A Semi-Automatic Geometric Digital Twinning Approach of Existing Buildings based on Images and CAD Drawings

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ABSTRACT

Despite the emerging new data capturing technologies and advanced modeling systems, the process of geometric digital twin modelling for existing buildings still lacks a systematic and completed framework to streamline. As-is Building Information Model (BIM) is one of the commonly used geometric digital twin modelling approaches. However, the process of as-is BIM construction is time-consuming and needed to improve. To address this challenge, in this paper, a semi-automatic approach is developed to establish a systematic, accurate and convenient digital twinning system based on images and CAD drawings. With this ultimate goal, this paper summarises the state-of-the-art geometric digital twinning methods and elaborates on the methodological framework of this semi-automatic geometric digital twinning approach. The framework consists of three modules. The *Building Framework Construction and Geometry Information Extraction* (Module 1) defines the locations of each structural component through recognising special symbols in a floor plan and then extracting data from CAD drawings using the Optical Character Recognition (OCR) technology. Meaningful text information is further filtered based on predefined rules. In order to integrate with completed building information, the *Building Information Complementary* (Module 2) is developed based on neuro-fuzzy system (NFS) and the image processing procedure to supplement additional

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building components. Finally, the *Information Integration and IFC Creation* (Module 3) integrates information from Module 1 and 2 and creates as-is Industry Foundation Classes (IFC) BIM based on IFC schema. A case study using part of an office building and the results of its analysis are provided and discussed from the perspectives of applicability and accuracy. Future works and limitations are also addressed.

Keywords: Geometric digital twinning; Industry Foundation Classes (IFC); Building Information Model (BIM); Optical Character Recognition (OCR) technology.

1. Introduction

With the increasing complexity of buildings in recent years, information regarding the buildings and indoor activities is required to support Operation & Maintenance (O&M) management [1]. Hence, efficiently accessing up-to-date information in operating and maintaining an existing building is vital. Consequently, maintaining the integrity and comprehensiveness as-is information is one of the most important tasks in the O&M phase.

The Digital Twin (DT) concept is a promising solution. It is predicted that half of the large industrial companies will use DTs by 2021, resulting in those organisations gaining a 10% improvement in effectiveness [2]. In the architecture, engineering, construction and facility management (AEC/FM) sectors, DTs have promising potential in the context of smarter management (e.g., data and information management). The National Infrastructure Commission – in their report 'Data for the Public Good' – set forth a number of recommendations for the government with regard to digital infrastructure [3]. One of those key recommendations was to develop a so-called 'National Digital Twin'. A DT is a dynamic digital representation of an asset/system and mimics its real-world behaviour, which combines different data resources, integrates intelligent functions (e.g., AI, machine learning, data analytics etc.) and digital models (e.g., BIM) to represent and predict the current and future conditions [3,4,5]. In the process of creating DTs, the geometric digital twinning (known as digital modelling) is an essential and foremost step. The current situation, however, is that the majority of existing buildings have only 2D drawings and text documents in hard-copy formats and/or in electronic CAD formats. These documents may not keep updated in time in the O&M phase [6]. Hence, missing or incorrect building information would lead to inefficient decision making in management processes, or may cause significant delays in responding occupants' daily requests and even emergency reports [7]. There is an urgent need for effective digital twinning approaches to support modelling exiting buildings conveniently and effectively in the O&M phase.

Building Information Model (BIM) has been proved to be an intelligent and parametric digital twin modelling approach and could support activities throughout the life cycle of a building, including facilitating design, construction, and operations and maintenance of facilities [8]. BIM is usually chosen as the digital model of a building DT [9]. It has been proved that BIM has wide implementations in building projects, such as design authoring, existing conditions modeling, maintenance scheduling etc. [10]. In addition, previous research has presented that implementing BIM in O&M can significantly minimise information loss and remarkably improve the efficiency of daily management [11]. However, most existing buildings do not have complete as-is BIM [12]. In recent decades, numerous techniques and approaches have been used and developed to effectively and efficiently construct as-is BIM for existing buildings [6,12-17]. These advanced technologies (e.g., digital cameras, laser scanning technologies and tagging) have significant functions in accelerating the speed of as-is BIM construction and further improved the accuracies of their resulting models. Moreover, various approaches (e.g., Structure from Motion (SfM) [17] and Simultaneous Localisation and Mapping (SLAM) [16]) have used in semi-dense/dense scene constructions from trajectory computation through images/videos. However, these models are far to achieve the completed BIM, which are object-oriented digital models and not only represent the geometries of existing buildings. The point cloud models produced by laser scanners or the semi-dense/dense scenes generated by image-based methods would include thousands of points from the target buildings and create geometries with high efficiency. But it still needs in-depth processing steps to remove redundant points and organise its internal logic and relationship. Moreover, the device needed (i.e., laser scanner) usually comes at a relatively high cost [6,12]. In general, research in past decades showed that no single approach could generate a 3D geometry model for an existing building and further present its topology structure and semantics at the same time yet [15].

In addition, besides the advanced approaches and technologies mentioned above, the existing CAD drawings are also the effective and reliable resources for assisting digital twinning, especially as-is BIM construction, which store rich building information including topological and geometrical aspects [15]. Moreover, prior hand drawn blueprints can also be scanned and saved in digital formats, and further processed and extracted useful information based on image-based methods [18]. However, the layout plans or even original functions of existing buildings might be changed in O&M phases. Building information (e.g., walls and zones) saved in construction drawings cannot represent the real as-is conditions and be the completed references for as-is BIM construction. Even so, CAD drawings are still extremely significant in extracting structural information (e.g., columns and beams), which would remain unchanged in common situations. Buildings nowadays would usually be decorated in O&M phases (including building interiors and external facades). For instance, in order to hide pipes or beams, the ceilings are commonly decorated with suspended ceilings. Hence, it is hard to recognise or distinguish structural components from their surrounding environments simply using images or point clouds. In addition, structural components (i.e., columns and beams) would usually be hidden inside the walls, as shown in Fig.1. These conditions would make it much harder to recognise the building components completely. Consequently, it would be flexible and very effective in recognising information on structural components through using CAD drawings.

Hence there is a clear need for an effective, convenient and applicable approach to assist geometric digital twinning (e.g., constructing as-is BIM in IFC) based on CAD drawings and images and further keep updating digital models during O&M phases.

[**Insert:** Figure 1 Structural components in existing buildings (photos taken by the author)]

2. Literature Review

In recent years, various methods have been developed to construct digital twin models, especially as-is BIM [6,12]. They mainly include the image-based approach, the laser scanning-based approach and others (e.g., radio-based technologies and manual methods).

Laser scanning [20-22] technologies are able to generate 3D point clouds with high geometrical accuracy. Lu and Brilakis [19] delivered a slicing-based object fitting method that can generate the geometric digital twin of an existing reinforced concrete bridge from four types of labelled point clusters. However, their research was limited to bridge areas. The resulting 3D point cloud models of buildings can be further converted to as-is models. Although laser scanning is considered as the top-prioritised method for constructing as-is BIM nowadays [6], there are several limitations of laser scanning-based approaches when implemented in O&M phases. Laser scanning cannot provide semantic information (e.g., materials) for further creating BIM

[17] and would not be suitable for daily O&M model updating due to their relatively high costs, inconvenient operations and high possibilities of data loss [6].

Automatic or semi-automatic BIM construction approaches have also been studied using radio-based technologies, tags or manual methods. When using radio frequency identification (RFID) technology [23-26] in existing buildings, it is needed to install the tags of RFID on target objects and be scanned using relevant readers within a predesigned range. Valero et al. [27] proposed an innovative approach using laser scanners and RFID to automatically construct 3D basic-semantic models of inhabited interiors. These technologies have shown promising opportunities for recording materials and facilities in the daily O&M management environments [28]. However, installation, scanning, and maintenance are all required during their application periods, which are labour-intensive and need trained workers.

Comparing to laser scanning-based approaches and radio-based technologies, image-based approach and its integration have gained increasing attention in recent years, and have been used as an economical, feasible and promising alternative in O&M phases. Image-based as-is BIM construction approaches can be further divided into three key steps (i.e. (1) data capturing and processing, (2) object recognition, and (3) as-is BIM construction) [2]. Various image-based systems have been developed to facilitate this construction process or focus on improving particular areas (e.g., automated recognition resources [29-33] and classification of materials [34-36]). This study would analyse image-based construction approaches according to four main categories of inputted resources (Fig.2).

