since the process of registration takes a long time, any unexpected incident could result in losing the data repeating the process from the beginning. The point cloud could be saved in RCP/RCS (Original ReCap file format), E57, etc.

The last performed task by ReCap for GASAG was cleaning the point cloud up. Since a high number of people were included in the data capturing and laser scanning, the point cloud was highly occluded. The automate clean up tools of ReCap did not sufficiently remove the unneeded objects, so this task was done manually. For this reason, the occlusions should be selected manually by different provided tools of software and be deleted. A Recent version of ReCap Pro offers the more powerful automate cleanup tools.

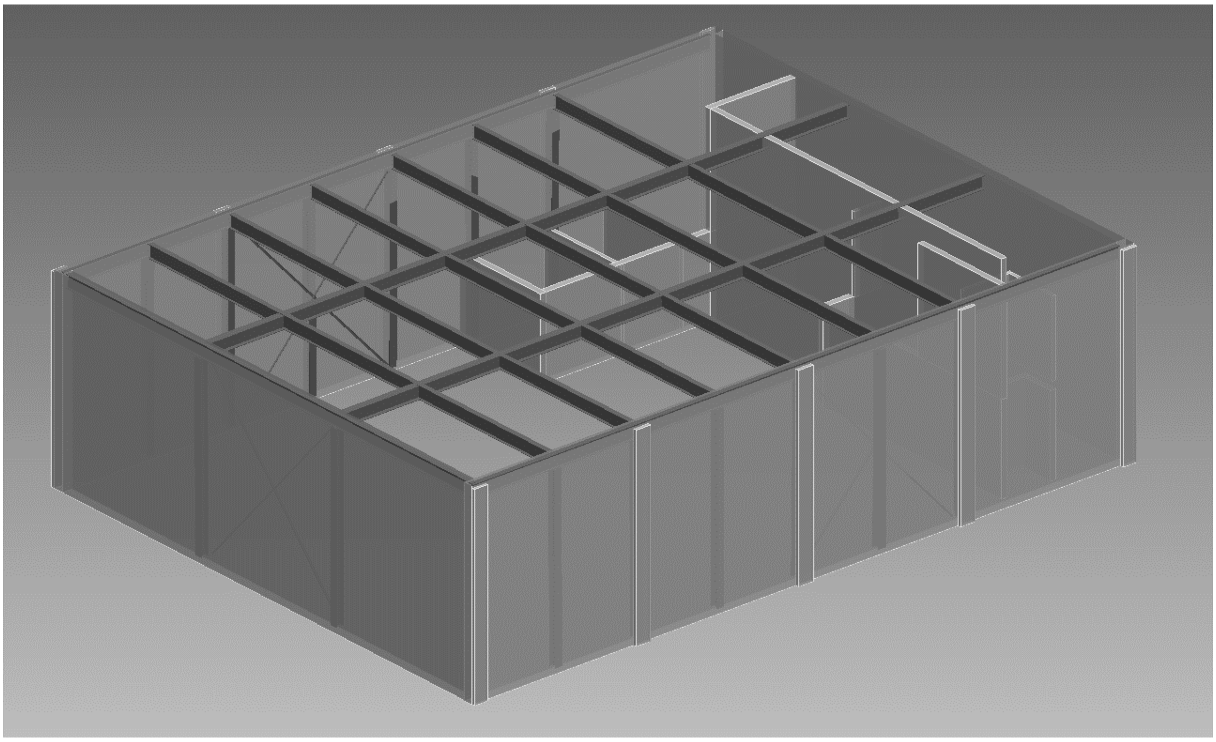

Figure 24 Modified walls and detected structure of GASAG

By finishing the cleaning up, the cleaned point cloud was saved as RCP file and was imported to Revit 2015. The modeling step was started by assigning the grids and levels based on the available as-design and as-built drawings. For this reason, the paper sheets were scanned and save as PDF file. Then the PDF files were imported to Revit to provide a basis for starting the modeling. The available as-design drawings only covered the architectural and structural elements and there were no available as-design, as-built, or shop drawings regard to MEP elements.

The architectural and structural elements were modeled base on the available drawings and point cloud. According to simple and uncomplicated structure and shape of the building, the modeling of these part did not take a long time. As it was mentioned before, the GASAG building is using as the main place of HVAC systems and it is occupied by the high amount of equipment, pipes, and ducts. Modeling whole pipes and ducts is very laborious and time consuming, so it was decided to focus on modeling of the east corner of the building which includes variety of elements include air pumps, pipes, ducts, etc. the GASAG building objects were detected by EdgeWise as a pilot study as part of the EdgeWise training of the group (Figures 20, 22, 23, 24, and 25).

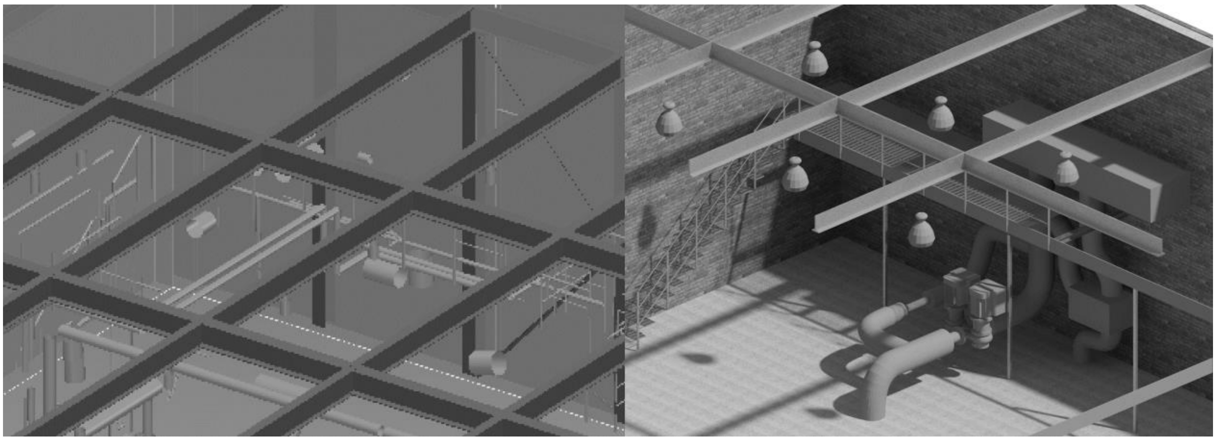

Figure 25 Detected elements by EdgeWise (left) VS. the final model in Revit (right)

4.2.2 Verbändehaus

Because of the different characteristics of the Verbändehaus and different aims and objectives in comparison with GASAG, the process of scan to BIM for Verbändehaus was done differently.

The building was scanned in two parts. First, the exterior was scanned which included the façade and the roof. Second, the interior scan includes the main entrance, lobby, atrium, conference rooms, and the bridges in front of the elevators was scanned. As it was mentioned before, the Verbändehaus consists of two parts which are connected by the elevators and bridges in front of them. the I-shaped part has one floor more than the C-shaped parts and the elevators rooms roof height are different from the buildings. These result to the differentiation in roof height. Because of the required time for scanning and the accessibility to different spaces of the building, the scanning was done in two separate days.

The biggest issue in scanning the building was to scan to glass roof of the atrium, and the glass curtain wall in front of the elevators. The glasses caused the reflection which resulted in the high occlusion in the point cloud (Figure 26). One of the most significant disadvantages of the EdgeWise software is that it is impossible to import the cleaned point cloud into it. In the current version of the EdgeWise, it is only possible to import the original TZF file. Even if the E57 file of the point cloud is imported into EdgeWise, the cleaned point will appear in the EdgeWise point cloud.

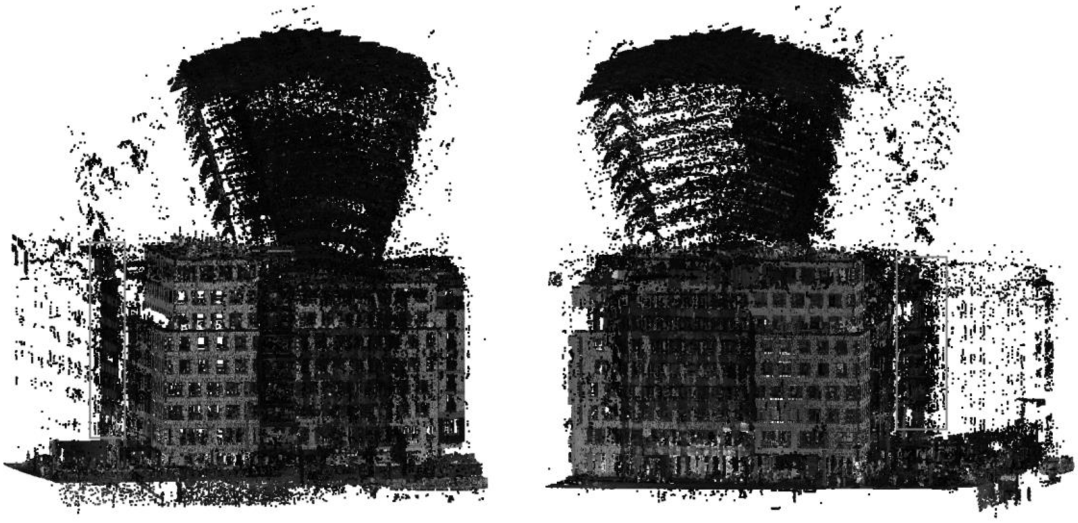

Figure 26 Occluded registered point cloud of Verbändehaus

The raw scanned file (TZF format) was imported into Realworks for registration, cleaning up, and segmentation. The registration process by Realworks is somehow automated, however, it has some deficiencies. The manual registration produces the more accurate and less occluded point cloud, on the other hand, the manual registration requires more time and efforts.

