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MASTER THESIS

Investigation and Characterization of Building Information Modeling Data

(Untersuchung und Charakterisierung von Daten des Building Information Modeling)

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TABLE OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AECOM	Architecture, Engineering, Construction, Operation and Maintenance
API	Application Programming Interface
BIM	Building Information Modeling
C4R	Collaboration for Revit®
CAD	Computer-aided Design
CAE	Computer-aided Engineering
CAM	Computer-aided Manufacturing
DDM	Distributed Data Management
DSM	Digital Surface Model
DTM	Digital Terrain Model
FEA	Finite Elements Analysis
FM	Facility Management
GCP	Ground Control Point
GIS	Geographic Information System
GPS	Global Positioning System
GSD	Ground Sampling Distance
IM	Infrastructure Management
IR	Infrared
MEP	Mechanical, Electrical and Plumbing
OM	Operation and Maintenance
RM	Risk Management
RTK	Real-time Kinematic
UAV	Unmanned Aerial Vehicle
XREF	External Reference

Appendix 4

Declaration of Originality

I confirm that this assignment is my own work and that I have not sought or used inadmissible help of third parties to produce this work and that I have clearly referenced all sources used in the work. I have fully referenced and used inverted commas for all text directly or indirectly quoted from a source.

This work has not yet been submitted to another examination institution – neither in Germany nor outside Germany – neither in the same nor in a similar way and has not yet been published.

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1 INTRODUCTION

In the recent years computer software played a prominent role in the field of architecture, engineering and construction (AEC) processes. Before involving computers in building activities, the value of wasted expenses was ranging between 30-40% of the total cost of a project. Moreover, there was a big drop in the information while delivering the project from a phase to another. It was complicated to share the project data with the different involved parties (e.g. designers, experts, contractors, clients, etc.). Computers started to contribute in the building design in the late 1970's in the form of Computer-Aided Design (CAD) software, which lead to an escalation in the productivity of architects and engineers. Subsequently, the Computer-Aided Engineering (CAE) software (e.g. Finite Element Analysis (FEA) software) as well became widely employed in the structural designing of the complex building structures [1]. However, there are still much more data and characteristics to model, visualize and simulate in order to increase the efficiency of AEC. Researches showed that 93% of building owners reported projects as missing their delivery date, and 85% of them stated that their projects exceeded the agreed budget. Even though, these conventional types of software are still utilized till now in the majority of AEC companies. Yet, companies are quite aware of the fact that there is a huge development potential in these computational tools despite that they are conservative and not willing to take the risk of changing their classical approaches, which is due to the lack of professionals who can deal smoothly with these advanced tools and to the inconvenience arise when an outsourcing company does not adopt the same methods [2].

1.1 MOTIVATION

Recently, a growing number of architects, engineers and contractors are using Building Information Modeling (BIM). Global trends are making AEC projects more complex, forcing companies to use more advanced technologies that help them work more efficiently and effectively. BIM is an intelligent model-based process that connects AEC professionals so they can more efficiently design, build and operate buildings and infrastructure. BIM is a framework for integrating technologies, processes and engineers to derive end-to-end efficiency in AEC operations. BIM provides a dynamic multi-disciplinary collaboration on coordinated models, allowing architects, engineers and contractors to have a better insight into integrating their work into the whole project. In addition, it helps in automating the construction process, generating documentations, minimize change orders and reduce coordination issues. Moreover, it could be used by the owners in operation, maintenance and facility management. However, it is not a solution; it is a methodology that enables AEC businesses to keep control of the increasingly complex construction projects through enhanced integration of activities at every phase [3].

For years, there were many endeavors to integrate BIM with Geographic Information System (GIS) for various purposes. GIS is a business information management system that supports capturing, analyzing and presenting of geo-spatial information on a computer-based model (GIS map). Integrating BIM and GIS provides architecture, engineering, construction, operation and maintenance (AECOM) with plethora of computational capabilities, such as energy analysis (building physics), solar irradiation, traffic and population capacity calculation, shadow, vegetation and hazard analysis, urban design and infrastructure development and many more functions which provide an extensive range of powerful applications in civil engineering [26].

1.2 OBJECTIVE

The aim of this thesis is to provide an understanding about data exchange in engineering workflows that comprise multiple software products. The main focus is to investigate and characterize the different data formats that are used by each involved software; thereafter, identify an effective automation method for the data exchange between these software. The investigation includes determination of the characteristics and the interoperability capabilities of the software formats (i.e. to check whether they are extendable, convertible, have special properties and attributes or not). Additionally, it is important to state if the findings could be generalized on the various domains of civil engineering by carrying out a comparison between the results obtained from the investigations in two different civil engineering domains.

Eventually, the outcome of the research would be prospectively used to establish an efficient distributed data management (DDM) system for composite software platforms, in order to automate the complex workflows and reduce the user interaction as much as possible.

2 STATE OF THE ART

Distributed database is a fundamental tool in any successful organization, as it facilitates communication and collaboration between the various corporate members by sharing data and information among the in-house devices. The management of distributed data streamlines the flow of information so that all the business processes are end-to-end connected. Distributed data is accessed, shared or edited by means of collaboration software with a suitable practical application programing interface (API). Otherwise, data and information are shared on intranet websites or shared directories [3]. In this chapter, an overview of the existing collaboration software is presented. In addition, collaboration software for AEC have been discussed.

2.1 COLLABORATION SOFTWARE OVERVIEW

Basically, collaboration software enables the sharing, processing and management of files, documents and other data types among several users or systems. This type of software allows two or more remote users to jointly work on a task or project. Collaboration software could be categorized according to many groups based on the type of data they share, the synchronization of work and the method of sharing. Formats of the shared data vary according to the type of the work performed, and hence the software competencies would differ to process each format of data files. The synchronization of work affects the method of software usage. Interactive collaboration software require instant synchronization abilities, otherwise the software would be used as an information reference or a library cloud. Software method of data sharing could be through intranet connection or internet with restricted access to defined users. Each of the mentioned categories has quite contrasting uses and applications. The most common type of collaboration software is the interactive software that are used for communication, information sharing and project/team management [3]. Examples of such software types are Asana[1], Slack[2] and Trello[3]. From the features of these software are organizing conversations, tracking the progress of work through charts and sharing different data files with the team members. These software are being utilized mostly in small businesses. Furthermore, there are more advanced similar software that contain databases of stored data (e.g. phone book, documents, drawings and contract templates), support white boarding, voice/video calling, email communication from external domains and contain software plug-ins that support various fundamental workflows, such as project planning, reporting and task management. The prior-mentioned group of software is mostly utilized in organizations that are

[1] https://www.asana.com/
[2] https://www.slack.com/
[3] https://www.trello.com/

engaged with complicated technical and management tasks such as contractor companies. Examples of these software are IBM: Notes[4] and Cisco: Webex[5]. On the other hand, there are online web-based integrated suites of applications and tools that allow collaboration of teams on clouds via internet such as G suite[6] and Office 365[7]. In addition, there are storing clouds that post and arrange different formats of data files for downloading, such as Google drive[8] and Dropbox[9] which are general storage cloud platforms. As well, there are specific server- or web-based clouds that aim to share particular sorted data files such as edr: docma PIX[10] for images and Planconnect[11] for engineering drawings.

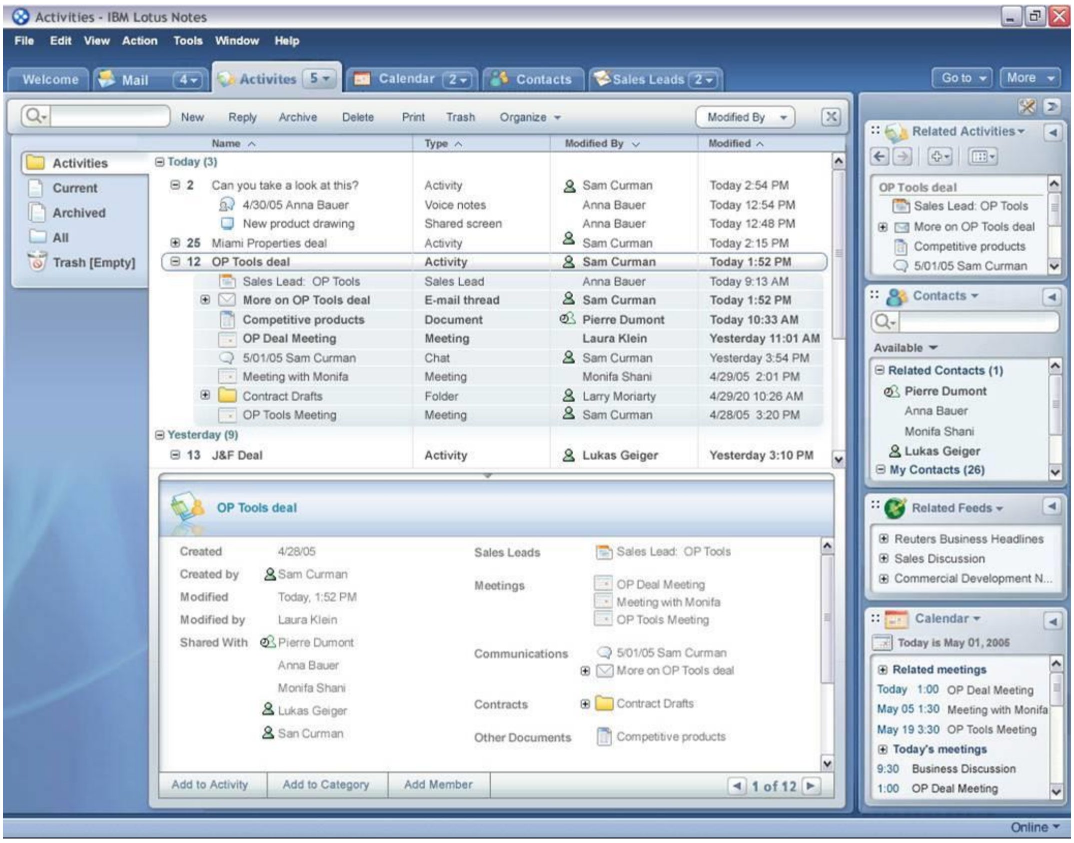

Figure 1: IBM: Notes user interface
[www.ibm.com/support/knowledgecenter/en/SSKTWP_8.5.2/com.ibm.notes85.help.doc/fram_elements_of_notes_c.html].

4 https://www.ibm.com/de-en/marketplace/enterprise-email/
5 https://www.webex.com/products/teams/index.html
6 https://gsuite.google.com/
7 https://www.office.com/
8 https://www.google.com/drive/
9 https://www.dropbox.com/
10 https://www.edr-software.com/loesungen/bildmanagement/
11 https://www.planconnect.de/

2.2 COLLABORATION SOFTWARE IN AEC

Dealing with serious and intensive technical tasks as of the AEC processes require highly advanced, special and time-saving collaboration tools. Starting with the architects, they need to effectively communicate with the owners and to track the engineering phase. The structural and MEP engineers require advanced engineering software to perform their complex computations and a highly interactive collaboration medium visualizing exactly the contribution of each engineer. Collaboration software are extremely important for contractors, as they require continuous communication with the different project decision makers, such as site engineers, senior/executive management, owners, subcontractors and technical office teams. A well-organized documentation, accessible updated drawings and recent information about the market are essential as well [2].

The ordinary collaboration software explained in the first part of this section are not sufficient for architects, engineers and contractors to perform their tasks. These software could be utilized in the basic management tasks, but however for the more complex computational problems another category of collaboration software should be used. This sort of software is capable of distributing the architectural model to the different engineering disciplines in order to update the model with the structural and MEP necessary elements in accordance with each other. This process takes place by providing the engineering disciplines with an access to the main architectural model through local network allowing them to add their own contribution to the model. The modifications appear on the source model instantly, which gives the architect, contractor and other disciplines up-to-date information about the project. The common software for this application is Autodesk: AutoCAD®[12], with its external referencing command (XREF) which allows the collaboration of many users on two-dimensional engineering drawings. The advanced method of collaboration is using a three-dimensional source model using a BIM software (e.g. Autodesk: Revit®[13] or RIB: iTWO[14]). From the advantages of the BIM software over the CAD external referencing is that it has a better visualization of the information, automatic detection of collisions and plethora of valuable uses during construction and even operation and maintenance [4].

[12] https://www.autodesk.eu/products/autocad/
[13] https://www.autodesk.com/products/revit/
[14] https://www.itwo.com/en/

3 INVESTIGATION AND CHARACTERIZATION OF BUILDING INFORMATION MODELING DATA

The methodology of investigation is to point out certain computer-based workflows from the civil engineering field. Thereafter, the involved data files have been characterized after the procedures of data exchange and format conversions. Afterwards, the obtained information were verified by carrying out practical case studies. Then, suitable data management solutions have been discussed. Eventually, development recommendations for the data management solutions were proposed based on the research findings that are supported by graphical representation for results.

3.1 COMPUTER-BASED WORKFLOWS IN AEC

In this section, two significant workflows of the AEC processes were chosen; the structural design and the drone-based land surveying. Structural design is an integral stage in the engineering of a building. On the other hand, land surveying is also an essential phase before the start of the construction process. The procedures of these two workflows have been investigated in order to observe the characteristics of the data file formats involved. It is also to check whether the outcome in each particular workflow could be generalized; and thus over the whole AEC workflows.

3.1.1 Structural Design Workflow

The structural engineering has a significant role in the construction of any building. In a typical project, after the architectural design, the structural engineering process takes place comprising five main phases, which are proposing a statical system, assuming reasonable loads, structural analyzing, designing, delivering of drawings and details. In parallel to the structural design, the mechanical, electrical and plumbing (MEP) engineering takes place in accordance with the architect and the structural engineer. Thereafter, if there are no collisions or implementation problems, the building shall be ready for construction.