From images/video: In general, image-based construction approaches (the inputs are images or videos) can be categorised into image-based point cloud construction approaches and image processing approaches [29]. The image-based point cloud construction approach generates semi-dense or dense scenes using thousands of overlapping images via matching features. Then, semantically-rich as-is 3D models/as-is BIM could be further created based on these resulting point cloud models. Multi-view stereo (MVS) and Structure from Motion (SfM) are the two most widely used and successful methods of constructing 3D point models for target scenes. Furukawa et al. [37] created an automated 3D reconstruction and visualisation system for building interiors using MVS and SfM. Golparvar-Fard et al. [17] also implemented SfM and constructed 3D point models for monitoring construction sites. Furthermore, they [38] proposed a new image-based 3D reconstruction pipeline for analysing the energy performances of existing buildings, which consisted of Graphic Processing Unit (GPU)-based SfM and MVS algorithms. A 3D thermal point cloud model of the target existing building could be created through using their developed 3D thermal modelling algorithm. Similar to the SfM, the feature-based monocular simultaneous localization and mapping (SLAM), improved by Mur-Artal and Tardós [16], could achieve better semi-dense/dense scene constructions based on trajectory computation. In order to create a dense point cloud, Brilakis et al. [39] achieved progressive 3D reconstruction of infrastructure with videogrammetry. Although image-based 3D point cloud models and verisimilar scenes can be constructed automatically and effectively nowadays, building objects, their topological information and further the completed BIM still need to be recognised and generated manually or relying on other additional methods.

Image processing approach would mainly use image processing algorithms to detect geometric primitives (e.g., points and patches, edges, and lines) and key features (e.g., colour) from collected images [40]. Dimitrov and Golparvar-Fard [8] thus proposed a new vision-based method for material classification through using a joint probability distribution of responses from a filter bank and principal Hue-Saturation-Value colour values. Xiong and Huber [41] identified wall-like objects by combining a conditional random field (CRF) model with the contextual information of indoor environments. Although image-based approaches have been rapidly developed and implemented in the Architecture, Engineering & Construction (AEC) industry, the completed as-is BIM cannot be generated via a single approach (i.e., only using images or videos), shown in Fig.2.

From CAD drawings/2D maps: CAD drawings are widely used in the AEC industry. Moreover, texts, symbols and predefined drawing rules of CAD drawings all could be key features for being extracted and analysed using image processing technologies, computer vision tools and pattern recognition methods [42]. Dosch et al. [43] proposed a complete system of analysing architectural drawings using image processing technologies and feature extraction. This system could create 3D models from 2D floor plans, but it didn't cover any topological information. The semi-automatic detection method conducted by Domínguez et al. [44] was workable for both straight and circular segments, and further included floor topology based on the wall adjacency graph (WAG). Gimenez et al. [15] applied pattern recognition and feature extraction in extracting information from scanned 2D floor plans. Then, they generated the Industry Foundation Classes (IFC)-compliant 3D models according to extracted geometrical and topological information. However, their system didn't contain the third dimension (e.g., the height of the building and openings). Text analytics and text mining are also applied in analysing CAD drawings. For instance, Yu and Hsu [45] developed a prototype system, which was Content-based CAD Document Retrieval System (CCRS), to retrieve key texts from CAD documents. Even if functions and layouts of existing buildings would be changed over time, CAD drawings are still important in assisting as-is modeling.

From 3D geometry models: Some researchers intended to automate the process of constructing BIM from 3D geometry models. Nagel et al. [46] developed a two-step strategy, which incorporated CityGML as an intermediate stage between 3D graphics models and IFC/BIM. *From images + laser scanner:* The integrated applications of laser scanning and image-based 3D construction techniques have also been proposed by some studies [47-49]. Since the laser-scanned point clouds may appear information loss at spatial discontinuities [50], image-based approaches can be complementary for laser-scanned approaches. However, as highlighted above, current laser-scanned approaches are not suitable for updating as-is conditions in daily O&M, considering their time-consuming and tedious process [51].

In general, based on extensive literature review [6,12,20,48], challenges in the automated creation can be summarized in three categories: (1) additional efforts and costs required to collect enough resources; (2) complex processes of processing data and needing additional technologies; and (3) unavoidable extra data errors and inaccuracy appearing during the construction processes. Comparing with previous analysis including input resources (e.g., images, point clouds etc.) and generation process, it still needs to develop a systematic, accurate and convenient approach to construct geometric digital twin (i.e., as-is BIM) for existing buildings and also has potential properties used for recording as-is conditions and daily updates in O&M management.

[**Insert:** Figure 2 The brief summary of publications about creating various models with different information level using image-based approaches]

3. Research Methodology

[**Insert:** Figure 3 The systematic framework of the proposed system]

In order to optimise and streamline this process, a reliable, systematic, accurate and convenient approach for representing digital models is imperative for existing buildings. As shown in Fig. 3, the developed system of geometric digital twinning (creating an as-is IFC BIM) can be divided into three main modules: 1) building framework construction and geometry information extraction based on CAD drawings; 2) building information complementary using collected images and as-is condition records; 3) information integration and IFC BIM creation. Through this system, object's relationships with others are identified and a semantically rich BIM based on IFC schema is constructed.

3.1 Module 1: Building Framework Construction and Geometry Information Extraction

In general, drawing symbols in architectural and structural drawings can be different and represent different meanings from each other. For instance, different countries may apply different drawing standards. Furthermore, decorations and functions of space arrangements would be changed over time. In order to make this study more applicable and follow the unified rules of drawings, this study chose column grids and their corresponding numbers as the basic symbols, which are the most commonly used structural symbols in CAD drawings around the world (as shown in Fig.5). Moreover, in general situations, basic structural components of existing buildings would not be changed in O&M phases, which would be a fixed reference for all existing buildings.

The general process of extracting structural components from CAD drawings is presented in Fig.4. The main functions of Module 1 are designed as follows: 1). CAD drawings pre-processing step; establishing the grids and blocks through recognising special symbols (i.e., column network symbols) in a floor plan. Then, 2) Text information filtration step; filtering the text information from the scrambled backgrounds. 3) Text information extraction step; extracting text data using the Optical Character Recognition (OCR) algorithm from two directions and saving them in Excel formats. Step 2 and 3 aim at selecting meaningful text items from the CAD documents based on predefined grids and blocks (step 1). Through this process, the resulting structural information would be extracted and provide foundations for creating structural IFC BIM in Module 3.

[**Insert:** Figure 4 The general process of extracting text information from CAD drawings]

[**Insert:** Figure 5 CAD drawings preprocessing step (a) Detecting circle symbols from CAD drawings and (b) creating blocks and grids based on extracted symbols]

In the CAD drawings pre-processing step (Fig.4), grids could be defined and created according to extracted symbols (i.e., circles) in the horizontal and vertical directions (Fig.5(a)). The symbols would be detected using the circle Hough transform (CHT). The original locations of grids would be determined by the centre of each circle symbol. The CHT is an effective technique used in Digital Image Processing, for detecting circular objects from images [52]. After detecting symbols, corresponding blocks and grids would be created to indicate the target areas (blocks) and grids (Fig.5(b)).

In the text information filtration step (Fig.4), first, the backgrounds (i.e., all vertical and horizontal lines) of the original CAD drawing would be removed (Fig.6(a)). However, noises (marked by red boxes in Fig.6(a)) would still appear in the whole processed image, which could affect and decrease the recognising accuracy of text information extraction. Hence, in order to get the pure text image without noises, this study innovatively introduced the mathematical morphology (MM) to fix the regions of text information and further remove the noises. The mathematical morphology is a theory and technique for analysing and processing of geometrical structures based on set theory, lattice theory, topology, and random functions [53].

[**Insert:** Figure 6 Text information filtration step (a) the sample image of eliminating the background (i.e., the text image with noises); (b) the sample image of the region plot; (c) the sample image of the text image without noises; (d) the four types of extracted text information appeared in a CAD drawing]

In order to get the region plot and figure out the locations of different texts (Fig.6(b)), two operators in MM are introduced, namely dilation and erosion operators. The erosion of the binary image A by the structuring element B is defined by:

$$A \ominus B = \bigcap_{b \in B} A_{-b} \qquad (1)$$

The dilation of A by the structuring element B is defined by:

$$A \oplus B = \bigcap_{b \in B} A_b \tag{2}$$

The region plot would be produced by going through the dilation operator and then being erased by erosion operators. Afterwards, the image (i.e., the text image with noises (Fig.6(a))) would be matched with the resulting region plot (Fig.6(b)) to distinguish text information and export the pure text image without noises (Fig.6(c)).