After registration, the point cloud was cleaned up and segmented (Figure 27). Realworks provide a powerful segmentation tool which can segment some elements (e.g. trees) automatically. This function significantly reduces the time and efforts in segmentation step. The Verbändehaus was segmented into its forming components. The segmentation was performed in different levels. First, it was segmented into two main building, then the buildings were segmented into different parts, and finally, the parts were segmented into their forming walls.

One of the biggest advantages of the segmentation is to reduce the file size by breaking it down into segments with the smaller size. Since the point clouds include millions of points, they have extra-large size (depends on the size number of scanning stations which are registered and the quality level of the scanning, the size of the point cloud could vary from one to hundreds of Gigabytes).

Since the segmented parts could not be imported into EdgeWise separately and the registered point cloud should be imported into EdgeWise as a whole, by finishing the registration, the registered point cloud was exported from Realworks and the exported files then were imported into EdgeWise. The object recognition step was performed simultaneously with the cleanup step.

The first stage in starting work with EdgeWise is to import the point cloud which called database in the Edgewise. It could be done by importing the TZF or E57 file into EdgeWise. At the starting point for importing the point cloud, the software asks to produce different databases which are; planes, Pipes, and ducts. The planes database is used for recognizing the building elements, Especially, the levels, walls, and windows. The pipes and Ducts databases are used for recognizing the MEP elements. To recognition of the structural elements, which should be done manually, a separate database should be defined afterward.

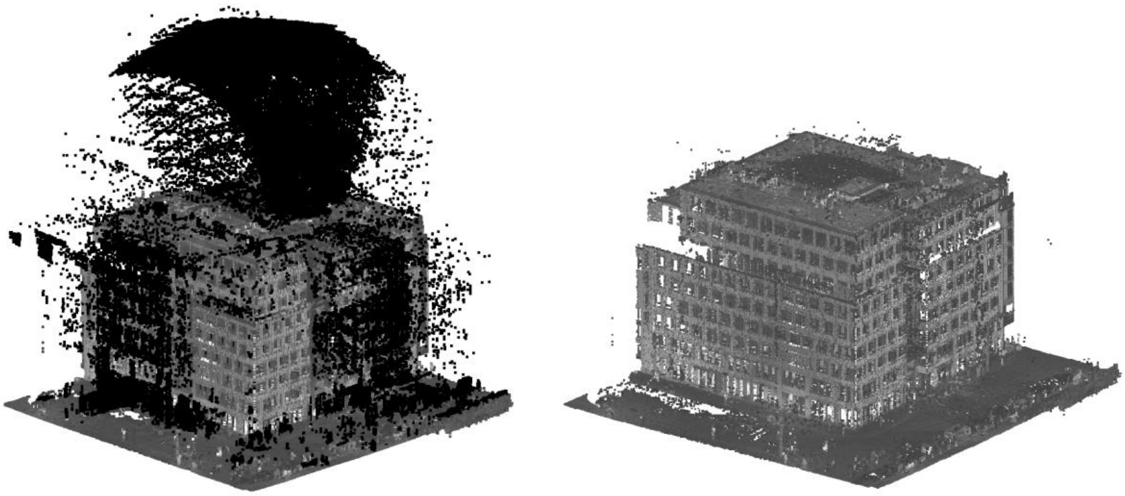

Figure 27 Verbändehaus before (left) and after (right) cleanup

The database creation stage takes about 12 hours long. As same as the all previous time-consuming stages, this stage was done during the night by running the software from the end of the working hour until the beginning of working hour in next day. By finishing the database creation, the point cloud will be created in the Edgewise and the pipes are automatically recognized.

As same as other 3D software, it is possible to set the section box to achieve the desired view and section. It is also possible to change the X axis by selecting a recognized horizontal element. To save each of the databases, it should be selected from the navigation pane and by clicking on the save tab the message for overwriting on the previous version will appear. This message always when it is desired to save the database.

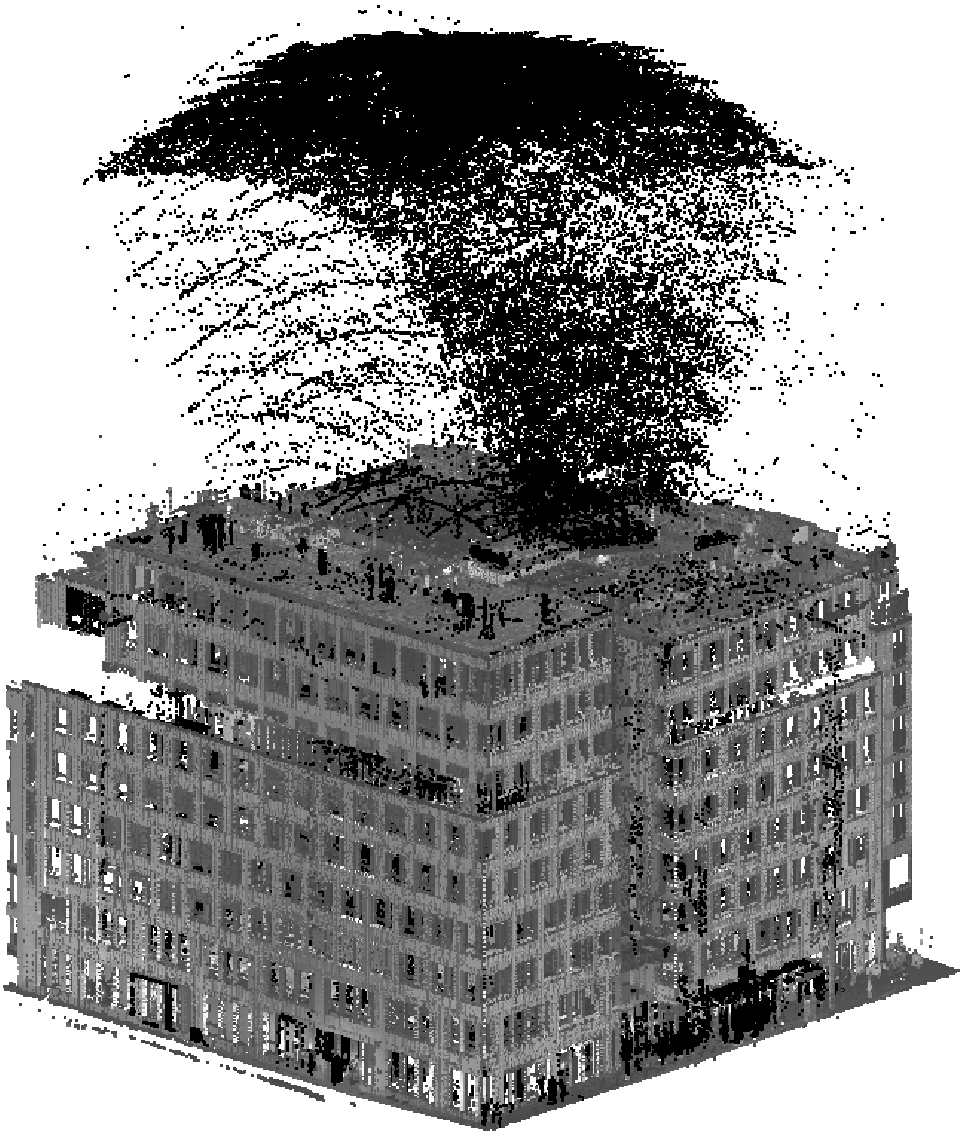

Figure 28 occlusion resulted from reflection of glass roof

As it was mentioned before, the biggest issue regards to the Verbändehaus was the glass roof and the resulted reflection. As It can be obviously seen in Figure 28 the reflection caused the occlusion and unreal points on the top of the glass roof and outside of the glass curtain walls. In addition, because of the inefficiencies of the automated registration of the point cloud which was done by Realworks, some occlusions appear in the point cloud in the interior spaces of the building.

The occlusion makes the object recognition step very difficult and reduce its accuracy because of the probability of recognition of the unreal points as a real object. The possibility of importing the cleaned up point cloud could significantly eliminate this issue and increase the efficiency of the object recognition considerably. In this study, the occlusion resulted in a considerable increase in the time and efforts to delete the unreal objects.