3.1.1.1 Conventional Structural Design Workflow

The traditional techniques of structural design in the engineering offices are mostly similar. The differences could be in the used structural analysis software and codes/norms of loads and design. Otherwise, the procedures of structural design are the same; including [5]:

1. Designing of the statical system in a CAD tool.
2. Digitizing the statical system (i.e. preparing the statical system for exporting to the structural analysis software).
3. Exporting the digitized statical system to the structural analysis software.
4. Inserting loads to the structural analysis model according to the codes.
5. Extracting the values of internal forces resulting from the structural simulations.
6. Inserting the structural analysis results into design spread sheets or software.
7. Obtaining the design results (e.g. dimensions and reinforcement).
8. Drawing the structural plans, details, beam heights color maps and slab levels plans using a CAD software.
9. Providing the architects and MEP engineers with the beam heights color maps and slab levels plans to perform the necessary checks (e.g. collisions).

In this research, the chosen software were AutoCAD®, CSI: SAP2000®[15] and Microsoft: Excel[16]. The previously mentioned software are being utilized worldwide by huge number of users and engineering offices [4]. Accordingly, the structural design workflow could be represented as shown in the flowchart in figure 2.

[15] https://www.csiamerica.com/products/sap2000
[16] https://products.office.com/en/excel

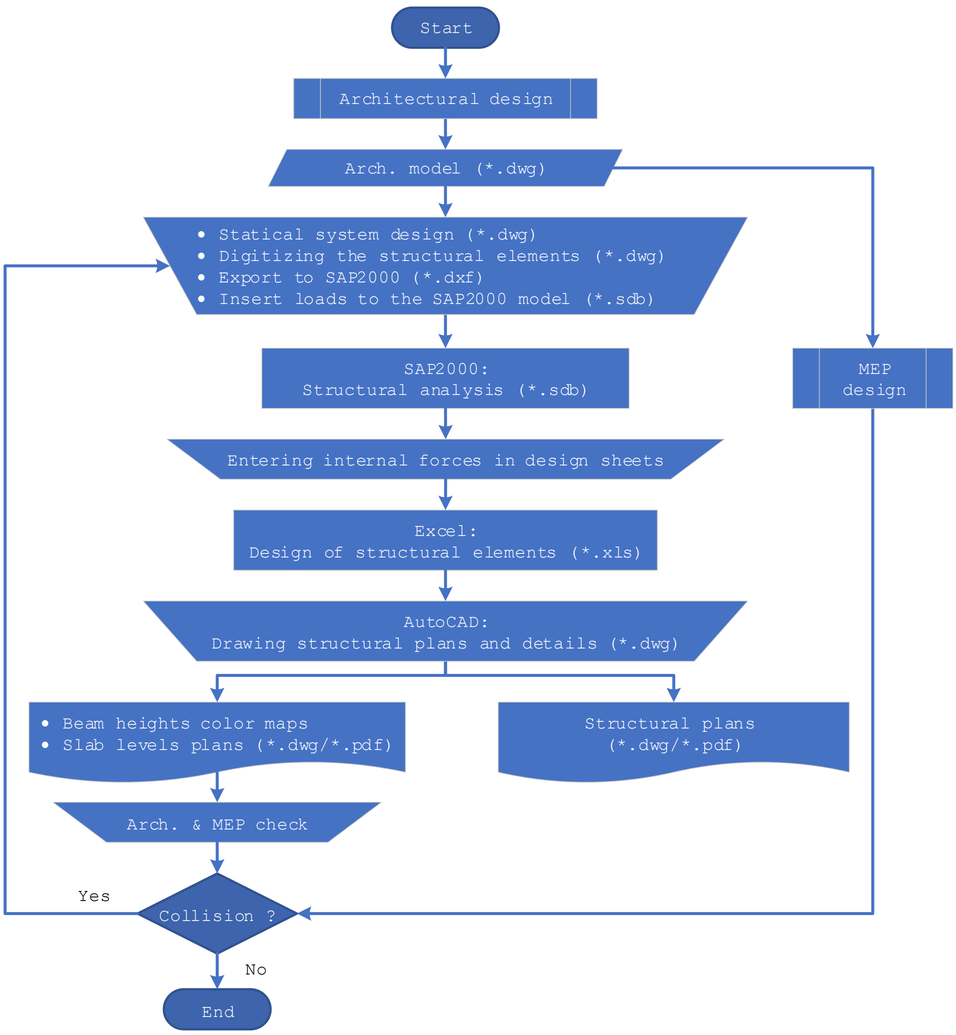

Figure 2: Flowchart of the conventional structural design workflow (see appendix: A1 for shape indications).

3.1.1.2 Advanced Structural Design Workflow

Recently, a limited number of AEC professionals started using the BIM software. Although it is a very powerful tool of collaboration between the different disciplines of building design, it is not the most commonly used approach. The advantage in this advanced workflow is that it offers insightful understanding and visualization of the project and allows most of the disciplines to work in parallel. As a result, it saves time, unnecessary expenses and provides data with high accuracy and preciseness. The workflow of structural design using such software is more automated than in the ordinary methods (i.e. it does not require considerable human interaction) [5]. The workflow using a BIM software encompasses:

1. Designing of the statical system in the BIM program.
2. Exporting the statical system to an associated structural analysis software.
3. Importing the internal forces as metadata to the building model.

4. Exporting the internal forces to the design spreadsheets through an intermediate software.
5. Importing the design results from the spreadsheets through the intermediate software again, and remodeling the structural elements of the building as per the design results.
6. Generate all the required drawings, documents and reports to proceed in the construction process.

The most common and advanced software in this application are the Autodesk products, including Revit®, Robot™[17] and Dynamo[18] for BIM, structural analysis and automation respectively [5], in addition to Excel sheets for structural design computations. Hence, the advanced workflow of structural design is illustrated as shown in the flowchart in figure 3.

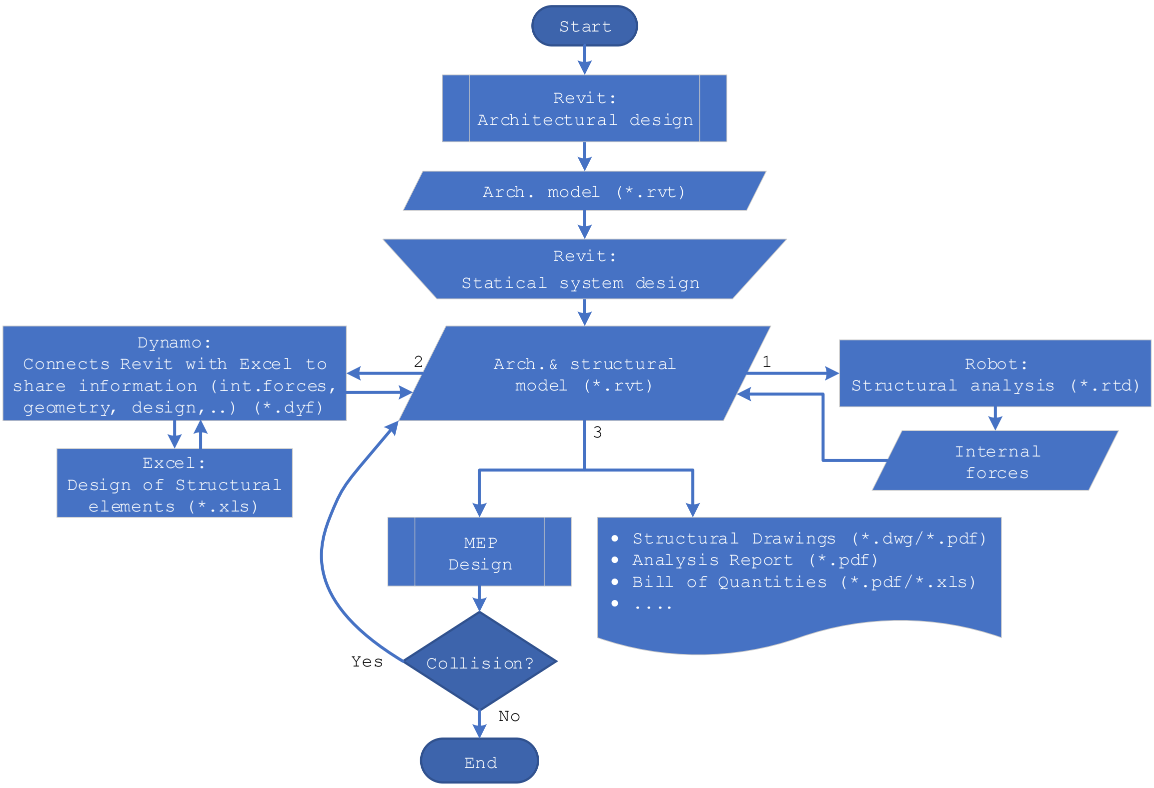

Figure 3: Flowchart of the advanced structural design workflow (see appendix: A1 for shape indications).

3.1.2 Drone-based 3D GIS Mapping Workflow

It has been consistently a crucial procedure to perform land surveying prior to embarking on any activity in the building construction. In the past few decades, land surveying technologies have witnessed a dramatic development. Recently, there are endeavors to employ unmanned aerial vehicles (UAV) as remote-sensing equipment in construction sites for being a powerful

[17] https://www.autodesk.com/products/robot-structural-analysis/
[18] https://www.autodesk.com/products/dynamo-studio/

tool of mapping. Drones provide the land surveyors and cartographers with an insightful bird-eye two- and three-dimensional view of land, which help them forming GIS framework to automate the necessary analysis for construction, including: distances/areas measurement, cut and fill volumes calculation, photo and video documentation, inspection, etc. [6]. In this research, the workflow of creating GIS 3D maps with the aid of drones equipped with real-time kinematic global positioning system (RTK GPS) and cameras with special capabilities such as infrared (IR) sensor, rotating, tilting device, object auto-detection, etc. has been investigated.

The workflow included four different sorts of software which are drone-programming, 3D-model-generating, spreadsheet, 3D CAD and GIS software. The function of the drone-programming software is to set up the drone with the suitable flying altitude and optimized route based on the given area boundaries, required ground sampling distance (GSD) and the specified forward and side overlap. A 3D-model-generating software is used to process the numerous aerial images and the flight log files that are captured by the drone to stitch them together and generate a textured 3D model of the surveyed field using the images metadata (e.g. altitude, longitude, latitude, inclination angle of the camera, etc.) as shown in figure 4. In case ground control points (GCP) are available, some 3D-model-generating software are capable of aligning, scaling and geo-referencing the 3D model. Otherwise, these procedures are to be carried out by a CAD software that supports 3D modelling. Moreover, the CAD software is substantial to digitize the main features on the 3D map (e.g. buildings, roads, etc.), i.e. creating a layer of vector objects complying with the geo-spatial position of the features on the raster map as depicted in figure 5. In parallel, spreadsheet software is used for the entry of attribute data (e.g. road names, building numbers, etc.). Ultimately, the GIS software imports the 3D model from the CAD software to geo-reference the 3D map along with the digitized data. In addition, it is used to import the attribute data tables and perform wide range of data analysis for various applications [6].

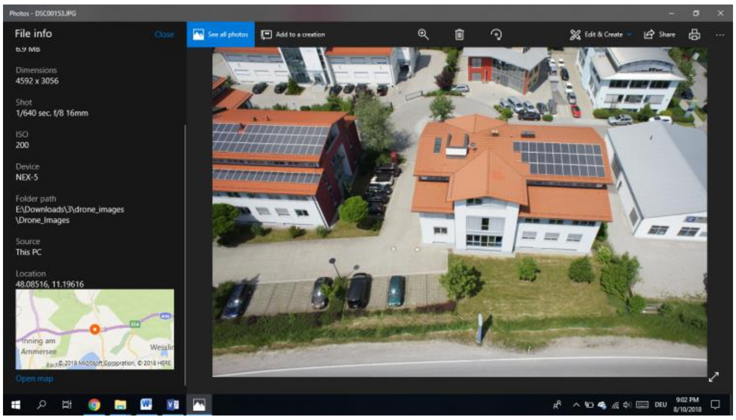

Figure 4: Aerial drone image with metadata (on left of screen).

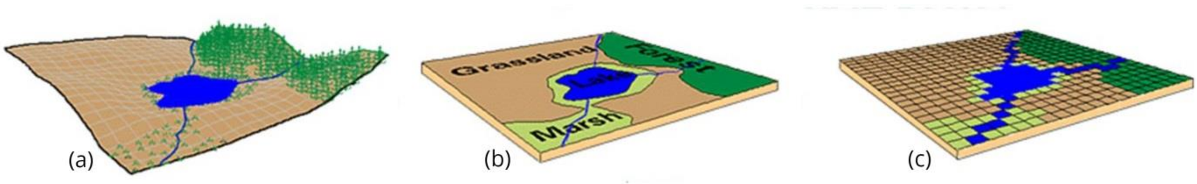

Figure 5: Digital geo-spatial data: a) Real world, b) Vector model with attribute data, c) Raster model [https://gis.stackexchange.com/questions/7077/what-are-raster-and-vector-data-in-gis-and-when-to-use].

So as to produce a three-dimensional GIS map with the aid of surveying drones, the following steps summarize the whole workflow [6]:

1. Importing a base map (e.g. scanned map) to the drone-programming software and highlight the boundaries of the area to be surveyed.
2. Planning an initial flight route for the drone, specifying the desired GSD, forward and side overlap percentage within the drone-programming software in order to calculate the suitable altitude, optimize the flight route and set up a program for the drone via connection between the drone and the computer (see figure 6-a).
3. Placing the drone on its take-off point that is determined on the drone-programming software to start the flight.
4. Obtaining the aerial images and flight logs from the drone, and import them to the 3D-model-generating software to process the captured data and produce a 3D model of the surveyed area. In case there are known GCP, alignment, scaling and geo-referencing could be carried out as well.
5. Exporting the 3D model to a 3D CAD software to perform alignment, scaling, coordinates transformation and digitizing of the map features.
6. Entering the map features attribute data to a spreadsheet.
7. Exporting the model to a GIS software to geo-reference the map and the digitized data, join the attribute data tables from the spreadsheet, produce a 3D GIS map and perform the required data analysis as shown in figure 6-b.