Furthermore, in the text information extraction step, text information would be extracted based on the OCR algorithm and saved in different Excel spreadsheets according to their relevant grids and blocks in CAD drawings. The function of the OCR algorithm is converting typed, handwritten or printed texts saved in image formats into encoded text [58]. This step aims to identify text items from CAD drawings and transfer them into machine-encoded text formats. Through this step, text information would be separated from original CAD drawings and further prepared for the subsequent module.

Four types of text information would be extracted and saved separately into four different Excel spreadsheets according to their locations in the CAD drawings. They include (Fig.6(d)): (1) Vertical 1: the text information locates inside the blocks and the directions of them are arranged vertically; (2) Horizontal 1: the text information locates inside the blocks and the directions of them are arranged horizontally; (3) Horizontal 2: the text information locates above the grids and the directions of them are arranged horizontally; and (4) Vertical 2: the text information locates above the grids and the directions of them are arranged vertically. The text information extraction and classification are also based on the region plot produced in the 2nd step.

Because extracted text information saved in Excel spreadsheets is unstructured data, the keyword-based text analytics method would also be used to assist in figuring out key meanings and information saved in large amounts of extracted textual documents. Keywords and their frequencies are used in the analysis process of this approach. Based on requirements of different design organisations, keywords in CAD drawings for structural components can be different. Hence, selection and summary of keywords in CAD drawings would be depended on different practical situations. For instance, the keywords of beams in Fig.7 use ‘BM’. There is no keyword for the column, but sizes (i.e., length and width) of columns can be identified and extracted based on their locations and frequencies in CAD drawings. The following statements are the outline of computing and extracting key information for structural components.

Case 1) If structural components (x) have definitions of keywords (K_x) in CAD drawings (such as beams with 'BM' in Fig.7), then search the corresponding keywords (K_x) in text information documents. Key information (I_1(x)) of structural components (x) is defined as the following:

$$I_1(\text{x}) = \#(\text{component in document D and has keyword } K_x)$$

Case 2) If these structural components (x) don't have definitions of keywords (K_x) in CAD drawings, then they will be evaluated if their geometry information is complete. If they are complete, the text information (i.e., length and width) will be assigned into column components based on their locations in Excel documents. This case will be discussed in detail in the case study.

Case 3) If these structural components (x) don't have definitions of keywords (K_x) in CAD drawing and they are incomplete text information. Then, this study would calculate the frequencies (F_x) with the same value (i.e., length or width) appeared in the same row (R) in that single document (D), and list the ranks (R_x) of other components according to their frequencies (F_x). The key information (I_3(x)) of structural components (x) is defined as following:

$$I_3(\text{x}) = \#(\text{component in the same row R and has the frequency } F_x \text{ \& rank } R_x)$$

Text analytics in this part enables to detect detailed structural information based on four extracted Excel documents. The geometrical information and location information would be used in creating the IFC BIM in Module 3.

[**Insert:** Figure 7 Samples of building components in CAD drawings]

3.2 Module 2: Building Information Complementary

This image-driven information complementary system contains two functions: an object recognition subsystem for recognising building components (i.e., columns, beams, windows, doors, and walls), and a material recognition subsystem for recognising surface materials. First, when inputting an image, the necessary data can be extracted from the input image via the primary definition for the object and material recognition. The building components recognition function then automatically recognises the types of extracted objects based on the developed neuro-fuzzy network. Meanwhile, the surface materials recognition function further recognizes the materials of the objects by following the image classification procedures supported by the extensible texture library. Finally, the objects and their material information would be integrated in the form of a txt file, which would be an output from Module 2. It would be further used in creating IFC BIM in Module 3. The overall workflow of this module is presented in the authors' publication [54], and each step and the detailed evaluation results are also published in it [54].

3.3 Module 3: Information Integration and IFC Creation

IFC is a widely used object-oriented open standard data schema for BIM and is a semantical model, including components, attributes, properties and relationships of a building [55], initiated by buildingSMART in 1994. Currently, it has been widely used and became a formally registered international standard as ISO/PAS 16739. IFC could support geometric representations and rich semantic information. In the IFC geometric representation, Constructive Solid Geometry (CSG) representation presents a geometric shape based on the CSG model [56]. A solid model represented by CSG is defined as combining a collection of primitive solids using certain operations. The advanced geometric representation can also be created using the CSG with enhanced profile types.

Furthermore, the IFC model implements the composition/decomposition to represent the relationship among the building elements. The aggregation relationship *IfcRelAggregates* is a special type of the general composition/decomposition relationship. Each *IfcRelAggregates* relationship would introduce a layer of the relative coordinate system. Fig.8 presents the aggregation relationship from the *IfcProject* to a common element such as *IfcWall* of a simplified building structure. The *ObjectPlacement* of IFC elements determines the translation for the coordinate systems. In the local coordinate system translation (LCST), the origin would relocate and the directions of the axes (i.e., the x axis, y axis, and z axis) would be calculated based on the vector components of each direction. The aggregation relationship starts from the top to the bottom, while, the translation process should conduct from the bottom to the top [57]. This study would follow the designed IFC structure and focus on the level of *IfcBuildingStorey* (Fig.8). *IfcBuilding* will be covered in future study.

[**Insert:** Figure 8 Aggregation relationship amongst building elements (extended based on [57])]

4. Case Study

The target building for evaluating the proposed geometric digital twinning approach is chosen to be the composite building selected from the campus of the University of Hong Kong (HKU). The CP1 to CP5 storeys of the composite building are parking places. Hence, it is convenient and open for the researcher to collect pictures. The input image sets were collected and generated via using handheld cameras (i.e., Nikon 7100). The CAD drawings were collected from the service department in HKU.

4.1 Data Collection

Three sources of data, namely building background information, CAD drawings and image information, were collected in this case study as input resources (Fig.9).

1). Building background information of the composite building, including, but not limited to, the building's overall statistics, general structure, history, and so on, were gathered from interviews with building service management and HKU building department management staff, review of documents, and recorded files.

2). The CAD drawings of the composite building, including the overall plan and the structural drawings of the target storey (Fig.9).

3). The collected image information should be collected following the predesigned route. For instance, as shown in Fig.9, the collected images of the target storey were collected following the route from (1) to (6).

[**Insert:** Figure 9 The input resources (i.e., the CAD drawing and images) of the CP2 storey of the composite building]

The aforementioned three sources of data were analysed respectively, and described as follows:

1). The building data gathered were categorized and captured using a structured form for each case study, which provided the contextual background for the existing building better understanding of other data and further benefitting for the daily O&M management.

2). The CAD drawings and collected images were the main sources of data for this research. This case study would use the structural drawings of the target building, which recorded the basic information of structural components. Since structural components were recorded, the framework (including the beam objects and column objects) of the target building would be obtained, even if the functions and arrangements of the target storey might be changed during the O&M phase. The collected images would record the as-is conditions of the target building, which would supplement additional objects (e.g., walls, windows) and modify the layout used currently.

Meanwhile, in order to achieve the convenience and practicability of generating IFC BIM, the basic principle of the proposed approach is to use data sources, which are easy and convenient to be accessed and obtained, and further record the context of the as-is conditions. Hence, this study used CAD drawings and collected images as the main inputs.

4.2 The Analysis of Module 1 and 2

The system of Module 1 Building Framework Construction and Geometry Information Extraction was developed in Visual Studio using c# language. In this system, the OCR recognition library used in this study was provided by Asprise OCR (https://asprise.com/royalty-free-library/ocr-api-for-java-csharp-vb.net.html). This section used the collected CAD drawings to evaluate the accuracy of extracting text information (Fig.10).

[**Insert:** Figure 10 The CAD drawing and its extracted symbols and keywords]

The developed prototyping system is presented in Fig.11. Each step designed in section 3.1 is also presented in detail (see Fig.11). After creating the grids and blocks based on the pre-processing step, in the following text information filtration step (as shown in Fig.12 and 13), the intermediate produced plots (e.g., the region plots processed through erosion operator and dilation operator) were generated for obtaining pure text images without noises and further assisting in distinguishing horizontal and vertical texts in the text information extraction step. The horizontal and vertical region plots (Fig.13) can be generated based on the region plot (Fig.11 (4)) and aim at distinguishing horizontal and vertical texts from the pure text images. In the text information extraction step, texts would be recognised and extracted using the OCR technology. In order to keep the robustness and increase the accuracy of the proposed system, texts would be recognised via a block-by-block method (Fig.14), other than directly processing the whole drawing. Four Excel files would be produced based on the locations of the text information in CAD drawings (Fig.15). In these four Excel files, 118 out of 122 words (including English letters and numbers) were recognized successfully and 12 out of 12 symbols (i.e., " × ") were recognised. The errors mainly appear in mixing up the character "M" with the symbol " × ", when recognizing the symbol " × ". The accuracy of recognising English letters can achieve over 95% by using this system and the calculation time is less than 15 seconds. These four Excel files would be the input in Module 3 for generating IFC BIM.