As it was mentioned before the pipes were automatically recognized by the edgewise. Since the Verbändehaus is an office building and only the exterior and some limited interior offices were scanned, no pipe had scanned which could be recognized by the software. The only elements with circle section which were recognized by the software as pipes were the structural cables of the glass roof. Because of high occlusion of the point cloud in the glass roof location, it was impossible to use this recognized cables in the next steps.

The main aim of using Scan to BIM in Verbändehaus was to create the architectural model. Based on this objective EdgeWise was mainly used for recognizing the building Elements include the levels, walls, and windows. The process was started by recognizing the levels. By selecting the building database, the whole recognized surface by the software was shown.

For recognition of the levels, the desired horizontal surface should be selected. By selecting the surface, the properties window appears which makes it possible to rename the level or even change the height of the level. The height of the levels is calculated based on the center of origin of the point cloud. The center of origin of the point cloud by default is set to the first laser scanning station location. It is very helpful and makes the calculation easier to change the center of origin to one of the corners of the building or at least at ground level (Height = 0).

In a case which no surface was recognized in a certain level, for example where the surface does not have a large area or is not smooth and horizontal like the top level of the parapet walls, it is possible to add a level manually. For this reason, one point on the desired level could be selected and its height by using the measuring tool will be given. Then the corresponding level could be added in the level properties windows by inserting its height manually.

Adding as much as possible level could be useful because it will help in the modeling stage in Revit. There is no disadvantage in adding the levels since they could be easily removed afterward in Revit. Adding level for all recognized horizontal surfaces reduce the risk of losing the height of elements in modeling step. It should be noted that deleting the level in the EdgeWise results in removing the recognized wall(s) which had been recognized between the deleted level and other levels.

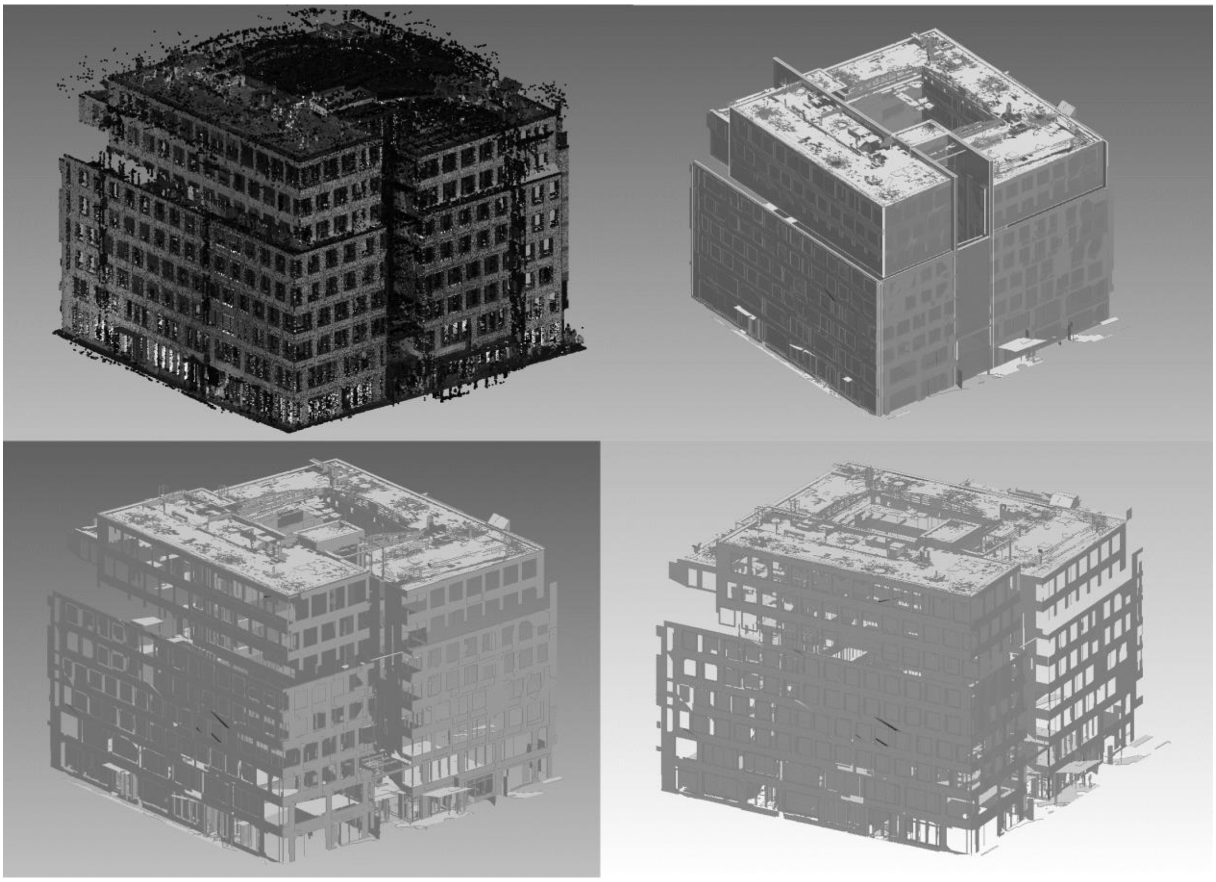

Figure 29 Object detection steps in EdgeWise: point cloud (left top), detected surfaces (left down), detected walls (right top), detected windows (right down)

After defining all the levels, the wall recognition could be done by clicking on the wall detection tab. The software recognizes the vertical objects between the horizontal levels as walls. This could result in recognizing some other elements e.g. cabinets, regales, or large boxes as walls. There is a function for modifying the walls. Using this function, it is possible to change the length, height, and thickness of the walls.

It is also possible to detect the walls manually. For this reason, the area of the wall in the plan view should be selected as a rectangular, then the software will recognize the element based on the existing points in the selected space. A disadvantage of the wall detection function is that it is not possible to rotate or change the angle of the walls. By deleting the unreal and wrongly detected walls, the wall detection step will be finished.

The next step is to detect the windows as openings within walls. This function works in two steps. First, select the area of one of the desired windows manually from view. Then, the software recognizes the source surface which the window is in it. By clicking on the detected surface, all similar windows in the selected wall will be recognized. Depends on the number of windows with different size, this procedure should be repeated until recognition of the whole windows. The edgewise defines a specific window for each window size.

After finishing the object detection (Figure 29), the database will be exported as a special file format, using the EdgeWise plugin in the Revit, the file could be opened as a Revit model. It is highly recommended that the modifications are done in the Revit, because of the higher performance of the Revit in modeling the details such as the wall connections and joints. The building was modeled base on the EdgeWise outputs and in the case of lack of information from EdgeWise, the as-design drawings were used.

Transition from Trimble to Autodesk

Since the laser scanning was done by a Trimble product (laser scanning machine) and the final model should be a Revit model, it is necessary to switch from the Trimble products into the Autodesk product within the Scan to BIM process. This transition is extremely significant regards to the interoperability issues. The scanned files from Trimble machine are completely compatible with the Realworks (which is products of Trimble as well). The ReCap and Revit are interoperable since they are products of the same company.

In most of the cases, the interoperability becomes an issue when it is necessary to switch from a product of a company to product of another company. Even though the IFC format had been established and aimed to solve this problem and was successful widely, the interoperability remains as one of the biggest problems regards to BIM and its usage. Using the EdgeWise is a very useful solution for this transition since it accepts the raw file format from Trimble and by using its plugin in Revit it is very easy to import the files into Revit.

4.2.3 Success Factors from Experiments

Conducting the experiments validated the importance of the found factors from the literature review. In addition to the found factor from a review of the literature, during the experiments, some factors are explored which could significantly affect the Scan to BIM process and its success. In this part, these factors which considering them is necessary for the success of the process are described.

Site visit before scanning

In order to have a better understanding of the building and become familiar with the target objects which should be modeled by Scan to BIM process, it is very helpful that the experts who want to work on this process visit the building. The visit before the scanning could help the group to specify the scanning stations regards to the temporary objects which are existing in the building and could cover the target objects. The inventories and the furniture which is not included in the drawings or could be placed in different locations in comparison with their location in the furniture drawings could surprise the group on-site and results to wasting the time of the scanning for changing the plan of the scanning stations.

Availability of list of inventories and machinery

One of the most important considerations regards to the FM is to manage the inventories, furniture, machinery in the buildings. While these items do not belong to the main disciplines of the buildings (Architecture, Structure, and MEP), they play an important role in the operation of the buildings. Since unlike the building elements these objects are movable, they location within the building always changes. This relocation could be done for different reasons such as changing the usage of the building, changing the user of the building, or changing because of the fashion. Whatever is the reason for relocation of the furniture and inventories, the list of them could be very useful in after scanning steps when the group try to detect these objects and model them based on their captured data. This information is more valuable in case of machinery especially the HVAC equipment. Since nowadays most of the HVAC system providers provide the 3D model of their products, understanding the brand and model of these systems could lead to easily finding the 3D model of them provided by the manufacturers.

Accessibility to all spaces of building

In the case of using Scan to BIM for the large buildings, especially the offices and industrial buildings, the security issues are very important. In some case, it is not very easy to get access to all spaces of the buildings for example in the hospital's access to the hygiene spaces is very difficult. The accessibility to all required spaces should be considered before the laser scanning since this issue requires the coordination between the FM and the security organizations.