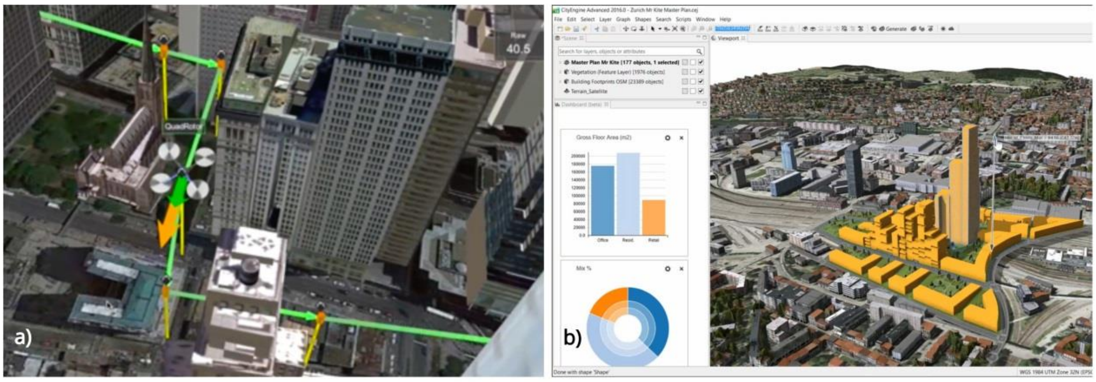

Figure 6: a) Drone route planning on drone flight automation software [21], b) GIS analysis of digitized geo-spatial data on Esri's ArcGIS platform (CityEngine plug-in) [http://www.aecbytes.com/newsletter/2017/issue_91.html].

SPH Engineering: UgCS[19], Autodesk: ReCap™[20], AutoCAD® Civil 3D[21], Microsoft: Excel and Esri: ArcGIS[22] have been chosen for this workflow as drone-programming, 3D-model-generating, 3D CAD, spreadsheet and GIS software respectively. Accordingly, the flowchart in figure 7 illustrates the workflow.

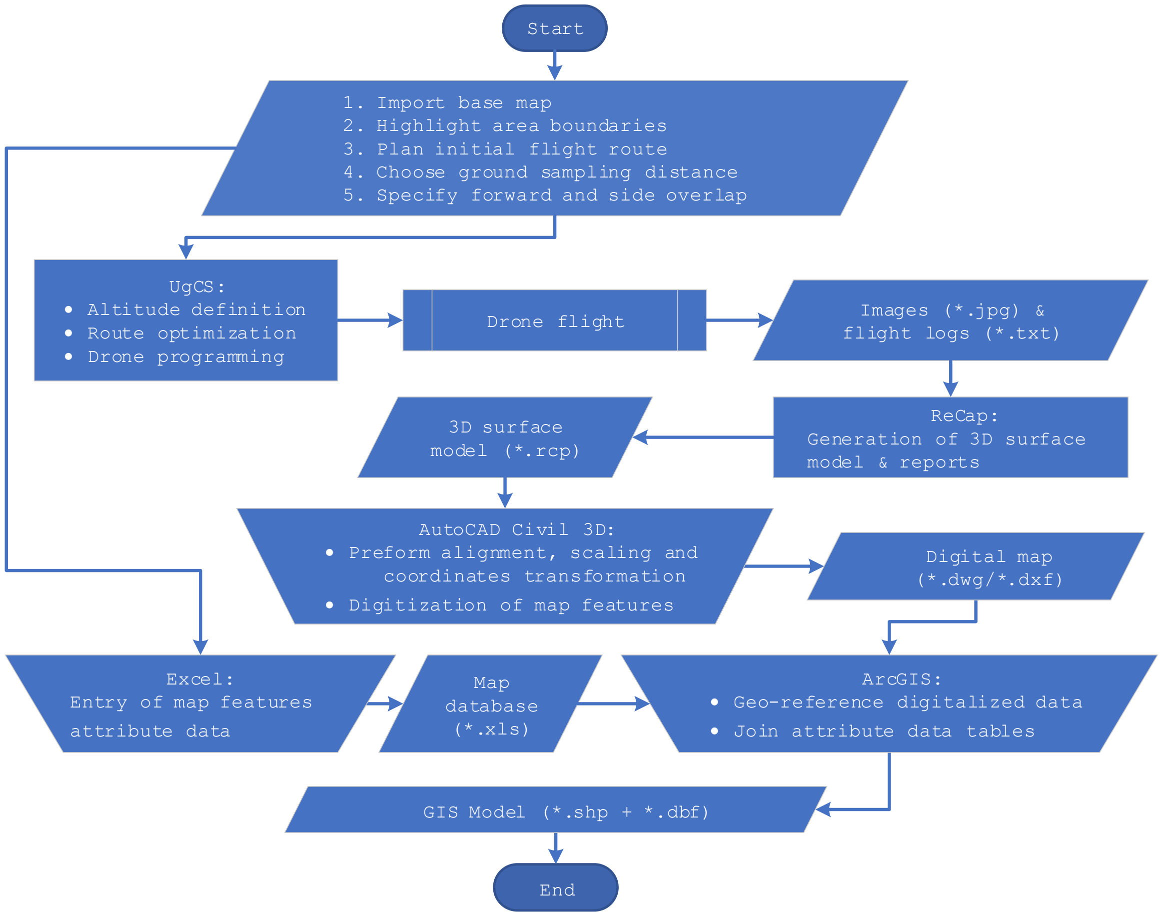

Figure 7: Flowchart of the drone-based 3D GIS mapping workflow (see appendix: A1 for shape indications).

3.2 DATA FORMATS CHARACTERIZATION

The main focus of the thesis is to investigate and characterize the different data formats which are used by the software of the structural engineering and land surveying domains. As discussed in the previous section, the workflow of structural design includes several file formats; such as **.dwg*, **.dxf* and **.sdb* for the conventional technique and **.rvt* and **.rtd* for the advanced approach. This workflow falls under the structural engineering domain. Whilst, the workflow of drone surveying for GIS mapping involved the **.dxf*, **.shp*, **.xls* and **.dbf* file

[19] https://www.ugcs.com/
[20] https://www.autodesk.com/products/recap/
[21] https://www.autodesk.com/products/civil-3d/
[22] https://www.esri.com/en-us/store/arcgis-desktop

formats, and it is considered to be a part of the land surveying and remote sensing domain of civil engineering. All of the data exchange occasions in the workflows of study are summarized in table 1.

Table 1: Summary of file format conversions took place in the example workflows.

Conventional Structural Design Workflow			
From		To	
Software	Format	Software	Format
Autodesk: AutoCAD®	*.dwg*	Autodesk: AutoCAD®	*.dxf*
Autodesk: AutoCAD®	*.dxf*	CSI: SAP2000®	*.sdb*
Autodesk: AutoCAD®	*.dwg*	Adobe: Acrobat	*.pdf*
Advanced Structural Design Workflow			
From		To	
Software	Format	Software	Format
Autodesk: Revit® Structure	*.rvt*	Autodesk: Robot	*.rtd*
Autodesk: Robot	*.rtd*	Autodesk: Revit® Structure	*.rvt*
Drone-based 3D GIS Mapping Workflow			
From		To	
Software	Format	Software	Format
Autodesk: ReCap™	*.rcp*	Autodesk: AutoCAD® Civil 3D	*.dwg*
Autodesk: AutoCAD® Civil 3D	*.dwg*	Autodesk: AutoCAD® Civil 3D	*.dxf*
Autodesk: AutoCAD® Civil 3D	*.dxf*	Esri: ArcGIS	*.shp*
Microsoft: Excel	*.xls*	Esri: ArcGIS	*.dbf*

The methodology of investigation is to discover the change in characteristics of data after the process of file conversion from one format to another. Thereafter, check how these data changes affect the workflow from the engineering perspective. Afterwards, express the results in the form of tables of comparison between the software alternatives which might be used in each workflow, along with justification of choosing each unique alternative software for this specific application. The findings were obtained through the documentations/manuals of the different software and verified by trying the software and observing the changed properties. In this research, the changes in most of the data characteristics were negative. The changes were in the form of information loss and/or data deformation. On the other hand, the changes in the remaining few conversions were neutral, (i.e. there were no lost information during data exchange).

3.2.1 Data Formats in Structural Engineering

In structural engineering, professionals tend mostly to deal with two categories of computer software; which are CAD and CAE software. In section 3.1.1, two approaches of structural design were introduced; a conventional and an advanced workflow. Both workflows comprised mainly importing the conceptual design of a building structure (statical system) to a FEA software to perform the required structural analysis. The central data exchange process takes place from CAD to CAE software in the conventional workflow and from BIM to CAE software and vice versa in the advanced workflow. Mostly, data formats are proprietary. This issue leads to conversion of files to a neutral format that could be read by the other systems. On the other hand, nonproprietary (i.e. open-sourced) formats support direct data exchange between the different systems without performing several intermediate conversions as shown in figure 8 [8],[9]. According to [10], the most common problems in converting proprietary 3D CAD model through neutral formats, particularly STEP and IGES formats are:

- loss of original file data structure
- loss of original color of the objects
- dislocation of objects from their original position
- visualization of 3D object details such as wireframe
- displaying the construction lines which were hidden in the original software
- change in the graphic information (e.g. interpreting circles as polygons such as octagon)
- change of hollow objects to solid objects
- change names of CAD files with numbers or names assigned to the directories where they are stored

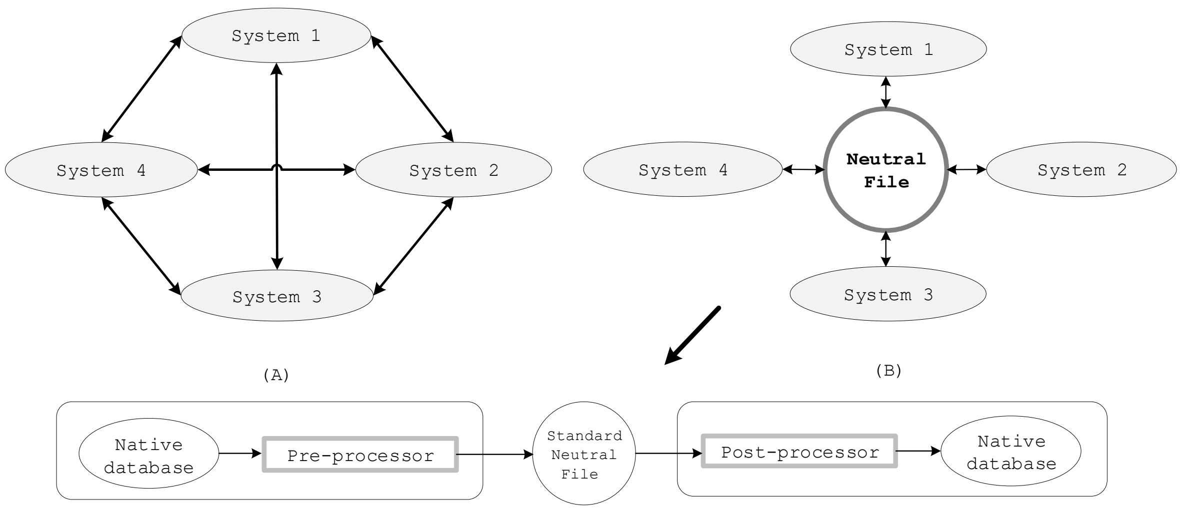

Figure 8: Data exchange methods: A) Direct data exchange, B) Indirect data exchange.

Starting with the conventional structural design approach, the main data exchange is importing CAD file to a FEA software. Four common CAD and BIM file format alternatives were chosen to be briefly compared together. This is to form an initial idea about each format before investigating the data exchange process with CAE software. Each format has unique characteristics and specific range of applications. The four formats are **.dwg*, **.dxf*, **.iges* and **.ifc*. DWG (DraWinG) is the default format of the software AutoCAD®, and it is a proprietary CAD file format for AutoCAD® and few similar software holding Autodesk's license [7]. DXF (Drawing eXchange Format) was originated by Autodesk to help in the exchange of the **.dwg* files, as it is a neutral CAD format [12]. IGES is a neutral format supported by most of CAD, CAE and CAM software as it comprises information of geometry, FEA and other mechanical engineering aspects [10], [12]. IFC is a neutral object-oriented file format that describes building and construction industry information [11]. Table 2 summarizes brief information about the previously-mentioned four formats.

Table 2: Comparison between DWG, DXF, IGES and IFC formats [7], [10], [11], [12].

Comparison Points	DWG	DXF	IGES	IFC
Stands for	DraWinG	Drawing eXchange Format	Initial Graphics Exchange Specification	Industry Foundation Classes
Expressivity	3D geometries, colors, text & layers	2D geometries, colors, text & layers	3D geometries, colors, text, layers, Mechanical & FEA data	3D geometries & alphanumeric semantic information about building components
Interoperability	Proprietary to AutoCAD® & few similar software holding Autodesk's license	Neutral (open source to most of CAD, CAE & CAM software)	Neutral (open source to most of CAD, CAE & CAM software)	Neutral (open source to most of CAD & CAE software)
Encoding	Binary	ASCII	ASCII	Data definition language: EXPRESS
Complexity	Handles 2D & 3D (solid) objects	Handles 2D vectors only (does not handle solid/surface elements)	Handles 2D & 3D (solid) objects	Handles 2D & 3D (solid) objects

Afterwards, the data exchange from CAD to CAE software was investigated by gathering information from the technical manuals/documentations of three chosen FEA software; CSI: SAP2000®, Autodesk: Robot™ and Dlubal: RFEM[23]. SAP2000® is an integrated structural analysis and design software that is developed in the United States of America over 30 years ago [14]. Robot™ is a professional structural analysis software with BIM-integrated workflows and dynamic link with Revit®, and it is an American software as well [15]. In contrast, RFEM is a German structural analysis software with powerful FEA capabilities in simulating complex 2D and 3D structure models effectively [16].

In the process of exporting CAD models to FEA software, the building geometry in the CAD file is converted to structural elements to be analyzed so that the internal stresses are calculated. A number of FEA software does not support this conversion (e.g. Robot™). They do not accept any structural elements created without the aid of their own drafting tools. However, these category of software import the CAD models as a background layer, which is a layer containing the CAD designs as hidden grid to assist modelling in FEA software utilizing the embedded drafting tools as shown in figure 9 [9].