[**Insert:** Figure 11 The prototyping system for processing CAD drawings (Module 1)]

[**Insert:** Figure 12 The intermediate produced plots for processing CAD drawings following the designed process in Module 1 (see also section 3.1)]

[**Insert:** Figure 13 The intermediate produced region plots for processing CAD drawings following the designed process in Fig.11]

[**Insert:** Figure 14 Text recognition using the OCR technology (block by block)]

[**Insert:** Figure 15 The four created Excel files]

In general, Module 1 mainly consists of three steps and it aims to provide a convenient and applicable process to produce four Excel files from CAD drawings and further support constructing as-is IFC BIM in Module 3, without requiring extra high cost and skilled workers.

For Module 2, based on the created coordinate system from Module 1, images would be ranked in order of their taken positions (Fig.9). The complementary building objects (e.g., walls and doors) would be extracted and recognised based on Module 2, referring to section 3.2. A txt file (integrating recognised objects and their materials information) would be produced as the input in Module 3 for generating IFC BIM.

4.3 The Analysis of Module 3

Following the designed methodology framework (section 3) and the collected data sources, four Excel files would be produced to generate the building framework through Module 1. The information in four Excel files includes the geometrical information of beams and columns and their locations. When these Excel files were inputted into the Module 3, it would automatically form a coordinate system for the whole storey based on information extracted from the CAD drawings (i.e., from the pre-processing step in Module 1) (Fig.16). The point of origin (Fig.16) in this coordinate keeps the same with the point of origin in Module 1. Moreover, the references for creating x-axis and y-axis of this coordinate are from the text information saved in Excel files (Fig.17). Hence, the completed coordinate system of this target storey would be as shown in Fig.16. Furthermore, a txt file would be produced from Module 2 as another input. This generated txt file includes building complementary information, namely object types, geometry sizes, surface materials, local and global locations.

[**Insert:** Figure 16 The coordinate system of structural components for the target building storey]

[**Insert:** Figure 17 The information resources of creating the coordinate system (from the Excel files of "Vertical 1" and "Horizontal 1")]

Module 3 includes two parts: information integration and IFC creation. The system of Module 3: Information Integration and IFC Creation were developed in Visual Studio using c# language. This IFC Creation part (Fig.18) is developed to create the IFC BIM, using *ifcengine* (http://www.ifcbrowser.com/). Both IFC2×3 and IFC4 are chosen to be the basic schema standards (Fig.18).

In the information integration part of Module 3, four excel files from Module 1 and the txt file from Module 2 are inputted. All information from Module 1 and 2 would be integrated based on the designed structure in Fig.19, which leading by ID numbers (1 to 5), and converted into a new txt file (i.e., the txt file is the one with the mark "*" in Fig.18). As shown in Fig.19, the ID number is the primary identifier for each object (e.g., 1 stands for the column object). In addition, other information, including the name, locations, geometrical size and material type of each recognized object, are also written in this output txt file following the designed structure in Fig.19. The resulting txt file would include the complementary information from Module 2 and the framework information from Module 1 and an example of the created txt file is shown in Fig.20. Then, when inputting the new created txt file into IFC creation function, the IFC BIM for the target building storey would be generated automatically based on the predefined format and the IFC schema (e.g., IFC4).

In the IFC creation part of Module 3, the process of IFC BIM generation would also start from the bottom to the top (based on the analysis of section 3.3 and Fig.8). This Module would create IFC BIM objects firstly. For example, the *IfcColumnStandardCase* is a column entity in a BIM in IFC. The related information about this column, such as its location (*IfcLocalPlacement*), material (*IfcMaterialProfileSetUsage*), shape (*IfcProductDefinitionShape*), and other semantic information could also be parsed and included. If the wall has one or several doors/windows inserted, the opening elements are needed to be generated firstly. Then, the related elements could be inserted into the opening. In the txt file in Fig.19 and 20, the "R" represents the relationship between the wall element and the door or window element. For instance, the door opening is created within the wall by *IfcWall(StandardCase)* o-- *IfcRelVoidsElement* --o *IfcOpeningElement*, then the door is inserted within the opening by *IfcOpeningElement* o-- *IfcRelFillsElement* --o *IfcDoor*. The numbers of "X1 Y1 Z1" in the txt files (Fig.19) presents the locations of each IFC BIM objects (i.e., doors and windows) in the local coordinate of the target wall object. After creating the IFC BIM objects, all objects would be located in the correct positions. The numbers of "X2 Y2 Z2" in the txt files (Fig.19) presents the locations of each IFC BIM objects in the global coordinate of the target storey (referring to the coordinate system in Fig.16). Then, based on each LCST, all created IFC BIM objects are further placed into the predefined coordinate system created in Figure 16.

In the IFC data schema aspects, firstly, in order to generate IFC BIM objects, objects are recognized firstly through their ID numbers (Fig.19). Then, the corresponding IFC BIM objects are generated automatically based on different data structures of building object types. In detail, for structural building components, *IfcColumnStandardCase* is used for modelling columns; *IfcBeamStandardCase* is used for beams; and *IfcWallStandardCase* for walls. For windows and doors, *IfcDoorStandardCase* is used for modelling door objects and *IfcDoorTypeOperationEnum* is defined as the *Single_Swing*. While, *IfcWindowStandardCase* is used for window objects and *IfcWindowTypePartitioningEnum* is defined as the *Single_Panel*. For the solid object modelling of topological/geometric representations in the IFC data model, this study used SweptSolid modelling as an example, one of the standard geometric representations. Lastly, in the process of 3D modelling, using the SweptSolid modelling method to create solid objects, the profile of a standard geometric representation is extruded along an axis to form a complete geometry.

In general, the whole semi-automatic geometric digital twinning approach of existing buildings based on images and CAD drawings can be summarised as Fig.21. Three Modules should work together (Fig.21): the building framework construction and geometry information extraction module defines the location of each structural component through recognising special symbols in a floor plan and then extracting text data from CAD drawings using the OCR technology; the building information complementary module is thus developed based on NFS and image processing procedure to provide complementary building information [54]; and the information integration and IFC creation module integrates information from Module 1 and 2 and create as-is IFC BIM. Fig.22 shows the sample of the created IFC file and the corresponding generated IFC BIM of a regular storey, which is opened in IfcViewer. When the information from Module 1 and 2 are integrated, the IFC BIM would be automatically created for the target building storey using this approach.

[**Insert:** Figure 18 The IFC generation application interface with inputs and output]

[**Insert:** Figure 19 The structure of output txt files (mark with "*") in Fig.18]

[**Insert:** Figure 20 The created TXT file]

[**Insert:** Figure 21 The process of digital twinning for the target building storey]

[**Insert:** Figure 22 The selected part of the created IFC file (a) and the visual model opened by IfcViewer (b)]

5. Results Discussion

The created IFC BIM mainly includes the structural and architectural information of building objects (i.e., columns, beams, walls, windows and doors), their locations, material information and partial inner relationships (i.e., *IsContainedIn*). The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of BIMs at various stages. The LOD Specification uses the basic LOD definitions developed by the AIA for the AIA G202-2013 Building Information Modelling Protocol Form and is organized by CSI Uniformat 2010. Through defining characteristics of model elements of different building systems at different Levels of Development, users could clearly understand the information level and limitations of their models. This proposed digital twinning approach has been proved to achieve the LOD 300 in generating BIM for the target storey of existing buildings. The resulting model includes the quantity, sizes, shapes, locations, and orientations of elements. Non-graphic information (e.g., material information) can also be attached to parts of building elements.

The results of this research confirm the importance of a systematic, accurate and convenient digital twinning generation system for facilitating the digital twin-assisted O&M, and have important implications for both O&M management practice and future research.

• Researchers in O&M management have put and are still putting efforts to continuously improve their management practices and capabilities. Digital twin-assisted O&M management has been proved to be an effective approach in O&M phases. Hence, as the foremost step of achieving Digital twin-assisted O&M, the as-is geometric digital twinning construction procedures/approaches/templates (i.e., the case study) establish effective, consistent, and concise processes and guidelines of a digital model (e.g., as-is IFC BIM) generation. The relevant case study in this paper is trying to start from examining a case in University campus and providing a template/guideline for further research.