5. CONCLUSION AND RECOMMENDATIONS

This study aimed to find the required factors for performing the Scan to BIM process successfully. For this reason, a comprehensive review of the literature was done through the 75 research papers from different databases. The total amount of 28 factor was found in three different step include; Before laser scanning, laser scanning, after laser scanning. The findings of the literature review were tested by two experiments include an HVAC plant building and an office building. Based on the experiments, three additional factors were found which should be considered in order to do the Scan to BIM process successfully.

5.1 Conclusion

Based on the findings of this study the success factors could be categorized in the following four functional groups.

User related

These factors are related to the team of laser scanning and those which could be affected by the human. The most important user related factor is the user skill. Since the Scan to BIM process consists of different steps which have completely different characteristics, a group of experts with different skills required for finishing this process successfully. The team should at least include a surveyor or an expert in working with laser scanning machine, a professional in point cloud creating and finalizing, and a team of 3D modelers (based on the number disciplines which should be modeled could varies from one person to a three complete team for Architecture, Structure, and MEP modeling).

Other factors related to the users are a number of laser scanning team, coordination between the different organizations which should cooperate in laser scanning process, for example, FM organization and security service providers. The planning for the laser scanning and the issue regards to how to do the laser scanning are should be done by the team. Defining the LOD, The number of stations and their locations are the important factors which could be heavily affected by the experience of the laser scanning team.

Technological

The technological factors are divided into two main subcategories. The laser scanner machine related factors should be considered from the early stages of the making decision for doing the laser scanning. Based on the requirements and the usage of the laser scanning technology, the type of laser scanning machine could vary. After choosing the appropriate type laser scanning machine, its brand and model should be selected based on the project requirements.

The interoperability of the laser scanning machine and its captured data with the available software package should be kept in mind. Consulting with the experienced surveyors before purchasing the laser scanning machine could result in significant saving considering the high cost of these machines. Having a plan and determining the laser scanning machine configuration before the scanning day could save a huge amount of time on-site and in the further steps.

The Second sub category of technological factors is software related factors. In Scan to BIM process, at least three software is required. First, a software for importing the raw data into it and doing the registration, indexing and cleaning up the point cloud. Second, an object detection software for recognizing the target elements and export them in a compatible format for 3D modeling software and within an appropriate BIM family.

Finally, a 3D modeling software which the final configuration of the model and finalizing the model based on the desired LOD could be done by it. The most important issue regards to selecting the software package is interoperability issue. It should be considered that the whole selected software supports the file format of the used software in the previous step. Since it is impossible to find a software provider which provides a complete software package which covers all the Scan to BIM process, the software from different software providers should be selected.

Data related

One of the most significant issues regards to Scan to BIM process is data related issues. Since the point cloud consists of million points, the size of the point cloud is from single to hundreds of Giga Bytes. Since processing this amount of data requires the high-performance hardware, reducing the data size could result in saving a significant amount of time and cost. For this reason, it is important to define the target objects which should be scanned and try to eliminate scanning the unnecessary objects. Setting the quality level of the scanning based on the desired LOD is another important way for avoiding increasing the data size.

Selecting the appropriate location of the laser scanning stations which provide the best overlapping coverage could reduce the number of the laser scanning stations and the data size consequently. After doing the laser scanning, the downsizing of the point cloud reduces the number of points in the overlapped areas. Cleaning up and removing the noises are also decrease the number of unneeded points in the point cloud. Finally, the segmentation could be used to break down the point cloud into several segments which have a smaller size than original point cloud and the processing of them requires less time in comparison with the whole point cloud.

Another issue regards to the data is the availability of the recorded data of the building. This data could include the as-built drawings, as-design drawings, a list of furniture and inventories, and shop drawings of equipment and prefabricated elements. These additional complementary sources could be used beside the laser scanning to increase the accuracy of the Scan to BIM process and results to a higher LOD and high-quality 3D model. Since the laser scanning only captures the geometric spatial information of the elements, the complementary information regards to the semantic information of the elements such as materials, brands, the thickness of the layers, date and time-related information, etc. should be collected from other sources of the information.

Process related

The Scan to BIM process like every other process could be more efficient if it is done systematically. The process should be started by defining the objectives of and desired usage of the point cloud. This issue could affect all further efforts significantly. The hardware and software selection should be done regards to the desired quality and available budget. Forming the laser scanning team needs the understanding about the required skills and time for finishing the project.

For each laser scanning project, the planning should be done based on the specific characteristics of the building and the objectives of the laser scanning. The number of laser scanning stations and their location should be defined in the planning stage. The data management method must be well defined in order to avoid the potential risk of huge data size and control the scope of the project.

5.2 Limitations (Theory, Methods)

As it was mentioned previously, the Scan to BIM process has been recently introduced to the AEC/FM industry and there are few number of companies which have been established this process within their organization well. Two major factor which was limited this study was time and availability of the experts in the area. This makes it impossible to gain profit the opinions of a group of experts in this study.

The available hardware and software limited this study as well. There was only one laser scanning machine available for conducting this study. Based on the high cost of the laser scanning machines, this issue is considered as a limitation in most of the research. Although the software packages are not as expensive as the laser scanning machines, they could also limit the research and its scope.

Available buildings for laser scanning was limited and regards to the available time it was impossible to cover more than two buildings in this study. Based on this limitation, it was tried to select the buildings with different characteristics to achieve the maximum possible experience through the experiments.

5.3 Implications and Suggestions for Further Research

As it was mentioned in previous part, some factors limited this study and its scope. In the case of becoming the Scan to BIM more popular within the industry and finding the minimum required experts with experience in this filed, the questionnaire survey or interview could be conducted to validate the findings of this study. Although it was tried to validate the findings of the literature review by two experiments, the survey could be a more reliable method for validating the found data of this study.

In terms of the technological aspects, there is recently released software which designed to facilitate the Scan to BIM process. It is anticipated that the number of the software released by the software providers increases significantly in short term. Doing experiments using the another combination of software and compare the results with the results of this study, could help to find the efficiencies and deficiencies of the selected software package in this study.

Since in this study the experiments were done for only two buildings, doing experiments for the buildings with different usages and size could result in more reliable findings. Further research could be performed to find out the Critical Success Factors (CSF) for using Scan to BIM process. For this reason, validating the results of this study via questionnaire survey or interviews could be done. The CSFs could help the managers in finishing the Scan to BIM process successfully.