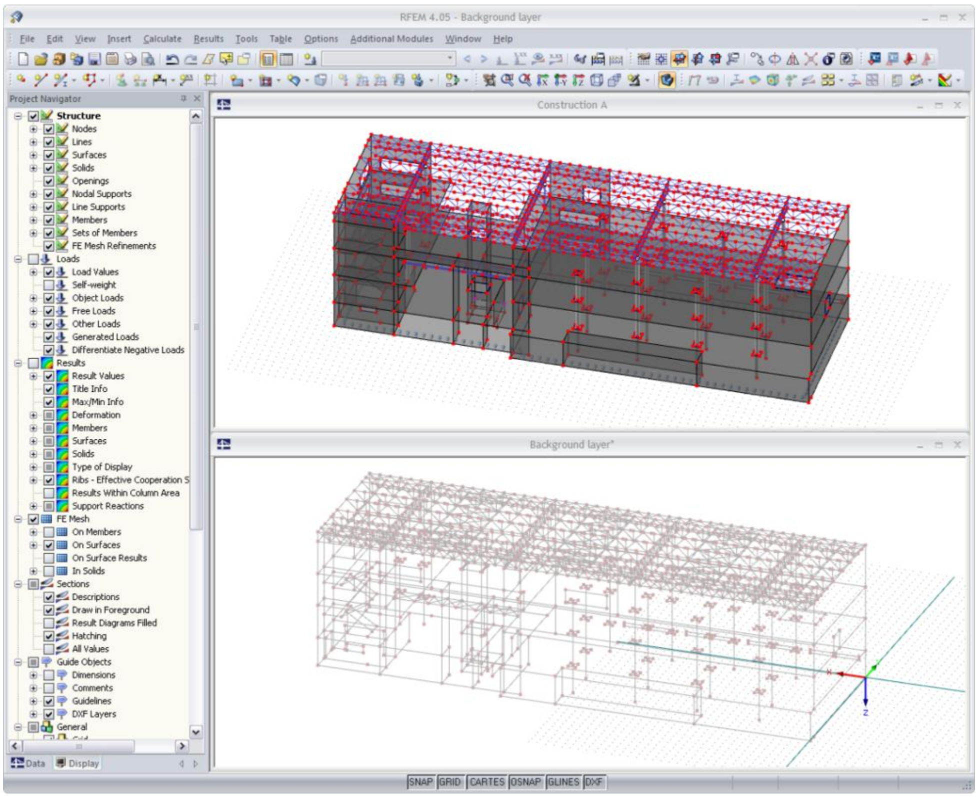

Figure 9: Representation for structural elements and background layer in Dlubal: RFEM [16].

23 https://www.dlubal.com/en/products/rfem-fea-software/

Generally, whether the conversion is as structural elements or as background layer, a part of the information in the CAD files is lost or changed during the data exchange process [8], [9]. Table 3 summarizes the changes in the CAD file information that result from exchanging the building models from *.*dwg*, *.*dxf*, *.*iges* and *.*ifc* to SAP2000®, Robot™ and RFEM.

The final data conversion in the conventional structural design workflow is saving the CAD structural drawings as *.*pdf* files. This conversion is essential for preserving the structural details as designed and to make the structural plans more versatile (i.e. to prevent the file contents from being edited, and to be easily viewed or printed by computers that are not equipped with CAD software). On the other hand, the files lose much information after this conversion; including font style in some cases, drawing resolution (maximum achievable resolution is 4800 dpi), precision (i.e. deformities and round-off errors arise) and the third dimension (i.e. all viewports, model space or layout of 3D and wireframe visual styles are converted into raster and path objects respectively as illustrated in figure 10). However, PDF formats retain layer information and raster data [17].

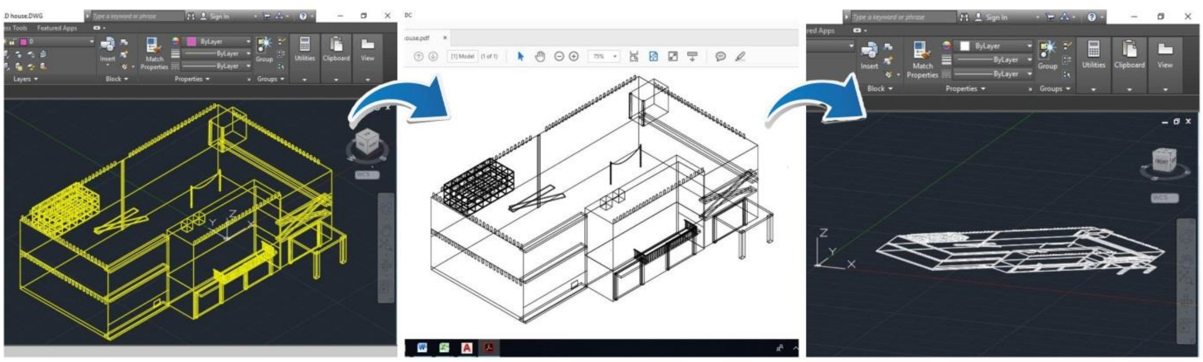

Figure 10: Format conversion of 3D CAD file from *.*dwg* (478 KB) to *.*pdf* (119 KB) to *.*dwg* (451 KB).

Table 3: Summary of observations on FEA models in different software after importing building models from CAD files with various formats [14], [15], [16].

	CSI: SAP2000® (*.*sdb*)	Autodesk: Robot™ (*.*rtd*)	Dlubal: RFEM (*.*rf5*)
DWG	Conversion is not possible (*.*dwg* files are not readable in SAP2000®).	• DWG model is transferred as a background layer only. • Attribute data are lost (e.g. annotations, dimension lines, axes, etc.). • Layer data are lost. • All objects are lost except: Lines.	Conversion is not possible (*.*dwg* files are not readable in RFEM).
DXF	• DXF model is transferred as structural elements. • Attribute data are lost (e.g. annotations, dimension lines, axes, etc.). • Layer data are lost. • All geometric entities are lost except: Point, Line, 3D Face and Polygon Mesh.	• DXF model is transferred as a background layer only. • Attribute data are lost (e.g. annotations, dimension lines, axes, etc.). • Layer data are lost. • All objects are lost except: Lines.	• DXF model is transferred as a background layer or as structural elements according to the desire of user. • Attribute data are lost (e.g. annotations, dimension lines, axes, etc.). • Layer data are lost. • All objects are lost except: Line and 3D Face. • Z-axis is automatically inverted to the opposite direction.
IGES	• IGES model is transferred as structural elements. • All geometric entities are lost except: LINE (Type 110), ARC (Type 100), MATRIX (Type 124), SPLINE (Type 126) & SURFACE SPLINE (Type128). • All FEA entities are lost except: Node (Type 134), 1-Beam (BEAM - Type 136), 2-Linear Triangle(LTRIA - Type 136), 5-Linear Quad(LQUAD - Type 136), 17-Linear Solid(LSO - Type 136), 27-Spring (SPR - Type 136), 28-Grounded Spring (SPR - Type 136), 28-Grounded Spring (GSPR - Type136), 29-Damper (DAMP- Type 136), 30-Grounded Damper (GDAMP - Type 136), Nodal Load/ Constraint (Type 418), Mass (MASS – Type 136) & Nodal Load/ Constraint (Type 418).	Conversion is not possible (Robot™ is closed to few formats which are: *.*dxf*, *.*dwg*, *.*ifc*, *.*rvt*, *.*sdnf* & CIS/2).	• IGES model is transferred as structural elements. • All geometric entities are lost except: Lines, NURBS-surfaces & TRIMM-Surfaces. • All FEA entities are lost.

IFC	• IFC model is transferred as structural elements. • All objects are lost except: IfcBeam, IfcColumn, IfcSlab, IfcStructuralCurveMember, IfcStructuralSurfaceMember, IfcStructuralPointConnection.	• IFC model is transferred as structural elements. • All objects are lost except: bar objects and 2D panels with openings (without transferring bar sections).	• IFC model is transferred as structural elements. • All data are lost except structural data such as nodes, lines, materials, cross-sections, members, supports, surfaces, solids, load cases and loads.

Moving forward to the advanced structural design workflow, it has two main conversions which are from the BIM software Revit® to the FEA software Robot™ and vice versa. Comparing to the conventional structural design workflow, the conversions of the advanced workflow were the most efficient and effective, as Autodesk have designed a dynamic link between Revit® Structure and Robot™ that provides bi-directional integration. The exact Revit® Structure data, analysis, edition of structural data and updating of the Revit® Structure model are transferred to Robot™ model in a seamless and dynamic way. This includes structural engineering data (e.g. sections, loads etc.), but also semantic information of elements such as member numbers, releases etc. – without the transfer of this data the user risks compromising the integrity of the BIM Model. Moreover, Robot™ has the ability to update the building model in Revit® with the structural analysis results and any modifications in the structure made by the user in Robot™. Delivering the data back to Revit® Structure takes place in a single step, without manipulating any BIM data [19].

Though, Revit® does not contain the FEA information required in Robot™ to perform the structural analysis (e.g. boundary conditions). Accordingly, such adjustments are to be set manually once the model is exported in Robot™. For this reason, Autodesk has created the boundary conditions and analytical model tools panels in Revit®. In addition, Robot™ creates the structural line elements by auto-detecting the centerline of the structural members in Revit®, which causes element discontinuity in some cases (e.g. reduced columns) as shown in figure 12. This results in computational errors and inaccuracy in the structural analysis results. On the other hand, the Revit®-to-Robot™ link automates several procedures which were done manually in the conventional workflow (e.g. auto-meshing of planar elements) [18].

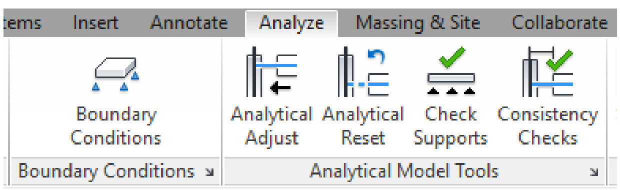

Figure 11: Boundary conditions and analytical model tools panels in the menu bar of Autodesk: Revit®.

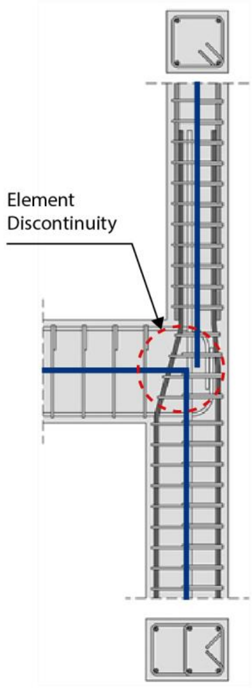

Figure 12: Illustration of the element discontinuity issue encountered due to structural members auto-detection feature in Robot™.

3.2.2 Data Formats in Land Surveying and Remote Sensing

Based on the workflow introduced in section 3.1.2, the significant data exchange processes took place were from ReCap (*.*rcp*) to AutoCAD Civil 3D (*.*dwg*) to AutoCAD Civil 3D (*.*dxf*) to ArcGIS (*.*shp*) and from Excel (*.*xls*) to ArcGIS (*.*dbf*). The exchange between ReCap and AutoCAD Civil 3D is to transfer the generated 3D model of the surveyed land to CAD platform to be able to perform the necessary adjustments. The 3D model is transferred as a raster image with defined elevations of each pixel representing the surface of the captured objects by the drone. Therefore, the surface model was transferred seamlessly to AutoCAD but with minor losses of data. The lost data are any non-raster data such as the attribute data of aerial images and GCP information. However, the transferred raster data are sufficient to adjust and digitize the model features [22].

Thereafter, the second conversion is to change the format of the CAD model from **.dwg* to **.dxf* in order to allow the exchange from AutoCAD to another autonomous software such as ArcGIS. As discussed in the previous section, the conversion from **.dwg* to **.dxf* leads to losing the three-dimensional objects data and increasing the size of the CAD file [23]. Alternatively, this conversion could be avoided by importing the **.dwg* file directly in ArcGIS, as it is supported in the late versions of ArcGIS. Although in the direct conversion from **.dwg* to **.shp*, some data are lost, since ArcGIS supports exclusively limited number of geometrical objects which are circles, circular arc, donut polygon, elliptical arc, ellipses, line, point, polygon, solid, surface, text and z values [25]. The lost data include geospatial data such as coordinate system, spatial index and transactions. This loss could be avoided by creating a WORLD file (*.*wld*) which is a six-line plain text sidecar file used to geo-reference raster maps. The WORLD file consists of six coefficients of an affine transformation describing the location, scale and rotation of a raster on a map. Furthermore, raster data and layers with external references in AutoCAD are lost [23]. In contrast, Esri Shapefiles retain layer information and attribute data of AutoCAD (e.g. annotations) [25].

Subsequently, the final conversion takes place while joining the excel table of attribute data to the map in ArcGIS. During such process, the *.*xls* file is converted to a proprietary geo-database file (**dbf*). The disadvantage of this conversion is that the information in cells with formulas are transferred as final values with certain attribute types which are characters, numbers, dates, logical and memo fields. Additionally, color data are lost. On the other hand, raster data are retained, which increased the range of analysis and applications a GIS map can execute (e.g. providing street-views) [24]. Table 4 summarizes the results of the investigation.

Table 4: Summary of observations about mapping file format conversions [22], [23], [24], [25].

Conversions		Observation
From	To	
Autodesk: ReCap (*.*rcp*)	Autodesk: AutoCAD Civil 3D (*.*dwg*)	▪ Aerial images attribute data are lost. ▪ GCP information are lost.
Autodesk: AutoCAD Civil 3D (*.*dwg*)	Autodesk: AutoCAD Civil 3D (*.*dxf*)	▪ Solid geometries are lost. ▪ Drawing items which cannot be converted into combinations of the set of basic drawing objects that can be represented in a *.*dxf* file are lost. ▪ Some of the non-visual data about the drawing are lost.
Autodesk: AutoCAD Civil 3D (*.*dxf*)	Esri: ArcGIS (*.*shp*)	▪ Geospatial data are lost (e.g. Coordinate System, Spatial Index, Transactions etc.) unless the user created a WORLD file (*.*wld*) to transfer the geospatial data. ▪ Supported geometry: circles, circular arc, donut polygon, elliptical arc, ellipses, line, point, polygon, surface, text & z values. ▪ Layer data and attribute data are retained. ▪ Raster data are lost. ▪ Externally-referenced (XREF) layers are lost.
Microsoft: Excel (*.*xls*)	Esri: ArcGIS (*.*dbf*)	▪ Supported attribute data types: Characters, dates, numbers, logical & memo fields. ▪ Color data are lost. ▪ Formulas are lost, but values are retained. ▪ Raster images are retained.