• From the perspective of time and cost, Guo et al. [61] tested three point cloud-based approaches. Except for collecting data and setting out the control points, over 8 hours were needed in data processing. Moreover, the equipment costed 250 SGD/day if a terrestrial laser scanning (TLS) was rented, and the hourly wages for an equipment operator and a software operator were both 17.930 SGD/h [61]. The digital camera or phone used in this study would be only around 1200 SGD if it was purchased. And the computing times for recognising each object were less than the point cloud-based method [54]. Hence, besides the data collection method is more convenient (e.g., the digital camera was used), this proposed system is also time-efficient and low-cost.

• The developed approach highlights the very important contextual implications for both practice and academic research. Apart from its generation process, researchers and users must also understand types of buildings, main limitations, and needs in order to establish the most practical geometric digital twinning approach and improve its implementations in O&M management practices.

• The developed geometric digital twinning approach only covers storey-level modelling, other than the building levels. It can be used for each storey of the existing buildings with regular layouts. Based on the results, this system provides opportunities and insights for further in-depth research for generating the completed digital model by integrating different storeys, which will be the future works.

• Moreover, the research results have achieved the LoD 300 and presented the most important aspects of digital modelling (i.e., the IFC BIM) for further achieving O&M management implementation. Future studies will also focus on building the connection between the as-is IFC BIM and the O&M information system and try to build an information-rich platform to support O&M management.

6. Conclusion

In order to fill in this research gap of the absence of a systematic geometric digital twinning approach for existing buildings, this research aims develops a semi-automatic geometric digital twinning approach based on images and CAD drawings for existing buildings in the O&M phase.

The complex as-is conditions are one of the main factors that impact the process and accuracy of constructing as-is IFC BIM for a building digital twin. Under the changeable environment with poorly-textured features or exposed to interferences, this study used images collected by handheld cameras and existing CAD drawings as inputs of the integrated approach. Three modules have been developed. They are (1) Module 1: Building Framework Construction and

Structural Geometry Information Extraction. This Module would construct building framework and extract structural geometry information, and further provide the coordinate system of constructing IFC BIM based on CAD drawings, OCR techniques and the MM theory. (2) Module 2: Building Information Complementary Module. This Module has two sub-systems: the object recognition sub-system was based on NFS, and the material recognition sub-system was based on the image classification procedures and the texture library. (3) Module 3: Information Integration and IFC BIM Creation. Information from Module 1 and Module 2 would be integrated into this Module firstly. Then, the developed IFC BIM generation system in this Module would automatically transform integrated information into the complete geometric digital twin model (i.e., an IFC BIM).

However, the Module 2 only focused on recognising regular building drawings at the current stage. The research team will include complicated geometry in the future works such as using diagonal line in the CAD drawings. The generated IFC BIM is only limited to the individual storey level and the whole building (including different storeys) should be further converted into the resulting IFC BIM and a comparison experiment that comparing with other approaches (e.g., laser scanner) will also be included in the future works.

More building information should be included to achieve an information-rich digital twin model. For example, the MEP (mechanical, electrical, and plumbing) information and movable components (e.g., furniture) through continuous collected images are also needed to be added into the building digital twin. Hence, a more comprehensive and information-rich digital twinning generation approach will be the target of our research team in the future works, including daily O&M management information and information-rich digital model in building digital twins.

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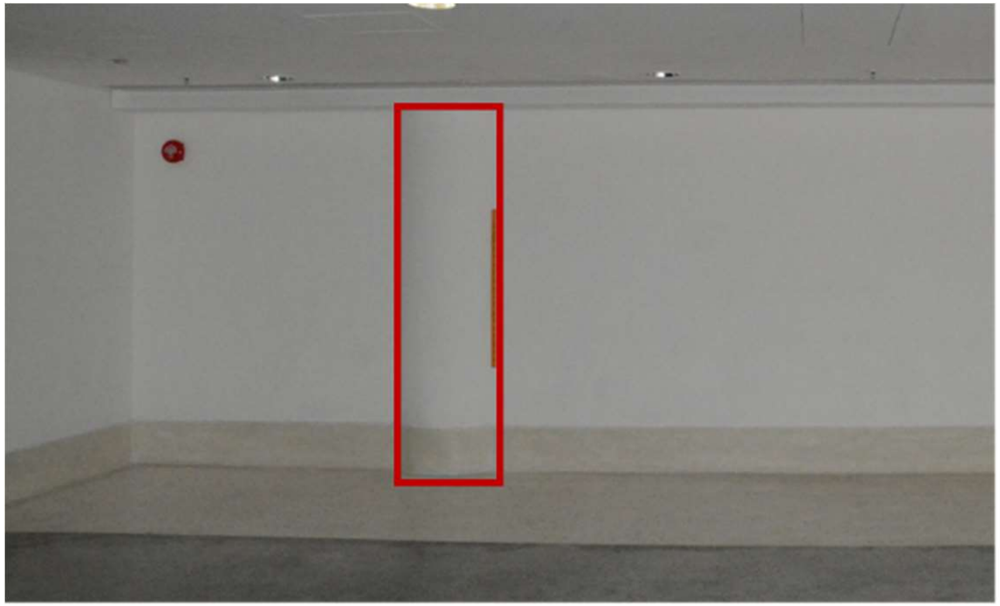
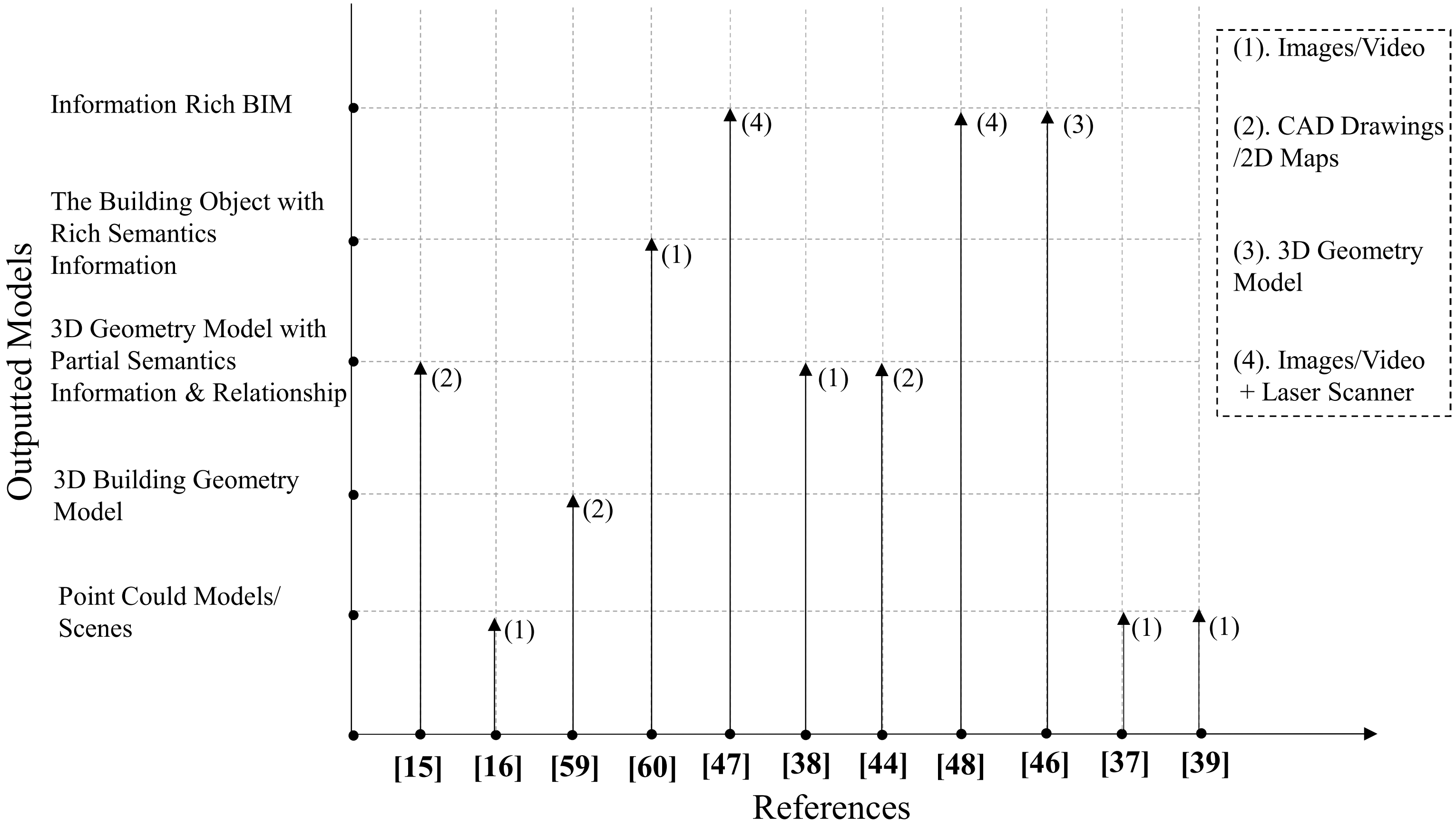
Figure Lists