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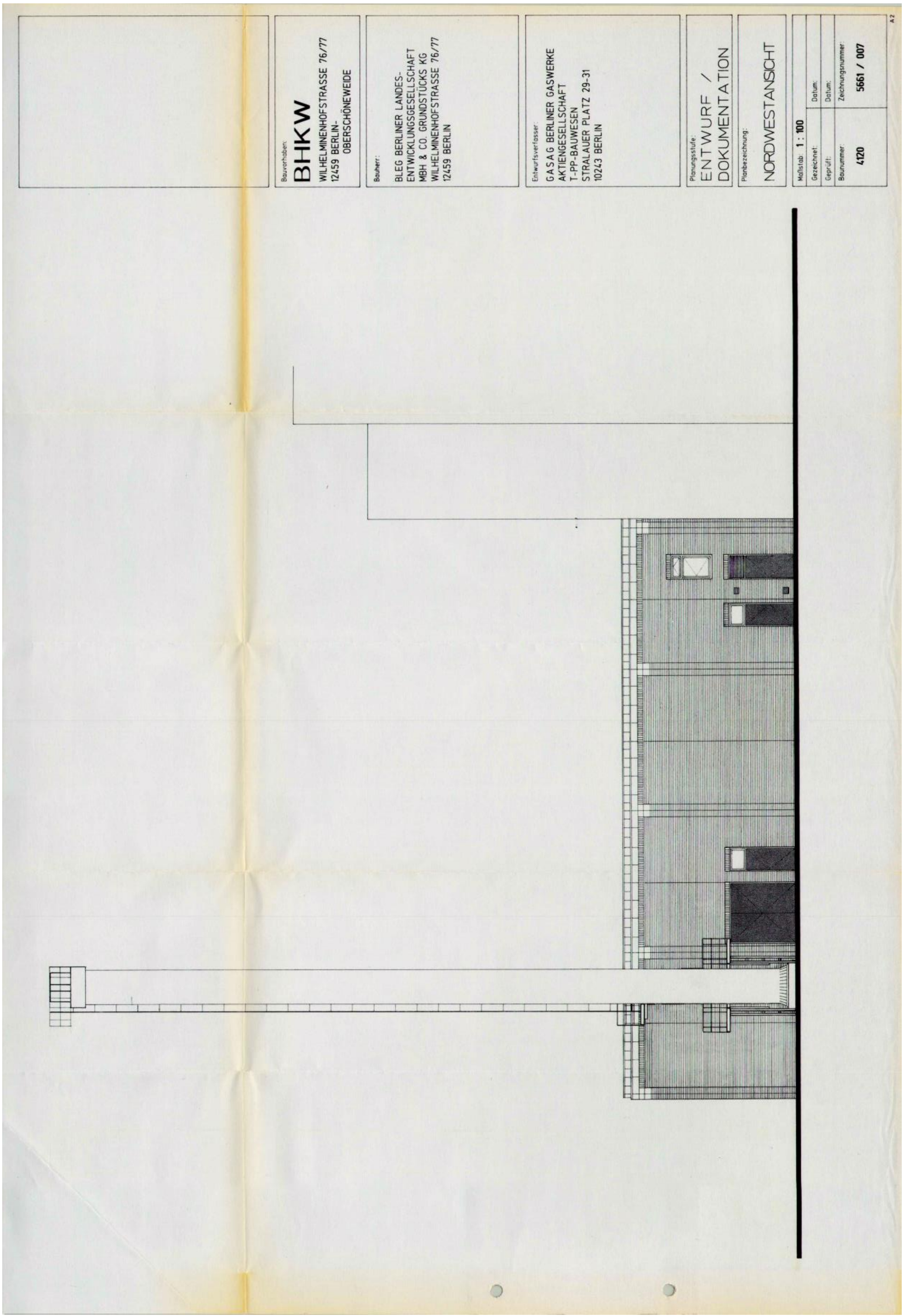
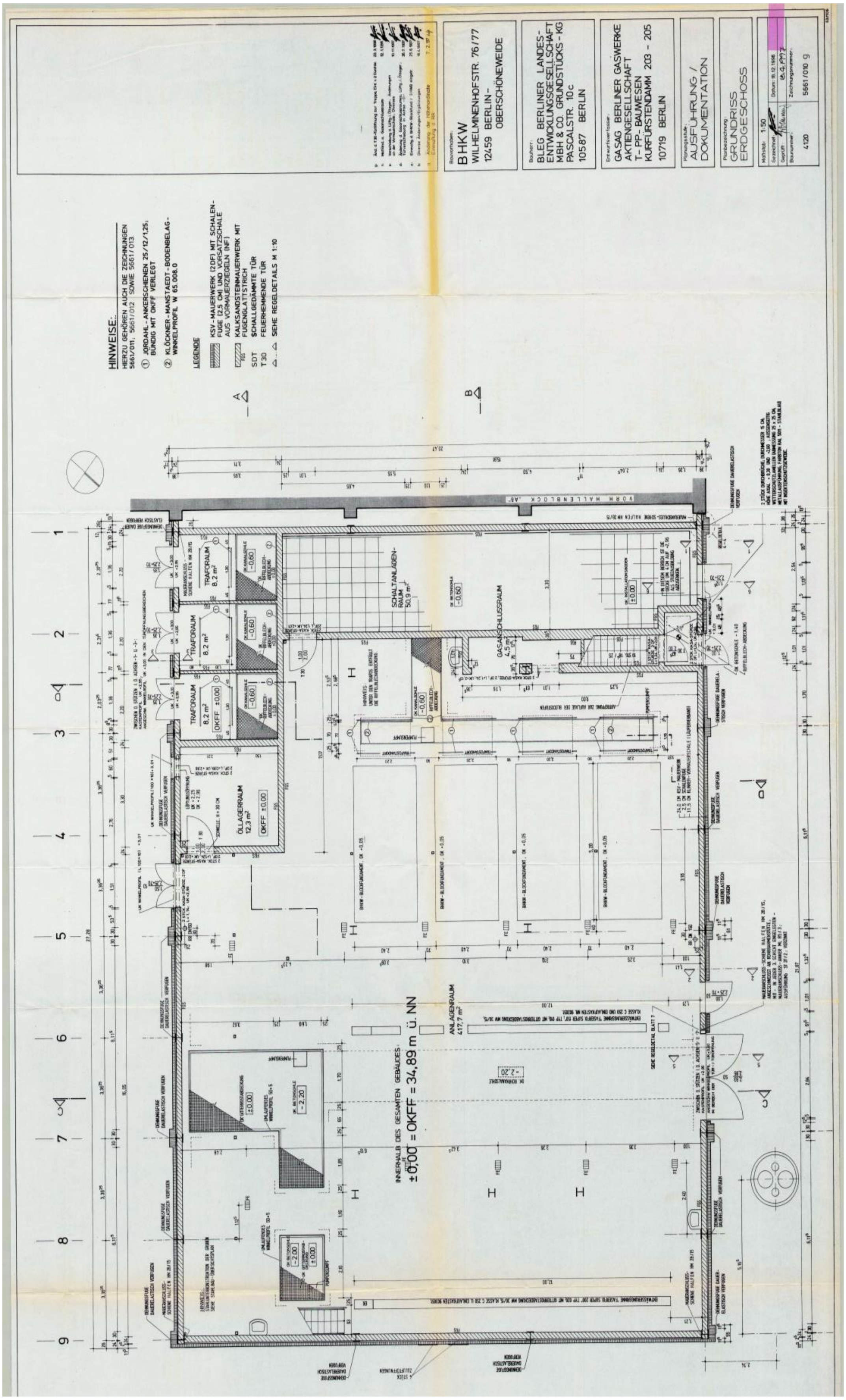
APPENDIX