3.2.3 Data Exchange between Structural Engineering and Land Surveying Workflows

There are many endeavors to integrate the GIS with BIM in AECOM. BIM and GIS are interdependent concepts providing an extensive range of powerful applications in civil engineering, including facility management (FM), infrastructure management (IM), risk management (RM), digital construction, and urban planning/development. BIM and GIS data exchange mainly takes place at two stages; the first stage is the design and planning phase for acquisition of required pre-design information, and the second stage is the after construction as-built documentation [26].

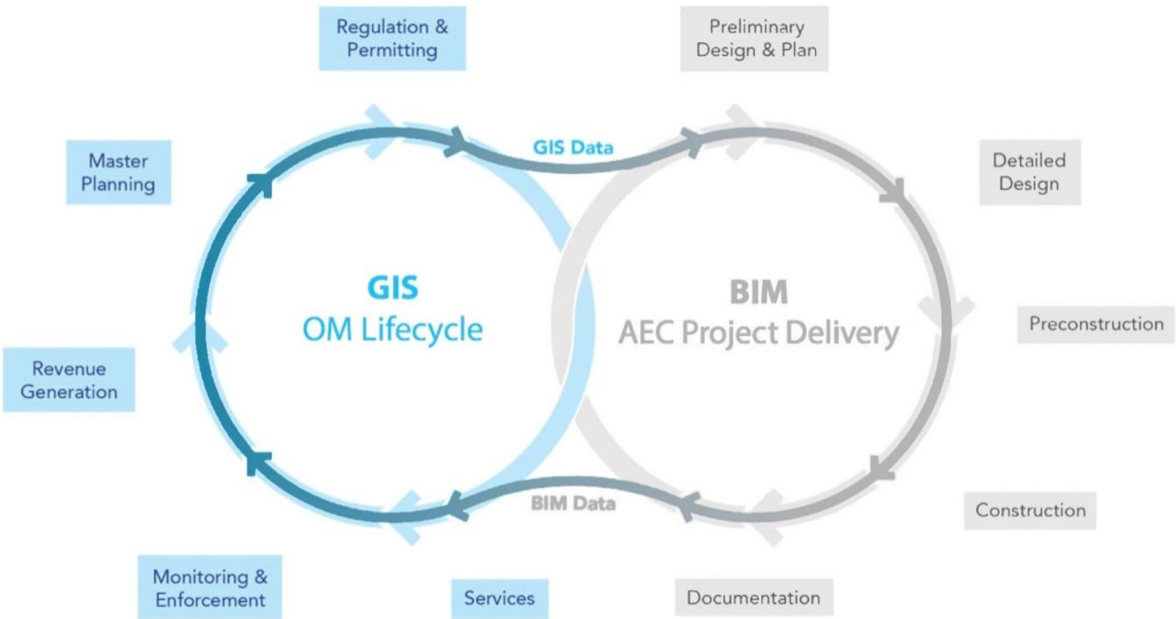

Figure 13: Representation of the possible data exchange between BIM and GIS systems.

Since the two methodologies are interdependent, the data exchange process starts either from BIM to GIS or vice versa according to which of the models was created in the first place. In case BIM model was firstly established, the data are transferred in the form of building as-built geometries, capacity, services, uses, resources, etc. Otherwise, if the GIS model was prior created, then the transferred data are geospatial analysis, constructability, geotechnical results, information about traffic and residents, etc. For existing buildings without BIM models, GIS mapping and remote-sensing methods are capable of accurately acquiring as-built geometry and details of the building with a simple workflow additional to the drone-based mapping workflow, starting with 3D laser scanning of the building from insides, and then the obtained laser scanning data are imported in ReCap™ as a point cloud along with the aerial images of the drone. Afterwards, ReCap™ is responsible for transforming the point cloud and the aerial images into accurate as-built 3D model, which is digitized into BIM model after exporting to BIM software such as Revit® [27], [28].

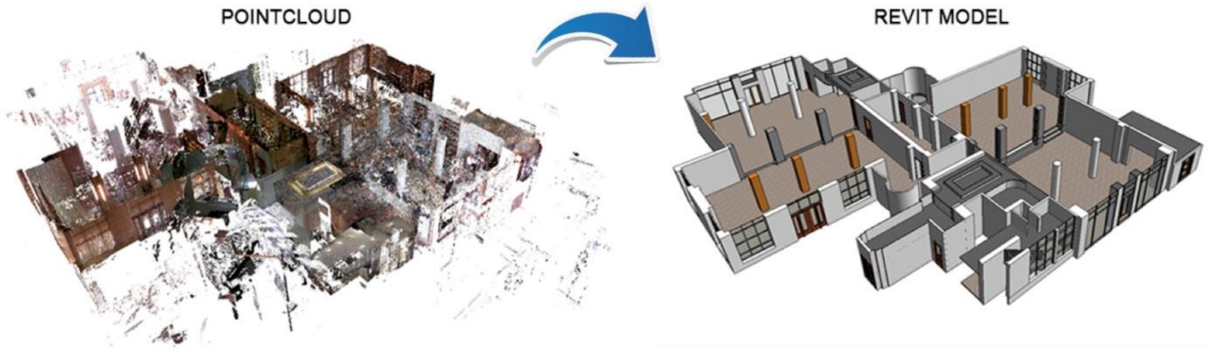

Figure 14: Conversion of indoor point cloud into as-built BIM 3D model
[https://www.architecturalbimservices.com/point-cloud-to-bim-services/].

3.3 CASE STUDIES IN BIM AND GIS

The aim of carrying out these case studies is to verify the obtained theoretical information about data exchange that are stated in the previous sections. This verification would support the findings of this research in case the results match the information gathered in section 3.2. Additionally, case studies are implemented in order to provide deeper practical understanding about the workflows of study, which would be the guide for future development recommendations by discovering the missing features, functions or tools in the workflows.

3.3.1 Case Study (1): Structural Design with Traditional Method versus BIM

A two-storey reinforced concrete building with a basement and pitched roof have been structurally-designed using the two structural design workflows discussed in section 3.1.1. The time consumed in performing the manual (i.e. non-automated) tasks have been calculated by the means of the employed software, as each software store the total editing time of the data file as metadata. Figure 15 illustrates the structural design model conversion phases starting from receiving the architectural designs to designing the statical system, digitization, meshing in AutoCAD and structural-analyzing in SAP2000.

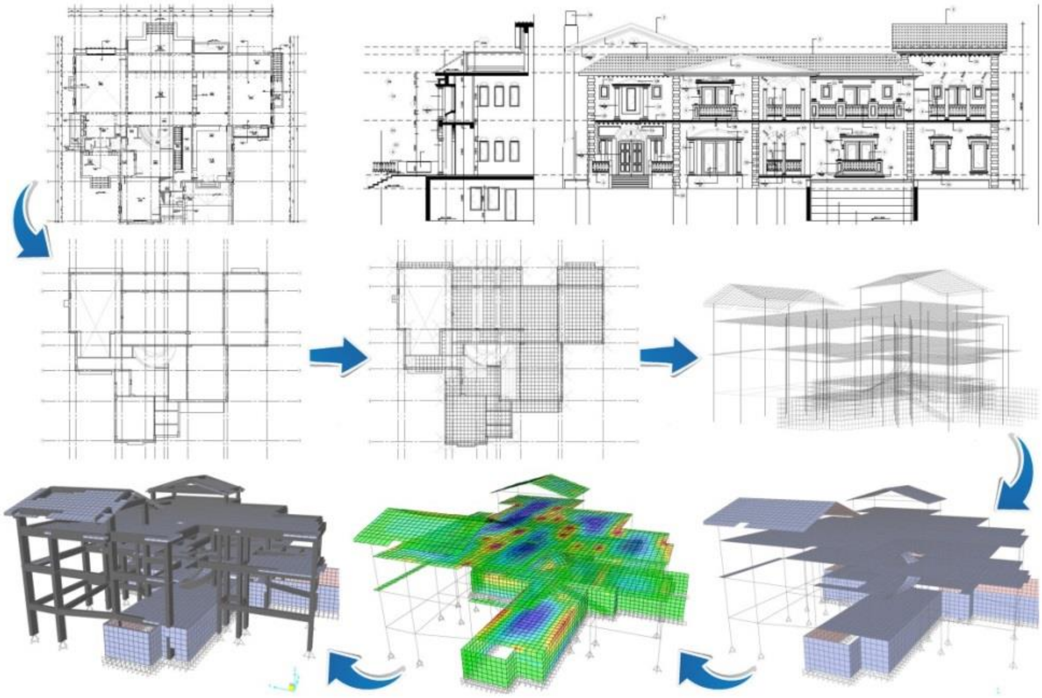

Figure 15: Structural design phases of two-storey building using traditional method.

Thereafter, the same building has been structurally designed for the second time using the advanced structural design method. The statical system has been modelled in Revit®, transferred to Robot™ and vice versa for structural analysis, then analysis results flow through Dynamo's algorithms to the excel design sheets and finally the design results are sent back to the central Revit model to supply it with the computed dimensions and reinforcement information. Part of these steps is depicted in figure 16.

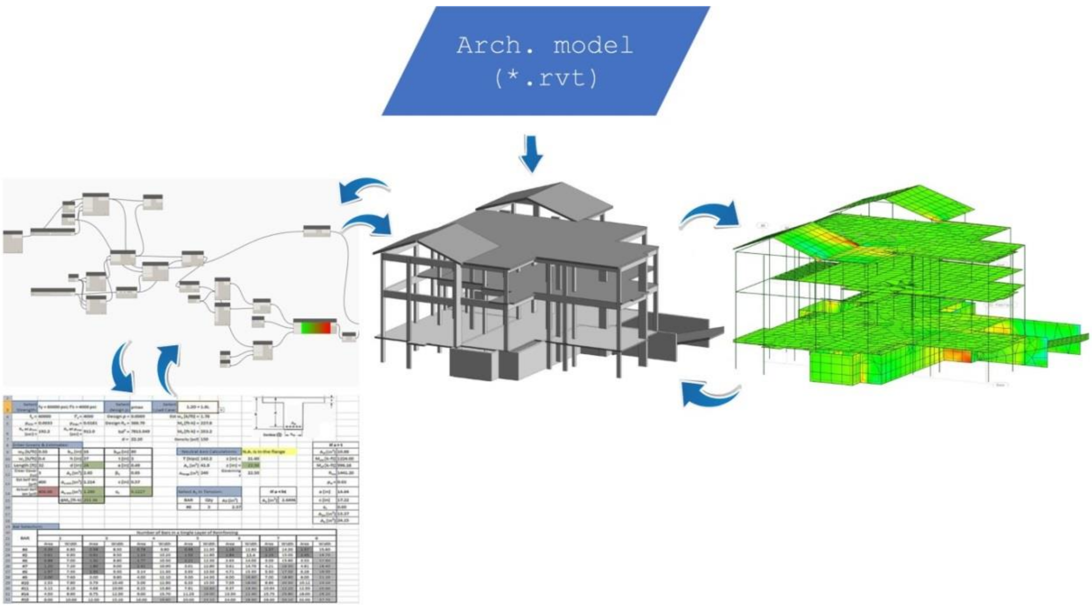

Figure 16: Structural design phases of two-storey building using BIM.

According to this study, it was found that the ratio of time spent on manual tasks between both workflows to finish the whole project is approximately 12:1, with 92 working hours for the conventional workflow versus 8 working hours on the advanced workflow. The breakdown of working hours is stated in table 5 and depicted as bar chart in diagram 17. The software computation time has not been taken into account in this comparison as they were negligible (i.e. fractions of a minute). Certainly, the previous ratio is not constant in all cases. It varies depending on the complexity and requirements of project.

Table 5: Comparison between manual tasks working hours of the studied structural design workflows.

Manual Tasks in Structural Design	Conventional Workflow Working hours	Advanced Workflow Working hours
Design of statical system	16	6
Digitization of structural elements and meshing	16	Automated task (structural elements are pre-defined)
Insertion of loads and actions	12	2 Semi-automated task (Revit® stores building uses & auto-applies loads)
Obtaining design results from Excel sheets	8	Automated task (Revit® & Excel exchange data via Dynamo)
Drawing structural plans	40	Automated task (user selects the views/details to be automatically generated in Revit®)
Total working hours:	92	8

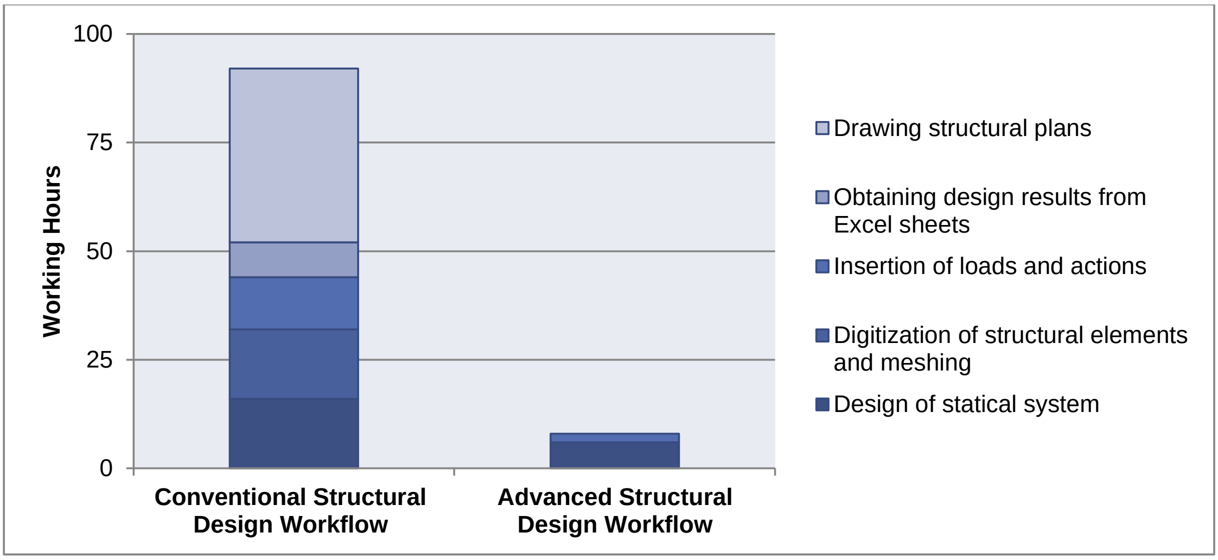

Figure 17: Comparison between manual tasks working hours of the studied structural design workflows.