Outputted Models
Information Rich BIM
The Building Object with Rich Semantics Information
3D Geometry Model with Partial Semantics Information & Relationship
3D Building Geometry Model
Point Could Models/ Scenes
(1). Images/Video
(2). CAD Drawings /2D Maps
(3). 3D Geometry Model
(4). Images/Video + Laser Scanner
(2)
(1)
(2)
(1)
(4)
(1)
(2)
(4)
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(1)
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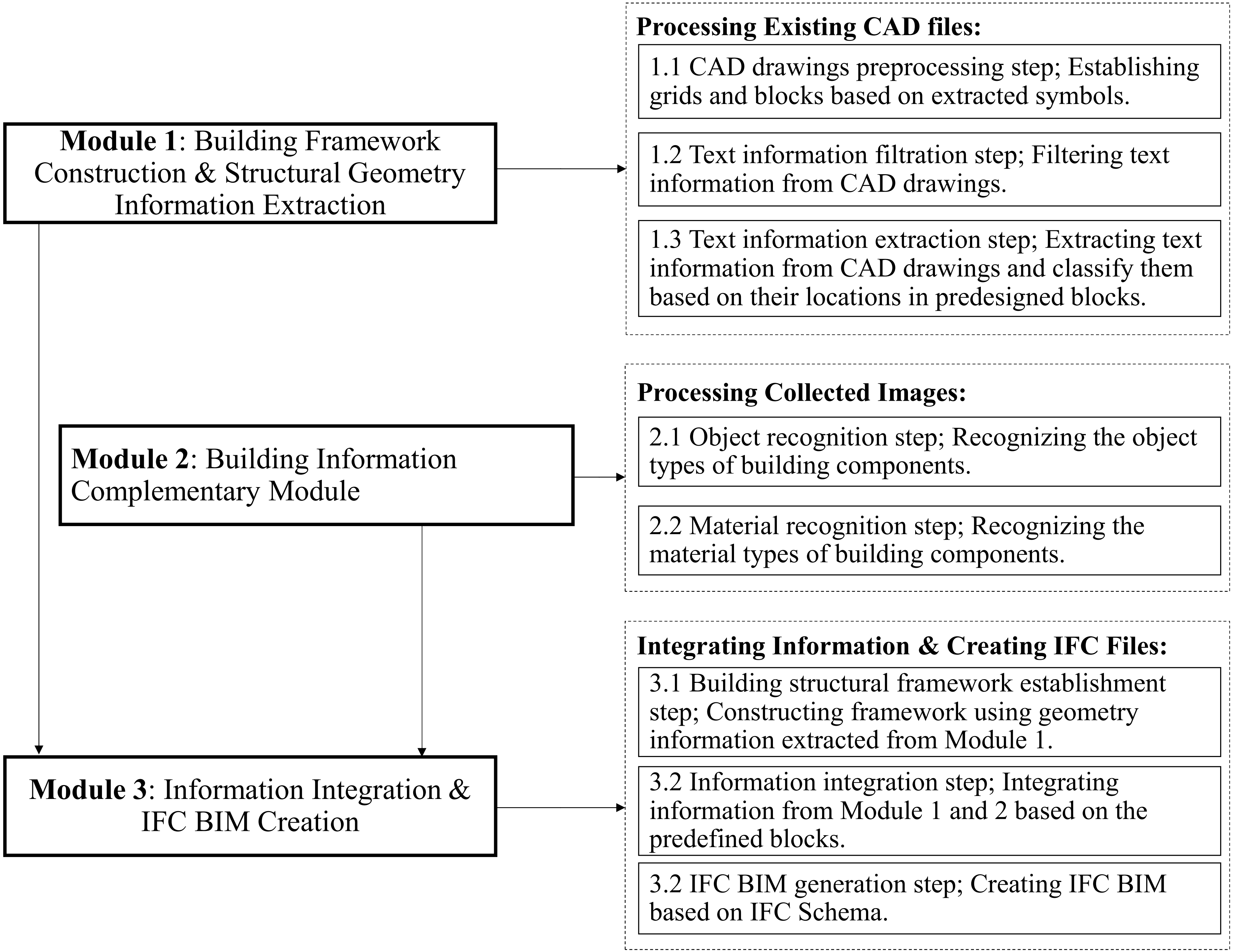
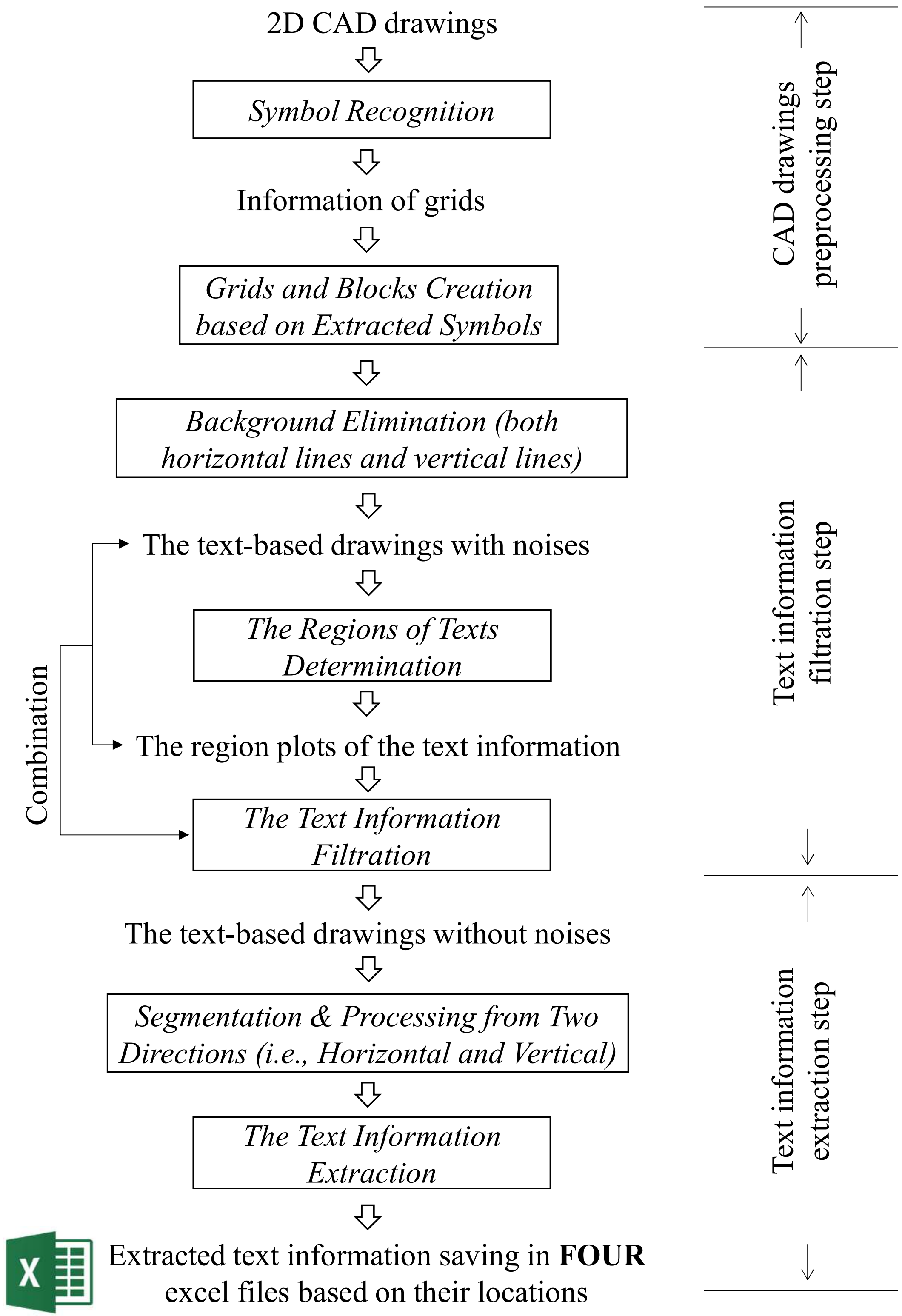
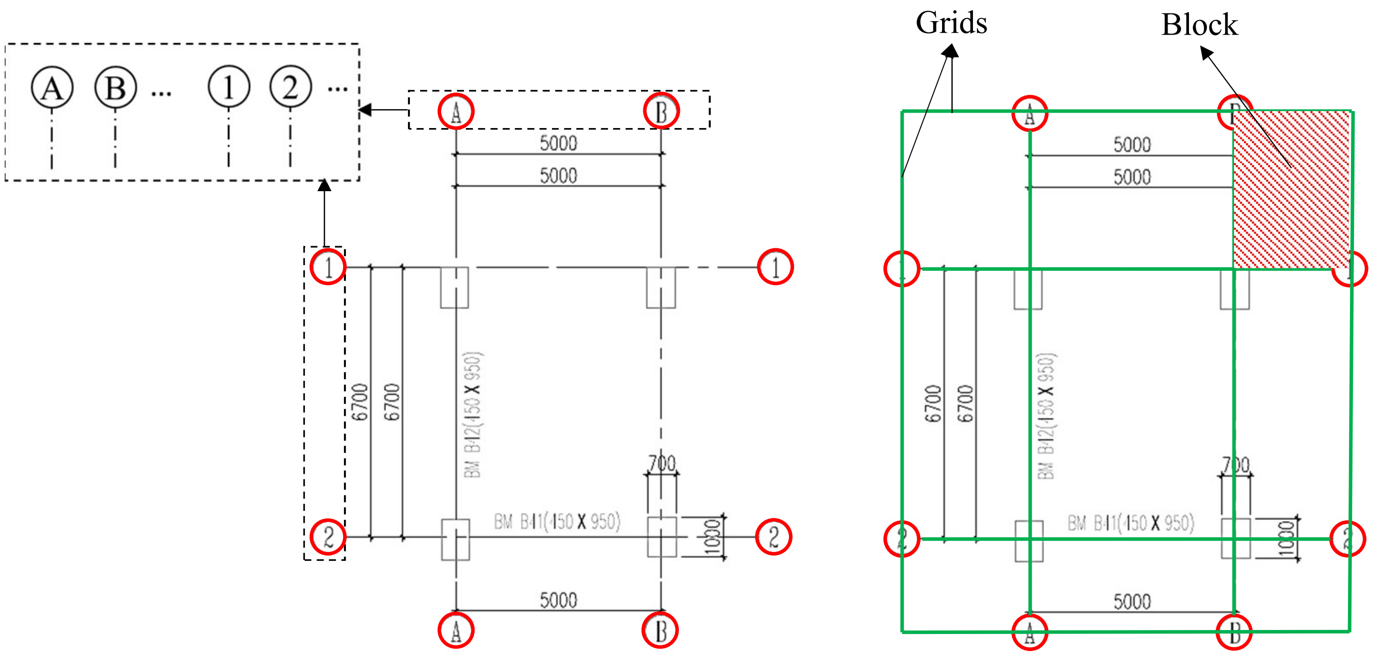
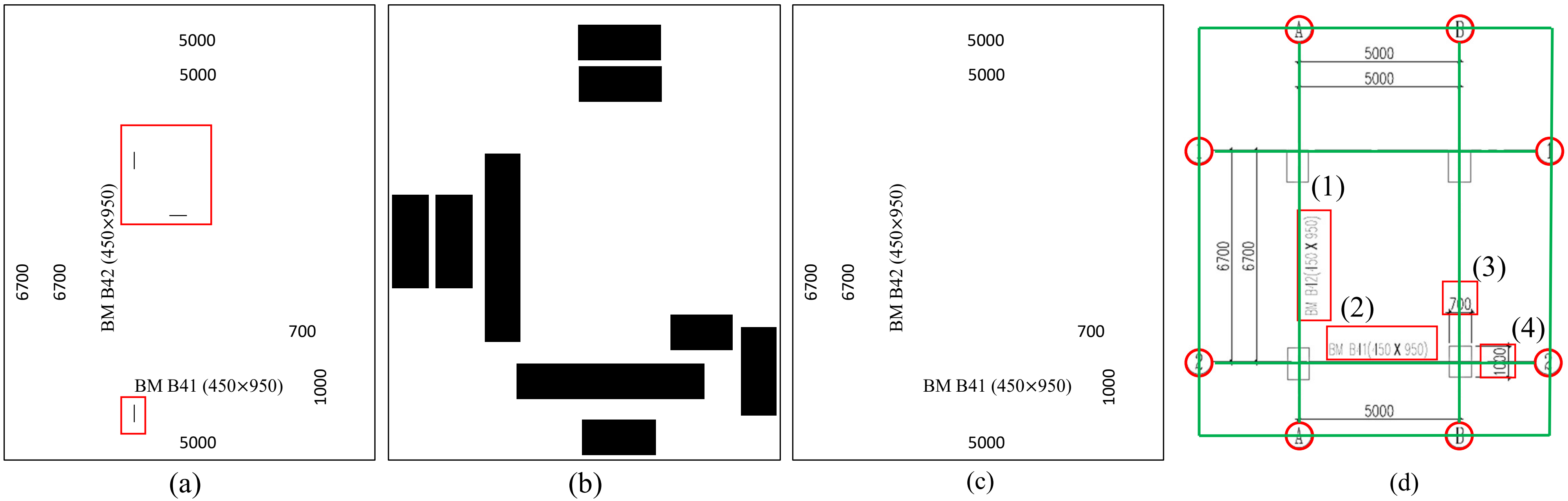
References