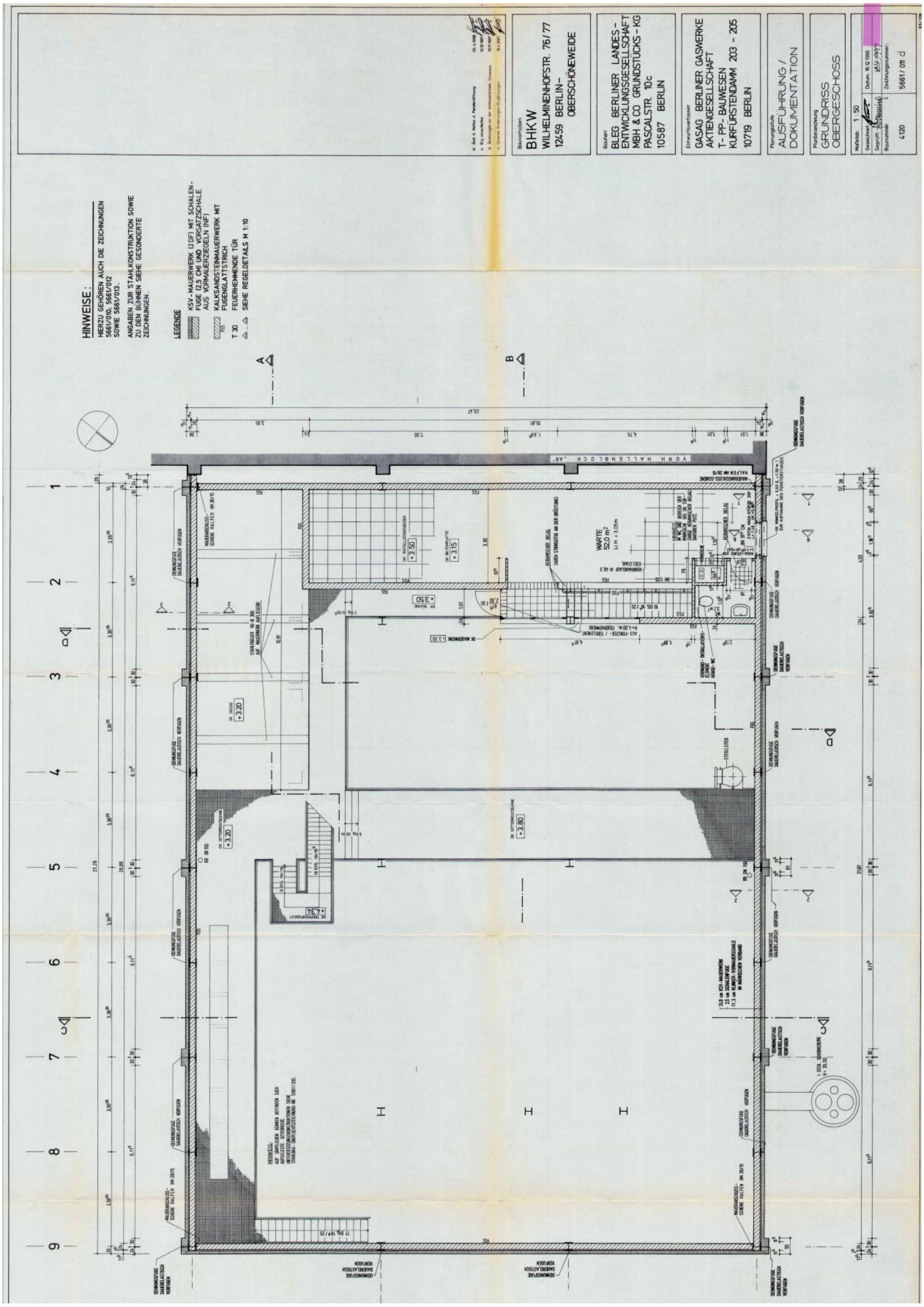
GASAG North-West View



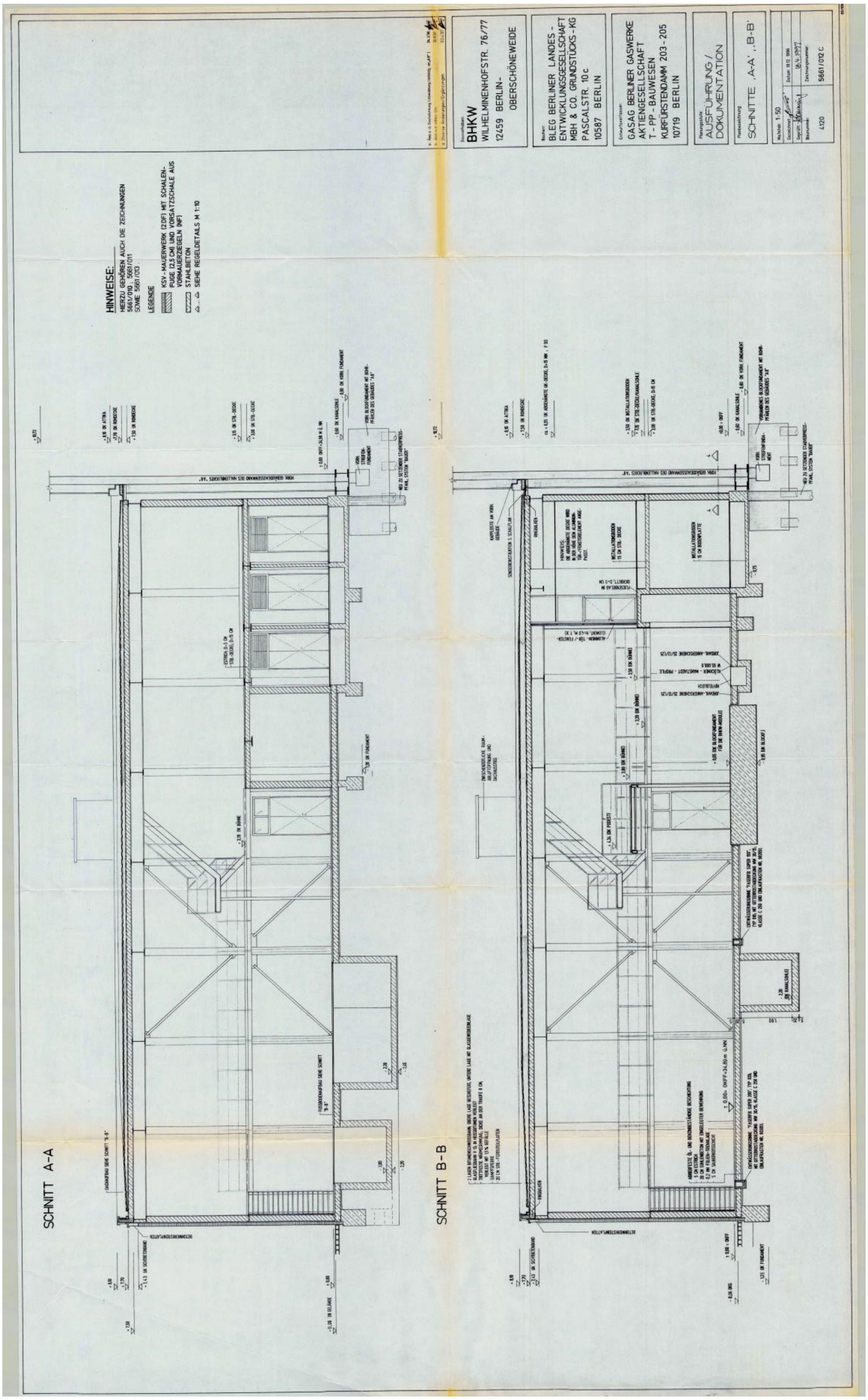
GASAG Ground Floor



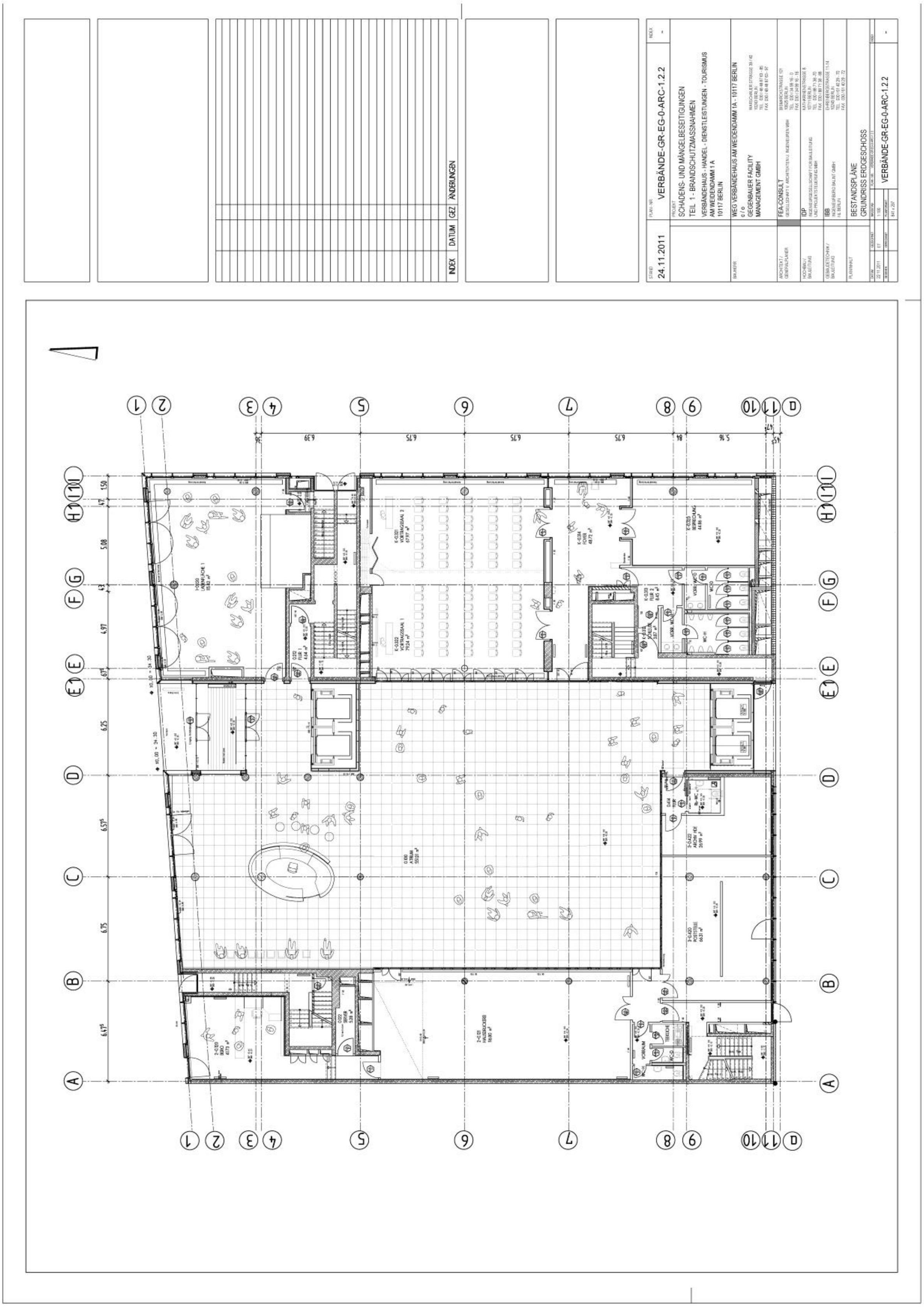
GASAG First Floor



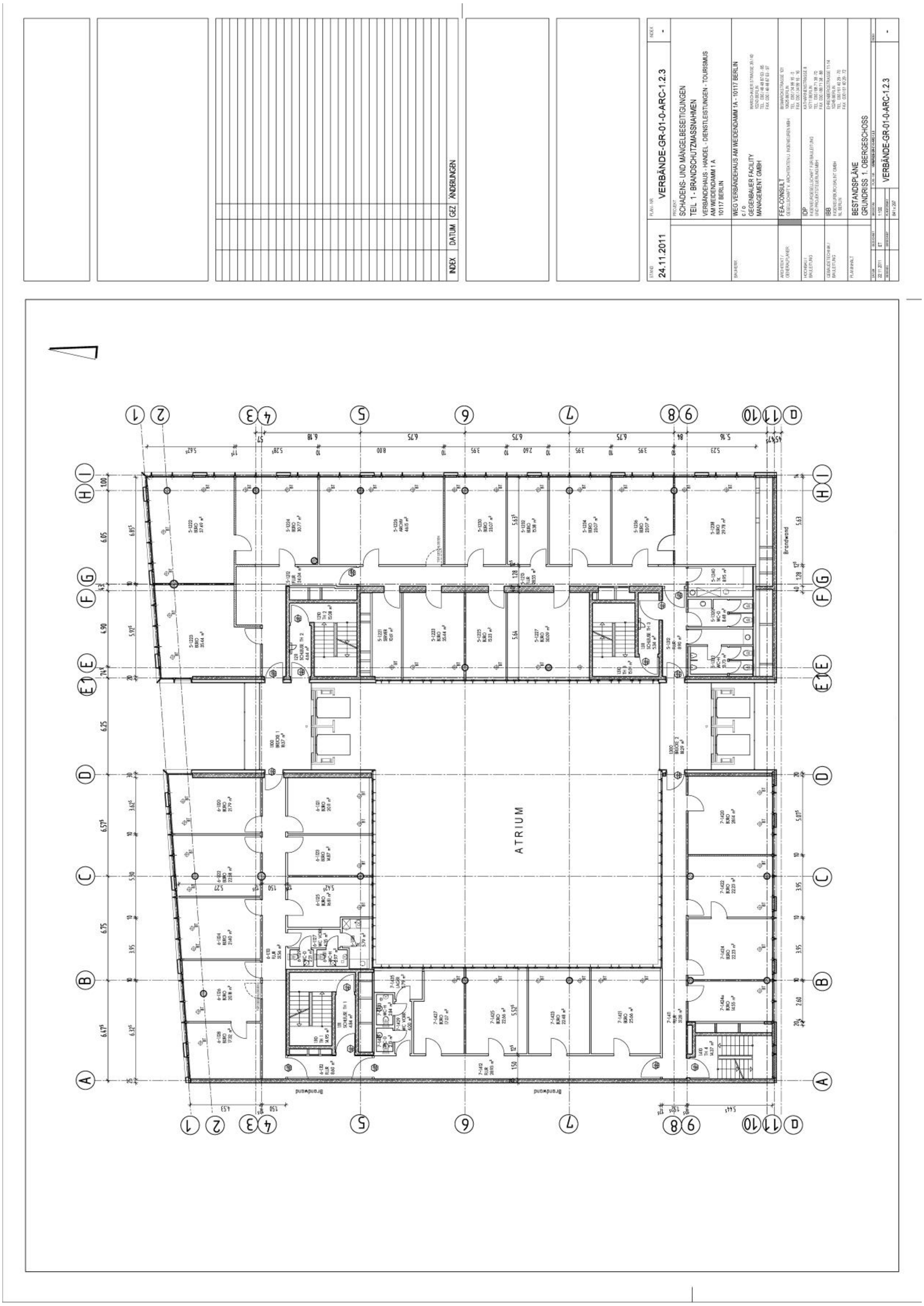