3.3.2 Case Study (2): GIS for Earthworks Analysis

This case study has been originated from a project [40] held by a drone photogrammetry cloud-based software known as Pix4D[24] in collaboration with the surveying company "SAPR". Pix4D is a drone photogrammetry data management solution with the ability to run simulations and analysis required in AECOM tasks. The software and the workflow used are explained in details in section 3.4.3.

In March 2015, it was intended to verify construction earthwork on an area of 64,000 m² using drone-generated 3D map. The data acquisition started by capturing a total of 101 aerial images with 3 cm GSD by an "AirVision NT4-Contras" drone with RTK GPS on board. Aerial data have been imported to Pix4Dmapper along with 4 GCP's on the construction site to be processed and generate 3D surface model. The 3D map have been analyzed in Pix4D to provide the required data, including DSM, DTM, soil stockpiles volume, etc. as shown in figure 18. The results were used to calculate whether the contractor has to import or export soil to reach the desired elevation. It has been concluded by the surveying company that drone-based 3D GIS mapping delivers results up to 80% faster than traditional techniques, with one day for data acquisition and one day for processing versus two weeks of continuous standard surveying work on site [40].

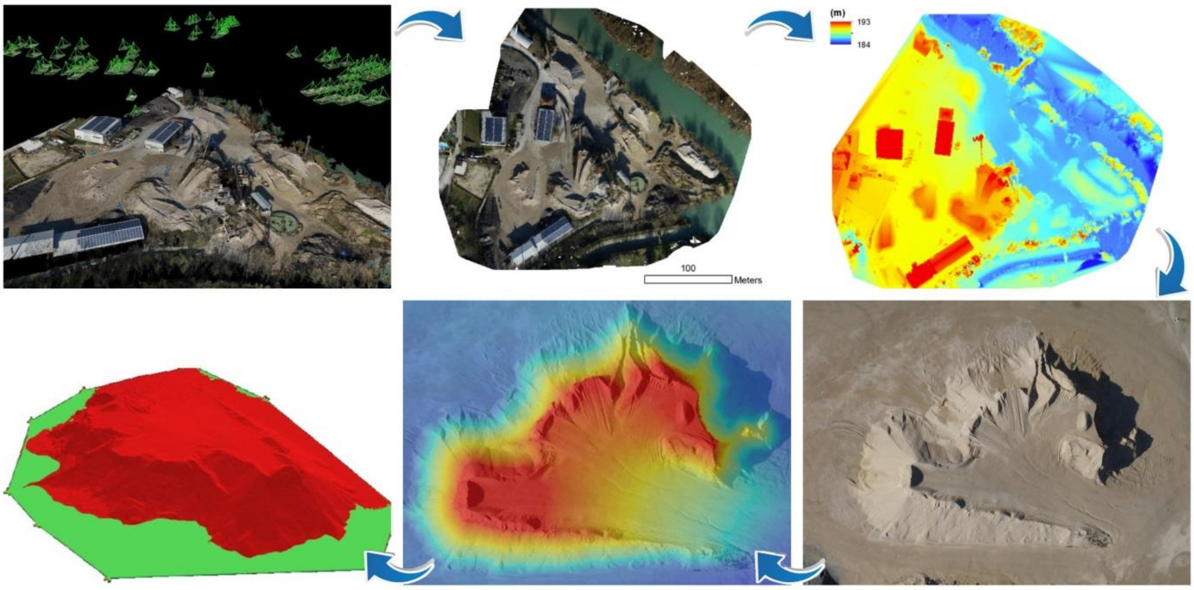

Figure 18: Earthwork analysis phases of construction site using drone-based 3D GIS mapping [40].

[24] https://pix4d.com/

3.4 DATA MANAGEMENT SOLUTIONS

In view of the prior investigated data formats and according to their characteristics, it is paramount to employ a convenient data management system complying with the requirements of AEC aspects and increasing the efficiency of the workflow with the least possible loss of information during each data exchange process. Unintentionally, there is a loss in the information while delivering the project from one phase to another. This information loss results mainly from two reasons: lack of documentation expressivity and uncommon supported features in data exchange from a system to another [29].

First of all, the data expressivity defines the level of understanding gained by the other party after receiving the data files. The data have to contain all the information documented clearly and well-organized to prevent any misinterpretation or neglection. Secondly, data exchange between platforms with different range of functionalities leads to loss of some details that cannot be represented since they are unsupported by the other system. The quantity of lost information depends on the utilized software and exchange formats of data files. The compliance and integrity of data management systems maintain - to some extent - full and seamless information transfer rather than suffering from drops in information at transferring the project from phase to another as represented in figure 19 [29], [30].

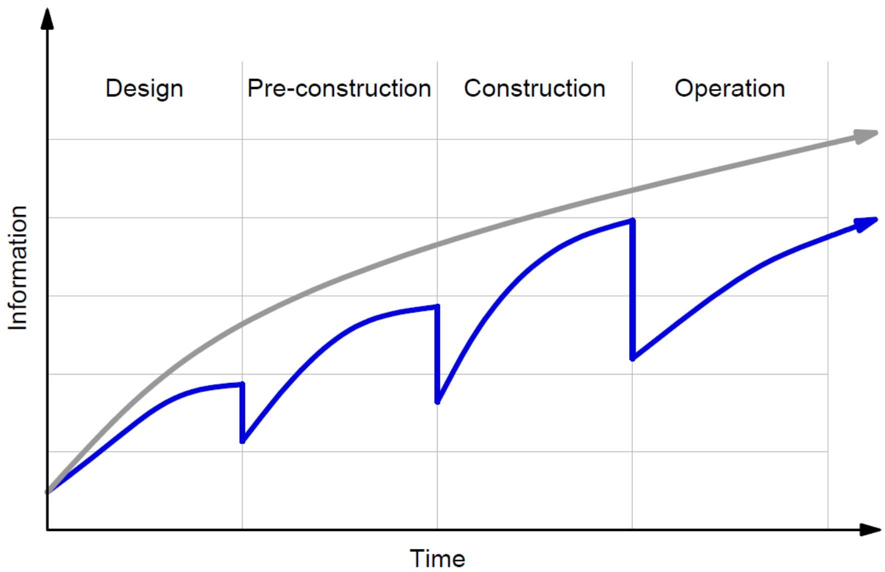

Figure 19: Relationship between the amount of information and time throughout a typical AECOM project lifecycle (blue curve is the actual relationship, while grey curve is the intended relationship of this research).

The main focus in this chapter is to investigate the existing data management solutions (DMS) for the workflows of study, or propose a suitable data management solution in case they do not already exist. To recall, various categories of collaboration software have been introduced in chapter 2. For building engineering and mapping, the CAD software with external referencing (XREF), BIM and collaborative GIS software have been considered. The native and neutral data formats have been investigated and the results were analyzed and judged forming accordingly an understanding about the appropriate data management solutions for each particular workflow. Based on this idea, it is possible to state whether the findings apply to all civil engineering domains or it is implausible to be generalized.

3.4.1 Discussion

The data exchange from AutoCAD to any other software obligated the conversion of **.dwg* files to **.dxf*. This conversion has been investigated in both of the studied workflows. In the structural design workflow, it was necessary to convert the design of a statical system from **.dwg* to **.dxf*, as most of the investigated FEA software did not support the **.dwg*, since it is proprietary to Autodesk software. The same conversion was carried out in the surveying workflow in converting the digitized 3D map from **.dwg* to **.dxf* format in order to be exported to the GIS software. In both cases, the conversion from **.dwg* to **.dxf* format led to the same consequences. After the conversion, the original **.dwg* file loses some non-visual data about the drawing and drawing items which cannot be converted into combinations of the set of basic drawing objects that can be represented in a **.dxf* file including three-dimensional geometries and dynamic blocks. This information is to be generalized in all the civil engineering, since it is a property in **.dxf* files that they do not have the ability to store the aforementioned type of information, hence, these data are typically lost in any case. Losing such type of data leads to misinterpretation of solid structure CAD models when converted from their native format to different software through **.dxf* format. Moreover, It leads to change of dynamic block object dimensions due to exploding the block which retained the user-defined dimensions of the object.

Additionally, there have been two common situations in the investigation of the workflows. The two workflows experienced data exchange between different software from the same developer company, as in linking the Revit® with Robot™ in the advanced structural design workflow and exporting the ReCap™ to AutoCAD® Civil 3D in the drone surveying workflow. In both cases, the results showed that the conversion took place seamlessly and with minimal information loss. Hence, it might be more favorable to perform conversions from software to another one of the same developer to minimize the loss of information. Specifically, it is preferred in a civil engineering workflow – from the perspective of information preservation only - to select software produced by one software company like the advanced structural design workflow which included Autodesk's Revit®, Robot™ and Dynamo. In the same manner, it is advised in the example workflow to perform the MEP and 5D analysis using Autodesk's Revit® MEP[25] and Navisworks®[26].

After all, the previous information were gathered from the user manuals and API documentations of Autodesk, and then the findings were verified by using the software and performing different data exchange applications. In the specific scope of this thesis, all the findings were verified and ensured that they comply with the information in Autodesk's references. In different cases, Autodesk's information are not reliable, as they might be biased to their own products as a way of marketing. Otherwise, any other finding could not be generalized, since the investigation was carried out on two workflows of different civil engineering domains and the givens are not sufficient to judge or infer a conclusion.

As per the formats comparison results, it is concluded that the advanced structural design method is more preferable than the conventional approach. Whereas, this workflow does not involve any conversion from **.dwg* to **.dxf* formats. Moreover, the only conversion in this workflow is carried out between two software of the same vendor. However, there were few disadvantages in interpretation of the structural model which are able be resolved manually in Robot™. From the perspective of collaboration, the advanced workflow proceeds effectively from team to another without the need of any intermediate conversions. It also allows the various project participants to work in parallel with high efficiency and in accordance with each other. Nevertheless, the collaboration could be enhanced by including aiding features to facilitate and organize the teamwork such as structured cloud platform, coordination API, communication and version management tool (e.g. notification messages for the changes, collisions or inquiries).

It was apparent in the workflow of drone surveying for GIS mapping that each individual software has a limited quantity of contribution. There are more advanced computer software that are capable of performing multiple tasks of the workflow leading to reduction in the number of conversions and data exchange. It is practical to include most of the required functions for the workflow tasks in a single software and avoid unnecessary conversions. This fragmentation in workflow had no evidence in the literature. Nevertheless, it is assumed that this fragmentation is due to the recent adoption of drones as a surveying tool for GIS and the absence of adequate data management solutions at that time. As an example, ReCap™ was first originated to handle point cloud data acquired by laser scanners, and lately, it has been developed to deal with drone aerial data. Therefore, it is predicted that utilization of a software specifically-

[25] https://www.autodesk.com/products/revit/mep/
[26] https://www.autodesk.com/products/navisworks/

developed for drone photogrammetry would be more professional and efficient in this particular workflow.

3.4.2 Existing Data Management Systems for BIM

Owing to the investigation results, an existing data management solution has been released by Autodesk three year ago, complying with the requirements and improvement intentions of the advanced structural engineering workflow that have been stated in the previous section. This data management solution is known as BIM 360™ Design[27], and it is a cloud platform for data sharing and design collaboration software specified for distributed multidisciplinary teams. It was created to connect teams across the project phases, centralize data to ensure accuracy and access, control information from conception through operations and analyze data to get insights and increase efficiencies. It improves collaboration and coordination across the entire project lifecycle; from design, through planning and construction to operation and maintenance [31].

The data management system of the engineering phase is divided into two separate servers hosting the files. The first one is called Collaboration for Revit® (C4R)[28], and it is the cloud platform of architecture, structural and MEP design and coordination. The C4R is a server-based live central Revit® model where all the engineering disciplines frequently synchronize their designs. The second and main server is the BIM 360™ which is responsible for the coordination and communication between all the project participants (including the engineering teams) as far as the project is handed over. The purpose of separating the two servers is to prevent the confusion of continuous synchronization of engineering modifications before coordination and approval, since the BIM 360™ server includes teams of different responsibilities such as cost estimation, planning and execution teams [31].

C4R has two main components which are C4R Accelerator and C4R Communicator. C4R Accelerator is a tool that detects the engineering changes instantly and updates the uploaded model. This is to avoid the synchronization of numerous changes at one time, which may cause crashing of the central Revit® file or blocking the connection between the file and the rest of the engineering team. C4R Communicator is an interactive tool of instant messaging privately or in groups with the ability to send specific views and screenshots of the model with markups and annotative comments. In addition, it comprises a dashboard for displaying notifications and sharing information about critical modifications or synchronizations as shown in figure 20 [31].