GASAG Sections



Verbändehaus Ground Floor



Verbändehaus First Floor



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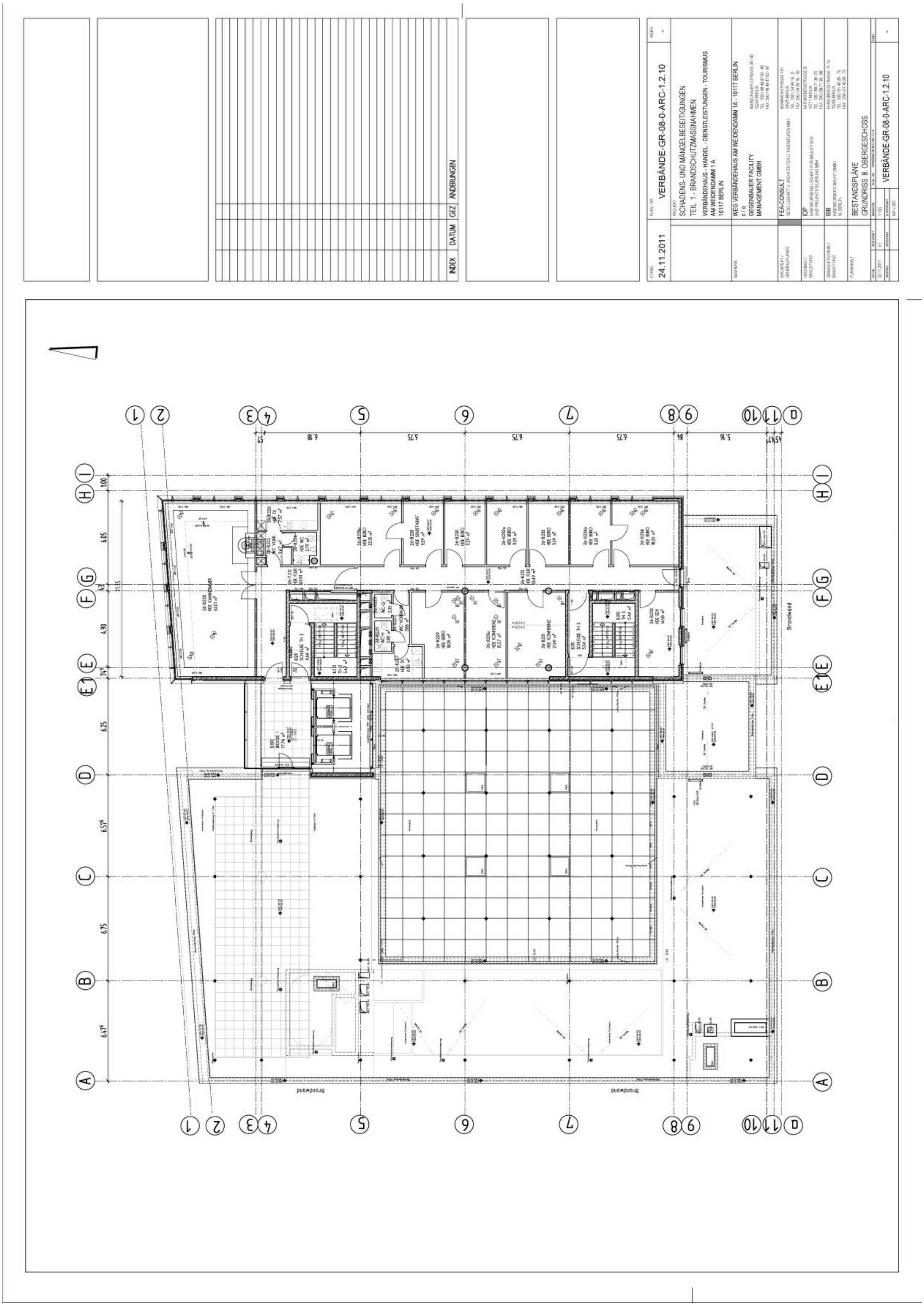
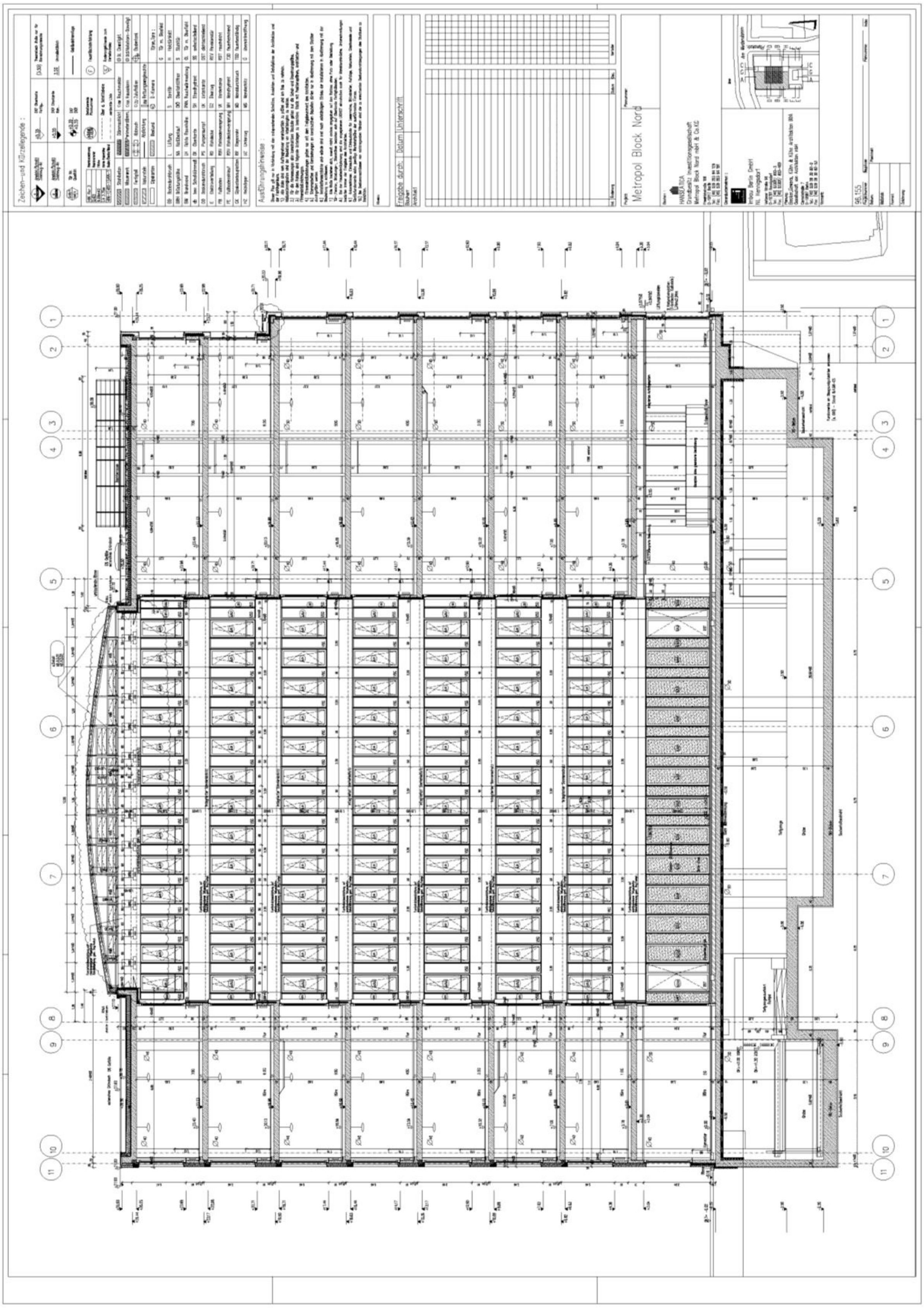


Verbändehaus Section 1



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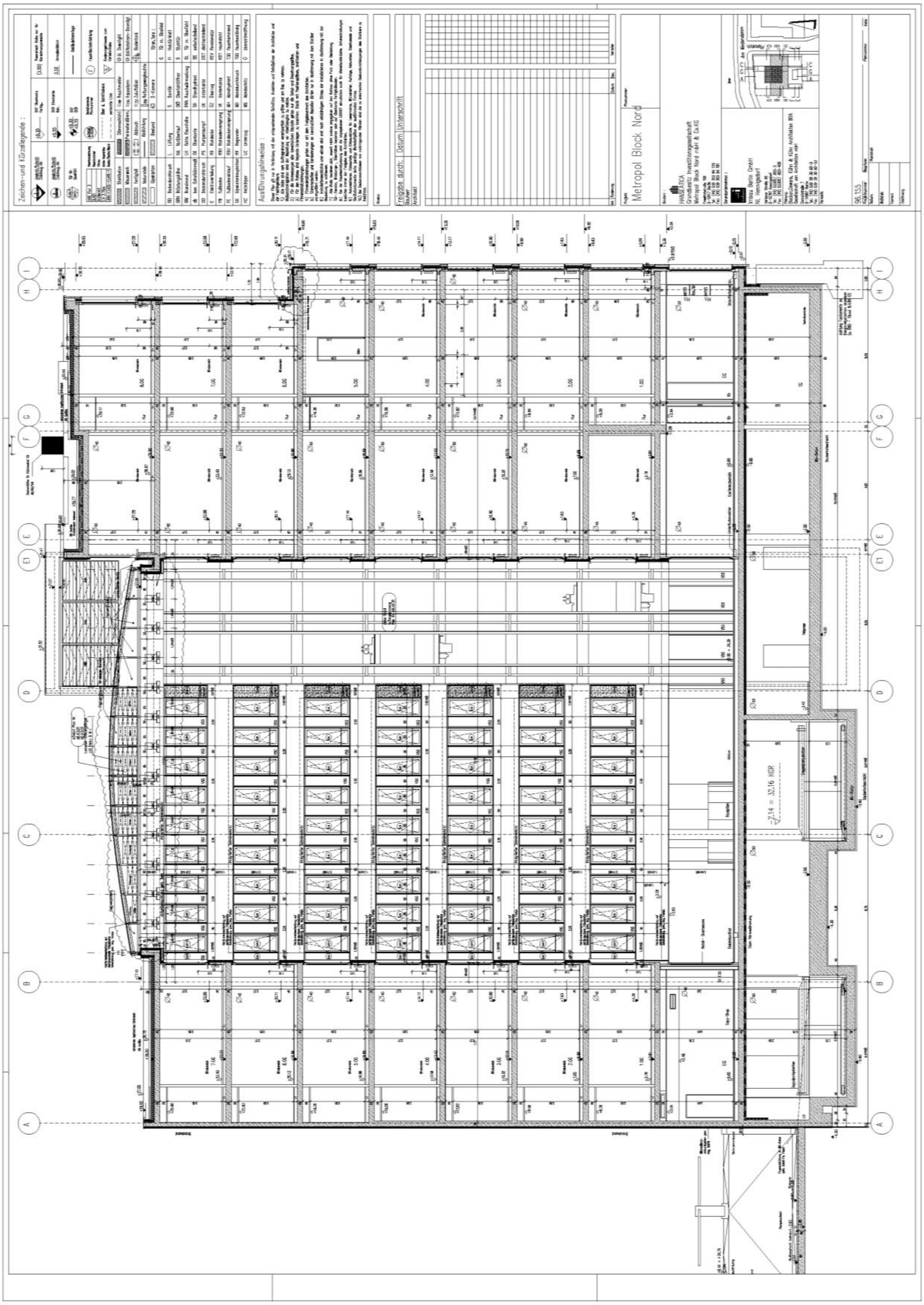

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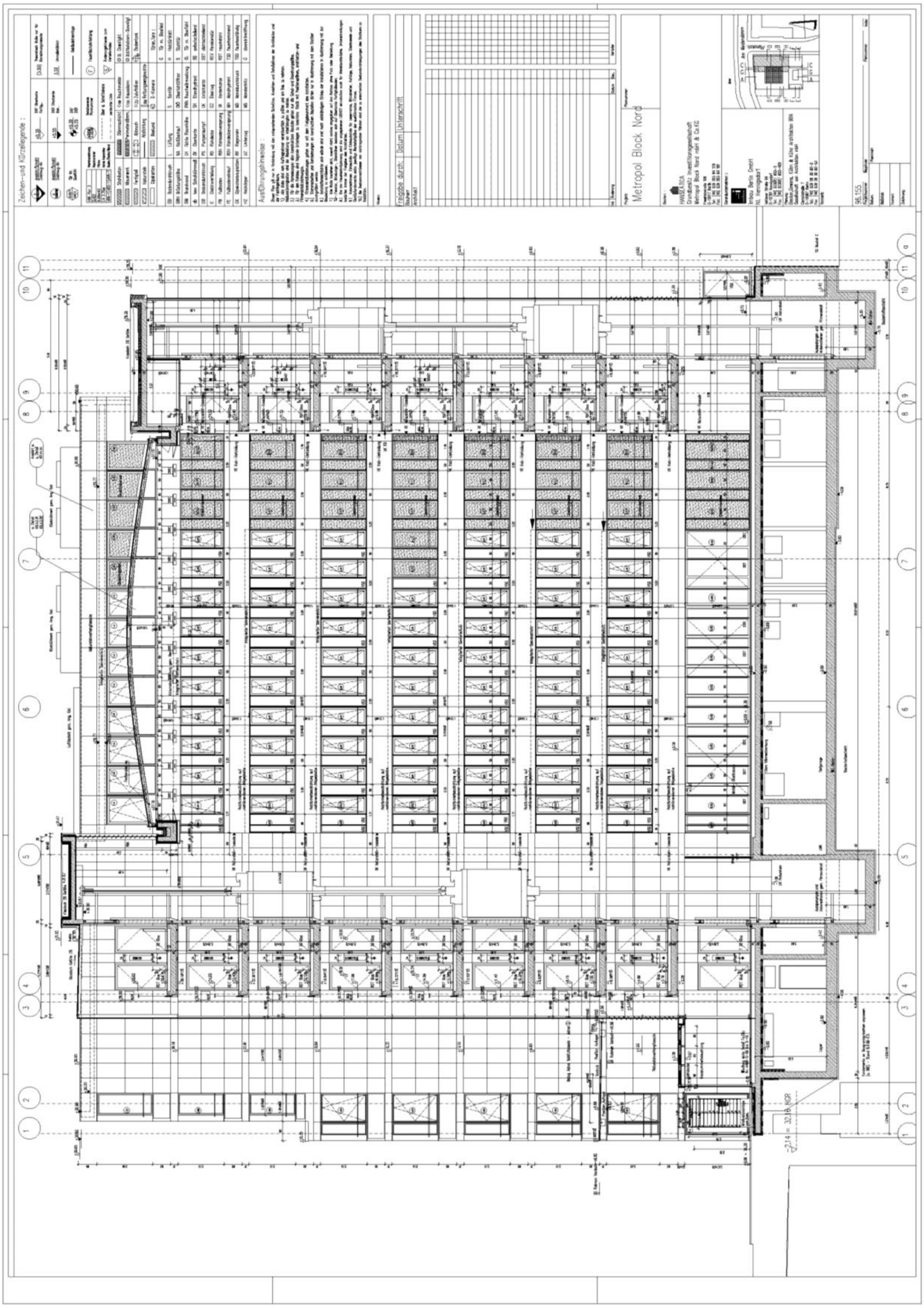

Verbändehaus Section 4