[27] https://bim360.autodesk.com/

[28] https://www.autodesk.com/products/collaboration-for-revit/

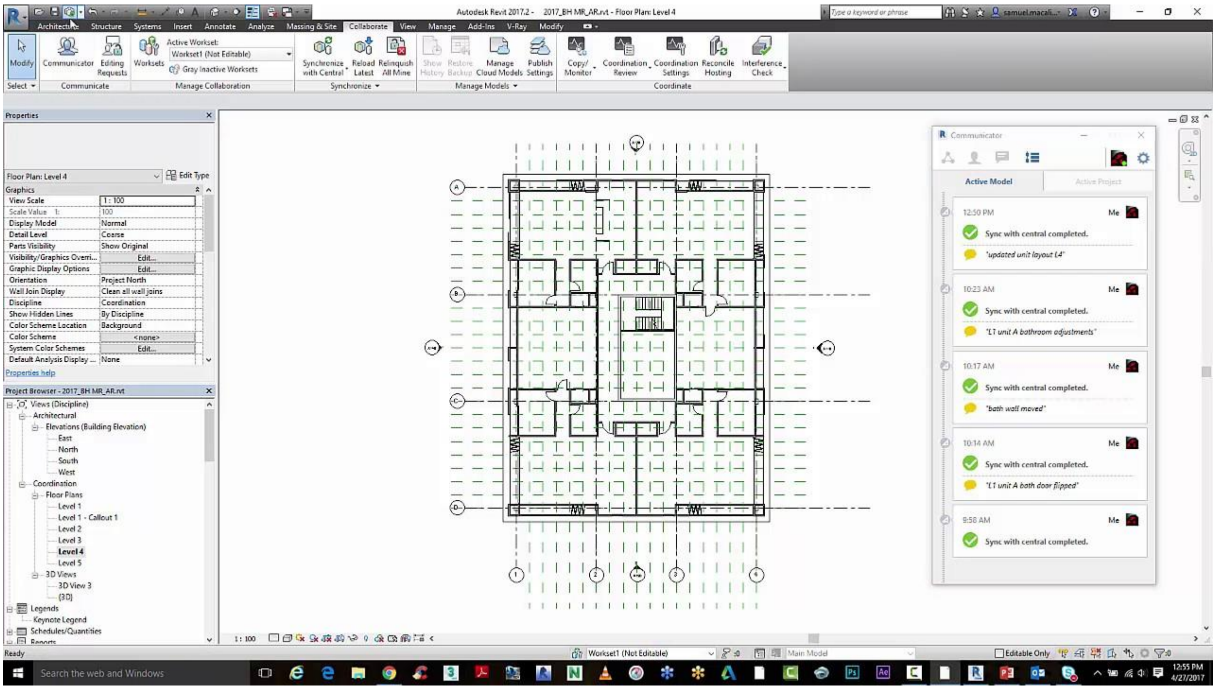

Figure 20: Collaboration for Revit® user interface with C4R communicator on the right side of screen [31].

In addition to BIM 360™, there is a number of competitor data management systems integrated with vendor-specific tools. Examples of these systems are GRAPHISOFT: BIMcloud[29], TNO: BIMserver™[30] and ALLPLAN: Bimplus[31]. A comparison between these data management systems has been carried out stating the capabilities and features of systems (see table 6).

[29] http://www.graphisoft.com/bimcloud/

[30] http://bimserver.org/

[31] https://www.allplan.com/products/allplan-bimplus/

Table 6: Comparison between BIM data management systems capabilities [33], [34], [35], [36].

Data Management System Capabilities		Autodesk: BIM 360™	Graphisoft: BIMcloud	TNO: BIMserver™	Allplan: Bimplus
Supported formats	*.ifc	X	X	X	X
	*.bcf		X	X	X
	*.rvt	X			
	*.nwc	X	X		
	*.smc		X		
	*.dwg	X	X		X
	*.3dm	X	X		X
	*.c4d		X		X
	*.skp	X	X		X
	*.stl	X	X		X
Design tools		X	X		
3D visualization		X	X	X	X
Online file storage		X	X	X	X
Online drawing viewing		X	X		X
Online drawing editing		X	X		
Lifecycle management		X			X
Simulations		X	X	X	X
Detailed management permissions		X	X		
Online sharing of file		X	X	X	X
Mobile apps		X	X		X
Browser based management		X	X	X	X
Folder hierarchy		X	X	X	X
File management system		X	X	X	X
Clash detection		X	X	X	X
Private cloud			X	X	X
Encrypted data		X	X		
http/https support		X	X	X	X
Multiple cloud servers		X	X		
Automated server backups			X		
User groups		X	X		X
Multi language support		X	X		X
Free trial version		X	X		
Open source				X	X

3.4.3 Existing Data Management Systems for GIS

In the domain of drone surveying, there is recently-developed photogrammetry software known as Pix4D. This software is a cloud-based storage, sharing and analysis platform for professional drone-based mapping using aerial images. Pix4D is capable of turning captured images into highly precise georeferenced 2D maps and 3D models efficiently, providing a wide range of civil engineering applications. In addition, it supports collaboration of the surveying team by allowing each authorized team member to contribute their acquired data, edit models, run analysis and obtain results efficiently in parallel with other project co-workers. The software has mobile application known as Pix4Dcapture that allows the user to attach his smartphone to the remote control device of the drone to plan the flight, determine the appropriate altitude, camera's angle, front and side overlap percentage. With Pix4Dcapture, the smartphone acts as a live feed monitor for the drone flight displaying either drone path on base map or camera view, along with correspondent information such as drone speed, remaining flight time and battery status. Afterwards, the flight data are processed in the second component Pix4Dmapper to generate 2D or 3D maps from the captured images. Pix4Dmapper geo-references the generated maps with marked GCP's and metadata of images (e.g. altitude, longitude, latitude, inclination angle of the camera, etc.) [32].

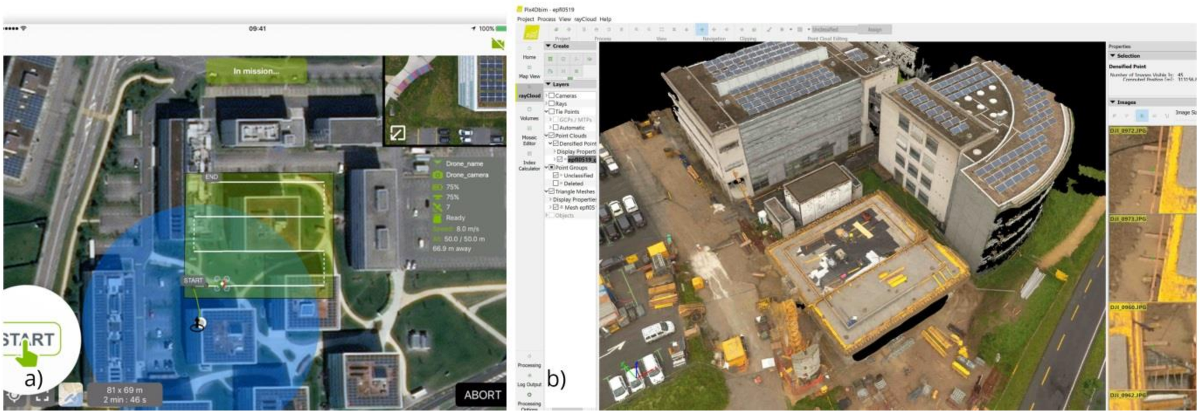

Figure 21: a) Pix4Dcapture controlling the drone flight, b) Pix4Dbim displaying 3D as-built model [32].

Pix4Dmapper has numerous AEC applications and data analysis potential, including:

- Intuitive inspection and accurate distance, area and volume measurements (with error up to ±0.40%, ±0.35% and ±1.00% respectively)
- Map features point cloud classification into five groups (ground, road surfaces (covered with asphalt), high vegetation, buildings and human-made objects)
- Digitization of 3D objects
- Contour lines, digital surface and terrain models (DSM & DTM) generation
- Thermal, Index maps generation with absolute values (e.g. vegetation and red edge)

The previous capabilities are useful for several AEC tasks such as construction site documentation, as-built monitoring, land surveying, earthworks and inspections. Additionally, there is a cloud-based server called Pix4Dbim, that overlays CAD drawings on the generated model for BIM verifications and comparisons between as-built and as-designed models [32].

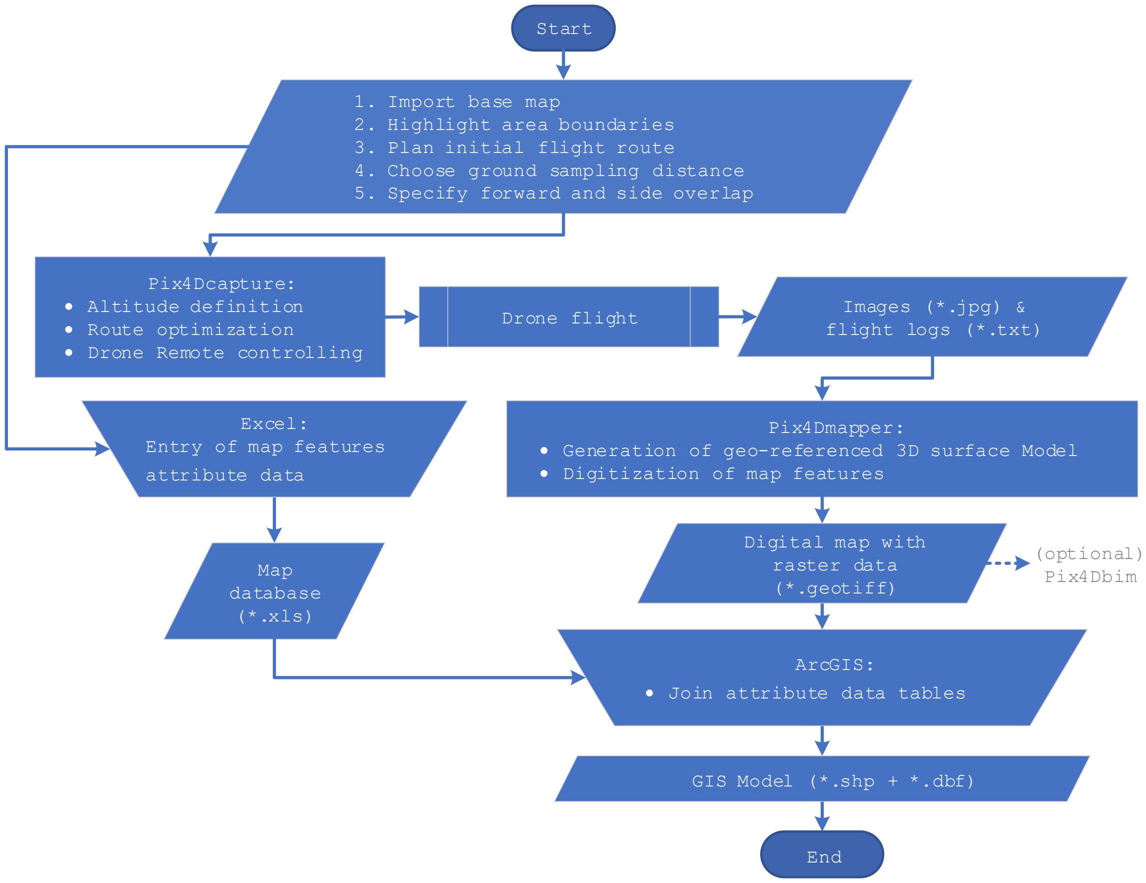

Figure 22: Flowchart of a recommended drone-based 3D GIS mapping workflow (see appendix: A1 for shape indications).

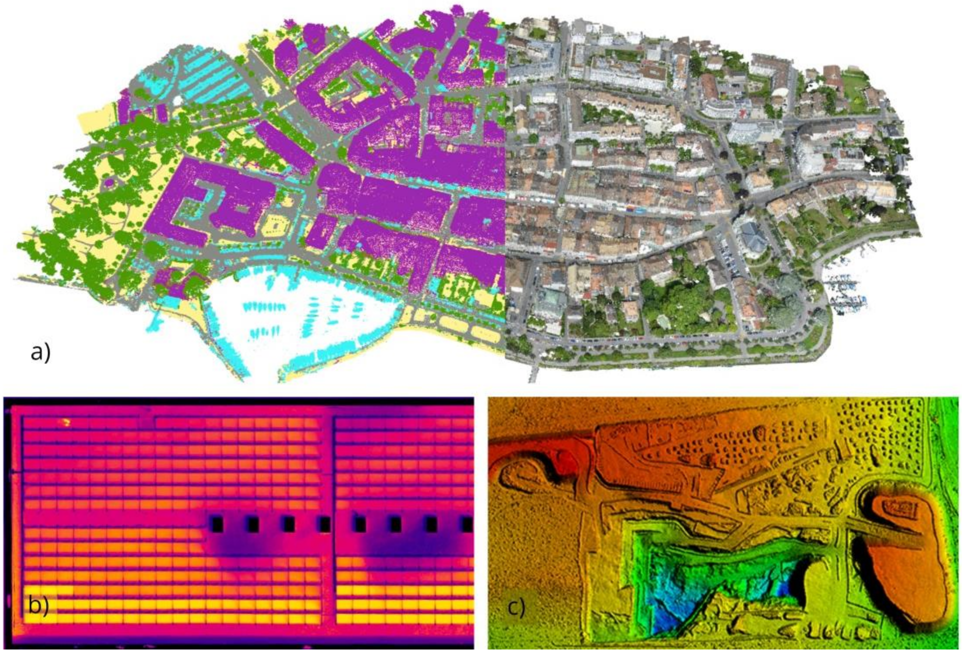

Figure 23: Analyzing capabilities of Pix4D: a) Point cloud classification and digitization (yellow: ground, grey: road surfaces (covered with asphalt), green: high vegetation, magenta: buildings and cyan: human-made objects), b) Thermal map of solar PV power plant, c) Digital surface model (DSM) [32].

Another 3D photogrammetry data management systems competing with Pix4D have been brought into focus as well to compare them and point out their capabilities and range of functionality. The systems include DroneDeploy[32], AgiSoft PhotoScan[33] and Skycatch[34]. Table 7 summarizes the points of comparison of the four drone-acquired GIS data management systems.

[32] https://www.dronedeploy.com/

[33] http://www.agisoft.com/

[34] https://www.skycatch.com/

Table 7: Comparison between drone-acquired GIS data management systems [32], [37], [38], [39].

Data Management System Capabilities		Pix4D	DroneDeploy	AgiSoft PhotoScan	Skycatch
Supported formats	*.jpg	X	X	X	X
	*.tiff	X		X	
	*.bmp			X	
	*.png			X	
	*.obj			X	
	*.las	X	X	X	
	*.xyz	X	X		
	*.ply			X	
	*.txt	X		X	
	*.csv	X	X	X	X
	*.dat	X		X	
	*.dxf			X	
Drone flight automation		X	X	X	X
Object digitization		X			
Geo-referencing		X	X	X	X
Concurrent co-working		X	X		X
Distance measurement		X	X	X	X
Area measurement		X	X	X	X
Volume measurement		X	X	X	X
Point cloud classification		X		X	
Contour lines generation		X	X	X	X
DSM generation		X	X	X	X
DTM generation		X	X	X	X
Thermal map generation		X	X	X	X
NDVI map generation		X	X	X	X
Automation scripting				X	
ArcGIS online Plug-in			X		
CAD file overlaying		X	X		
Live map			X		
User groups			X		
Mobile app		X	X		X
Cloud platform		X	X		X
Desktop platform		X	X	X	
Multi language support		X	X	X	X
Free trial		X	X	X	X
Open Source					

3.5 DEVELOPMENT POTENTIAL

The existing data management solutions for the workflows of study are quite practical. Still, they are not the preferred tools in some cases. There is still data management development potential that needs to be unlocked to serve the workflows more efficiently and cover all the project deliverables.

In the conventional structural design workflow, the development potential lies in the automation of manual tasks, such as digitization of structural elements, meshing, insertion of loads and actions, obtaining design results from Excel sheets and drawing structural plans. Despite that this conventional approach is reliable as it is controlled by human factor (e.g. structural engineers and professionals); however, it requires multiples of the time needed to complete the advanced structural design workflow according to the case study performed in section 3.3.1.

Based on the structural design methods comparison in section 3.3.1, it is concluded that the advanced structural design workflow is the development of the conventional workflow by automating the manual tasks except for the task of statical system design as it is a critical task with no specific rules and requires continuous expert judgement. In addition, the task of load insertion is not fully-automated to provide the user the flexibility to manipulate loads and actions upon desire. The architect defines the uses of each part of the building as meta-data, and accordingly the embedded standards in the structural analysis software apply the loads on the structure automatically. The role of the structural engineering team is to verify the automatically inserted loads, edit or add extra loads if needed, which is an advantage. Therefore, the existing data management solution (BIM 360™) for structural design is considered to be fulfilling the requirements of the workflow providing frictionless data exchange with minor loss of information.

Development potential in the existing data management solutions for drone-based GIS 3D mapping is relatively high, since they are not capable of several GIS functions required in the workflow of study. GIS software have numerous functionalities for analyzing spatial data that Pix4D cannot perform. The main function of Pix4D is to provide the input data for spatial analysis by processing myriad of images and generate point clouds, DSM, orthomosaic. In addition, it carries out a number of GIS functions such as measurements, volume calculations, contour lines generation, point cloud classification and vectorization. So as to harness the full functionality of GIS software, spatial data still have to be exported to a GIS software in case Pix4D does not cover all the project requirements of analysis results. Accordingly, the development suggestions for the drone-based 3D GIS mapping workflow are summarized in the following paragraphs.

It is advised to employ single software that is capable of performing the multiple functions of the drone-programming, 3D-model-generating and 3D CAD software to avoid time-wasting and loss of information caused by the unnecessary conversions. Drone photogrammetry software like Pix4D carries out all of the workflow tasks except for the advanced GIS analysis and attribute data entry. Even though, it has the ability to retain important information and meta-data while exchanging data with GIS software such as the raster data and geospatial data as it stores data on geo-references tagged image file format (*.*GeoTIFF*), and not ordinary image formats.

Developing cloud-based platform for drone photogrammetry and GIS software allowing collaborative work with dynamic link to enable seamless exchange of data between software is highly recommended. Alternatively, it is suggested to develop single software comprising both drone photogrammetry and GIS software functionality on cloud server supporting co-authoring and teamwork on the same project, since collaboration for this particular workflow is advantageous, as most of the tasks are doable in parallel (e.g. attribute data entry, digitization, drone photogrammetry in neighboring areas, etc.).

After all, it is recommended to establish built-in tools for communication and synchronization to facilitate the correspondence between the project participants and accelerate updating of maps after each adjustment without crashing the data files.

3.6 SUMMARY OF FORMAT CONVERSIONS IMPACT ON DATA INFORMATION

The final findings of this thesis are visually represented in figures 24 to 27, depicting the fluctuation of the amount of information occurs due to data exchange between the chain of software utilized in the workflow of each civil engineering domain.

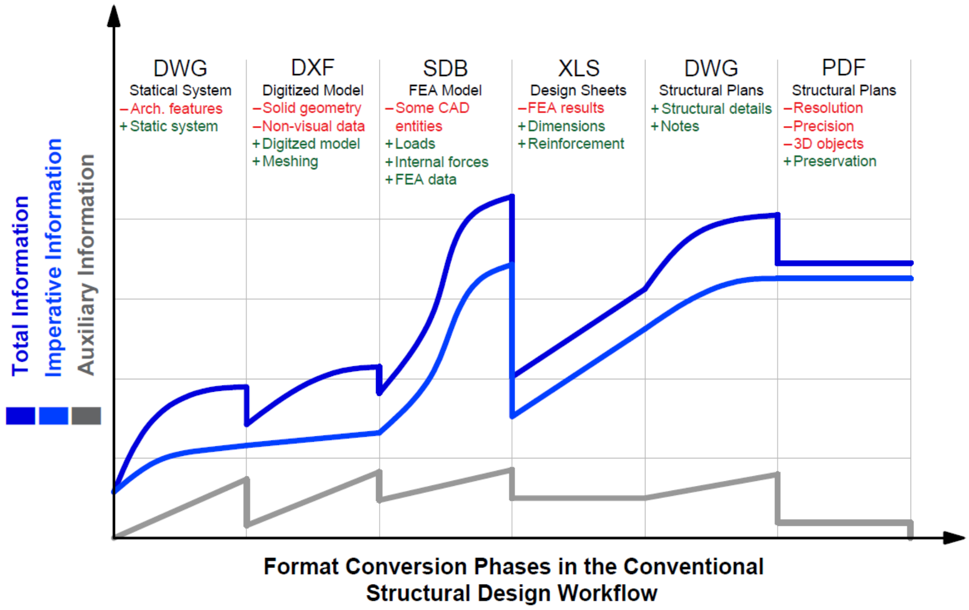

Figure 24: Relationship between amounts of information and the different format conversion phases of conventional structural design workflow.

In the description of the previous conversion-information curve, it is the relation between amount of information and the stages of file format conversion. The horizontal axis represents the format conversion phases, while the vertical axis represents the amount of three sorts of information; which are imperative, auxiliary and total information. Imperative information is the useful information for the user (e.g. FEA information for the structural designer). Auxiliary information is the useful information for the software to carry out and process the user applications (e.g. formulas in spreadsheet cells, and layer information in CAD). The total information is the summation of both types of information. The red bullet points at the top refer to the lost information in the corresponding phase. While, green ones represent the recently-added/processed information.

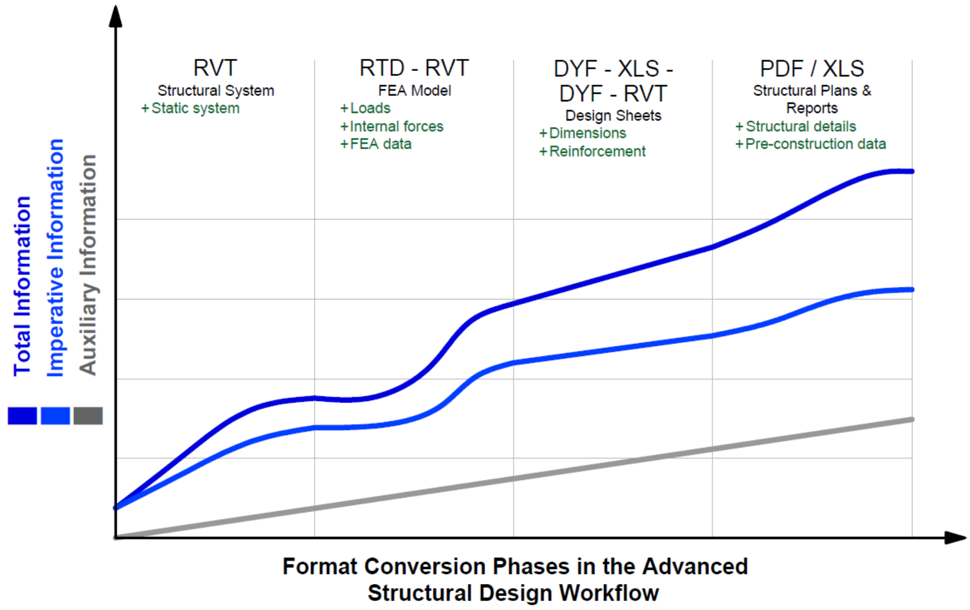

Figure 25: Relationship between amount of information and the different format conversion phases of advanced structural design workflow.

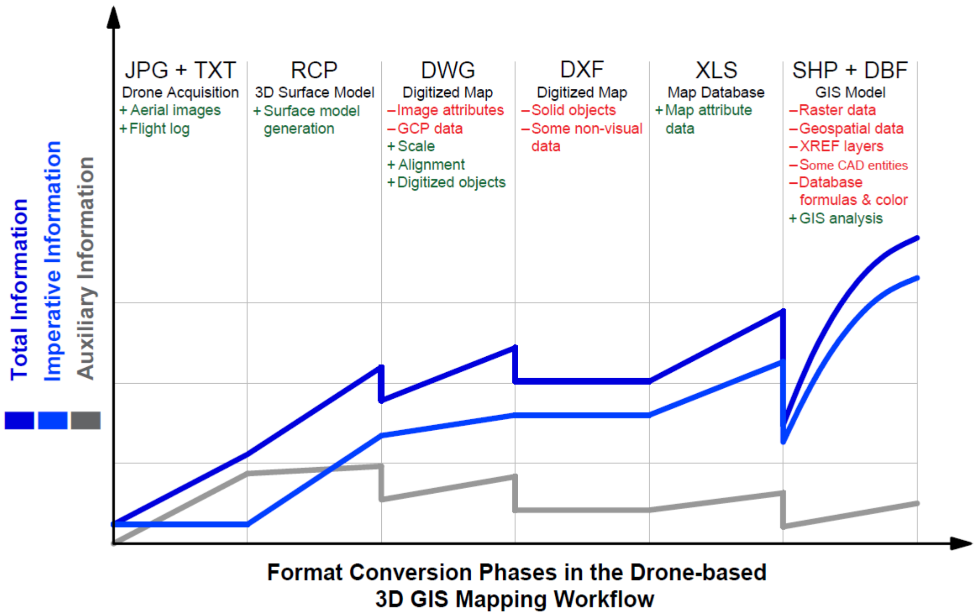

Figure 26: Relationship between amount of information and the different format conversion phases of drone-based 3D GIS mapping workflow.

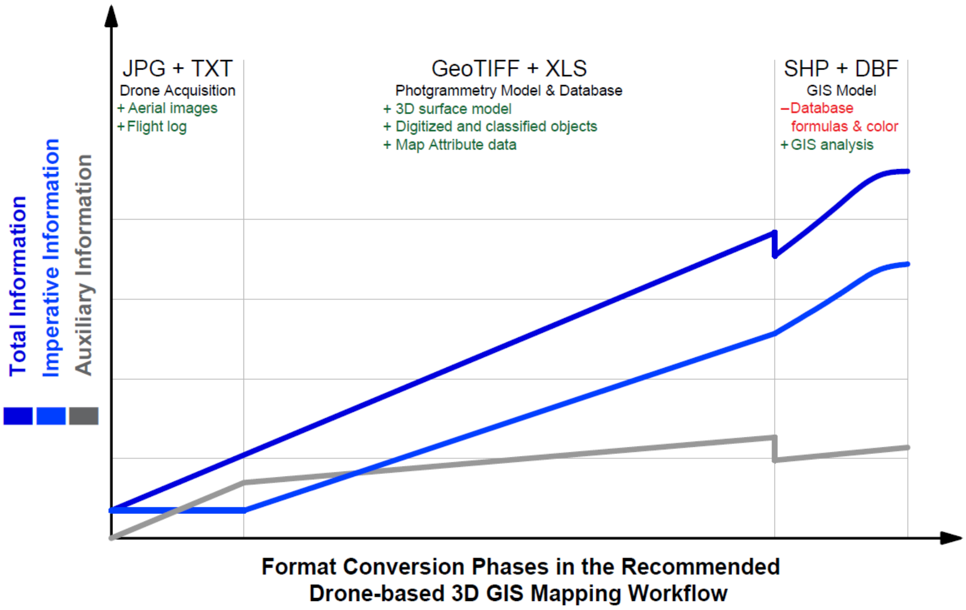

Figure 27: Relationship between amount of information and the different format conversion phases of the recommended drone-based 3D GIS mapping workflow.

4 CONCLUSION AND OUTLOOK

The thesis aimed to provide understanding about data exchange in AEC to develop efficient automation and information-preservative solutions, and distinguish the general findings that apply to entire AEC workflows. It is paramount to employ the convenient concatenation of formats for accommodating data files at the various stages of civil engineering project lifecycle. A number of file formats have been investigated in two vital civil engineering domains, namely structural engineering and land surveying. Computer-based workflows of different applications from the field have been introduced, analyzed utilizing user manuals of the involved software and verified by implementing small-scale projects to attain statistics and information about characteristics of each data file format at the process of data exchange. According to the investigation findings, the judgement has been delivered along with vivid depictions. Ultimately, prospective development suggestions have been proposed based on the analysis results.

The lost parts of information owing to data exchange procedures in AEC have been identified and verified with the aid of worked case studies. Moreover, automation methods have been discussed. Accordingly, it was concluded that avoiding native data exchange through neutral formats, avoiding fragmented workflows/software and utilizing workflow software products of the same vendor would typically lead to lower amounts of lost information and manual working hours.

So as to support this research, two main issues need to be considered, which are the running costs of the cloud-based collaborative solutions and the extent of distributed data security. Further proposals to increase the efficiency of cloud-based data management solutions have to be researched as well. In addition, it is advised to investigate German alternatives for the studied software to characterize their file formats and data exchange consequences, and thus provide development concepts. Furthermore, it has been discovered that integration of GIS with BIM is of considerable research potential, despite their expansive range of capabilities in collaboration with each other. It would be a significant transformation in the future of civil engineering, if such individual software is developed.

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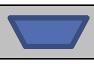
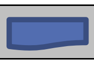
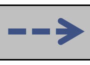
APPENDIX

A1

Table 8: Flowchart shapes indication.

Shape	Indication	Use in this thesis
	Terminator	Start/end of workflows
	Data (input/output)	Data could be manual or automated
	Process	Indicate processes performed by computer
	Pre-defined process	Refer to processes out of the scope of studied domain
	Manual operation	Indicate tasks performed by the user
	Condition	For decisions, checks or conditions
	Document	Documents could be drawings, models, maps, reports, etc.
	Connector	Lead to obligatory processes
	Option connector	Lead to optional processes