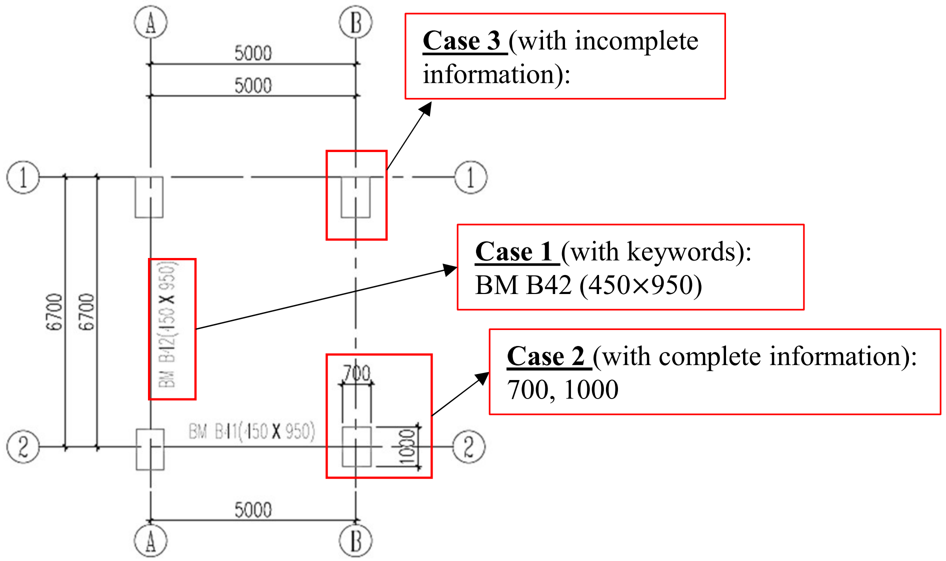


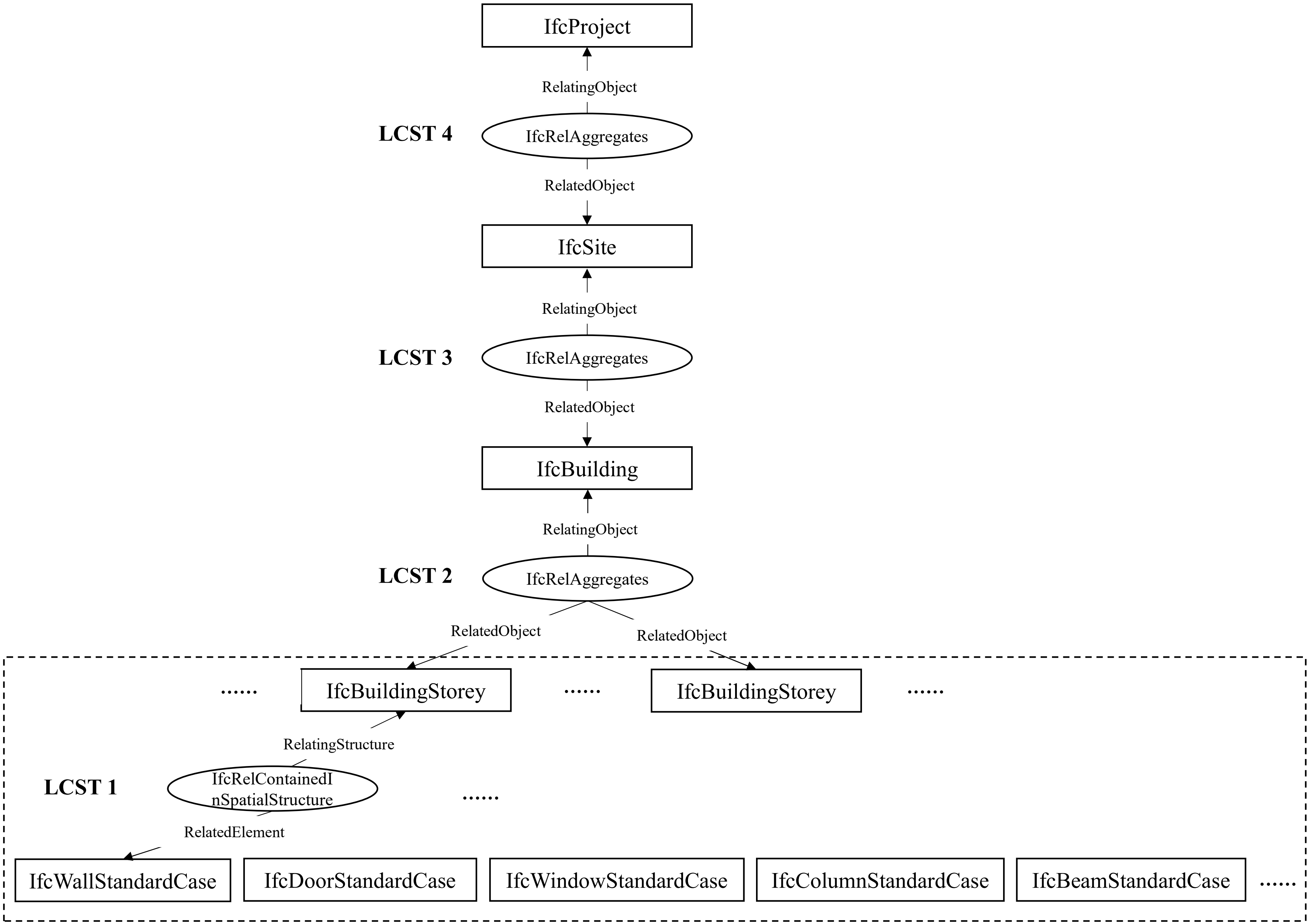
Module 1: Building Framework Construction & Structural Geometry Information Extraction
Module 2: Building Information Complementary Module
Module 3: Information Integration & IFC BIM Creation
Processing Existing CAD files:
1.1 CAD drawings preprocessing step; Establishing grids and blocks based on extracted symbols.
1.2 Text information filtration step; Filtering text information from CAD drawings.
1.3 Text information extraction step; Extracting text information from CAD drawings and classify them based on their locations in predesigned blocks.
Processing Collected Images:
2.1 Object recognition step; Recognizing the object types of building components.
2.2 Material recognition step; Recognizing the material types of building components.
Integrating Information & Creating IFC Files:
3.1 Building structural framework establishment step; Constructing framework using geometry information extracted from Module 1.
3.2 Information integration step; Integrating information from Module 1 and 2 based on the predefined blocks.
3.2 IFC BIM generation step; Creating IFC BIM based on IFC Schema.

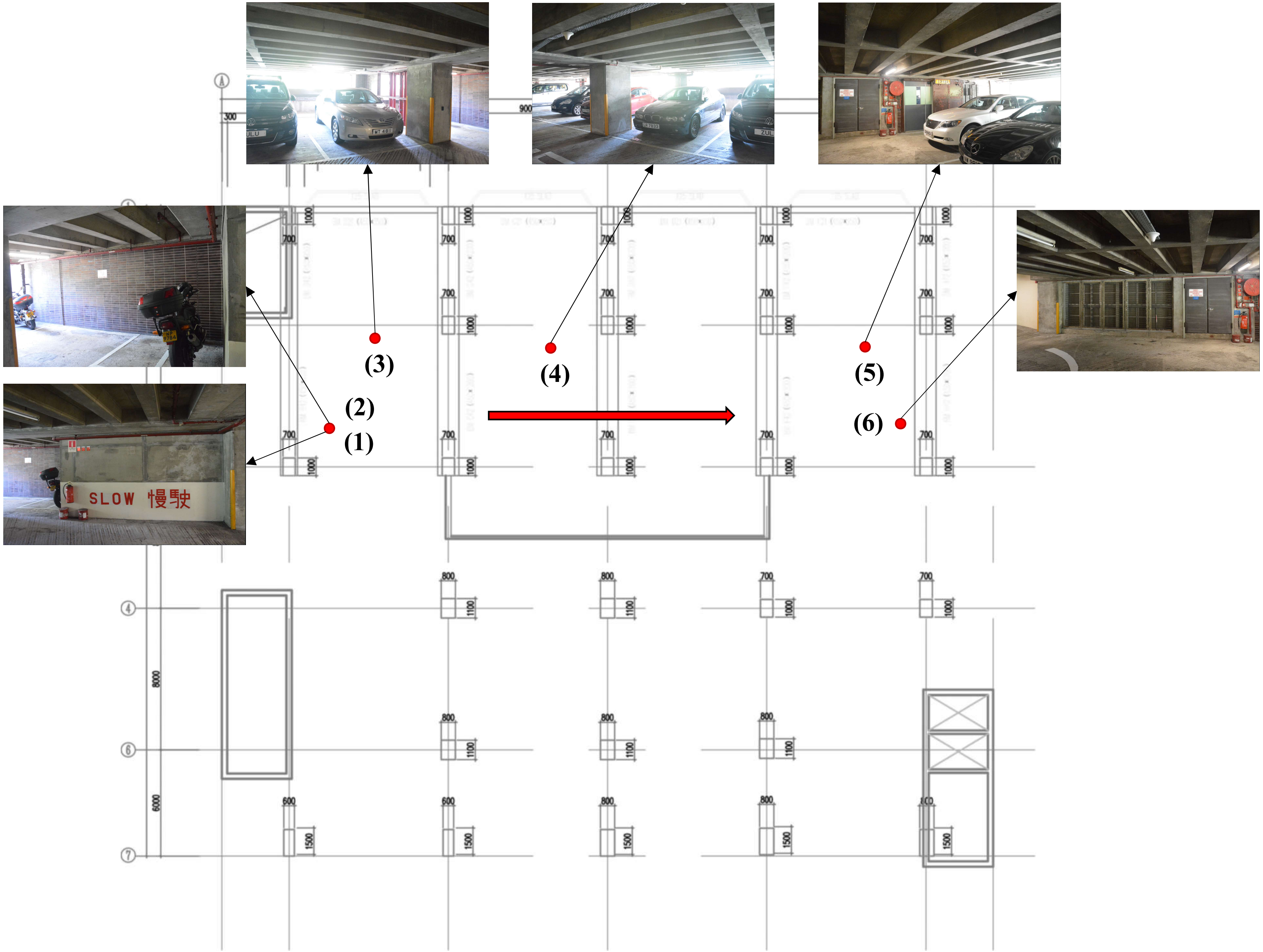

2D CAD drawings
Symbol Recognition
Information of grids
Grids and Blocks Creation based on Extracted Symbols
Background Elimination (both horizontal lines and vertical lines)
The text-based drawings with noises
The Regions of Texts Determination
The region plots of the text information
The Text Information Filtration
Combination
The text-based drawings without noises
Segmentation & Processing from Two Directions (i.e., Horizontal and Vertical)
The Text Information Extraction
Extracted text information saving in FOUR excel files based on their locations
CAD drawings preprocessing step
Text information filtration step
Text information extraction step


Grids
Block
A
B
1
2
5000
5000
6700
6700
700
1000
5000
BM B41(450 X 950)
BM B42(450 X 950)
(a) (b)

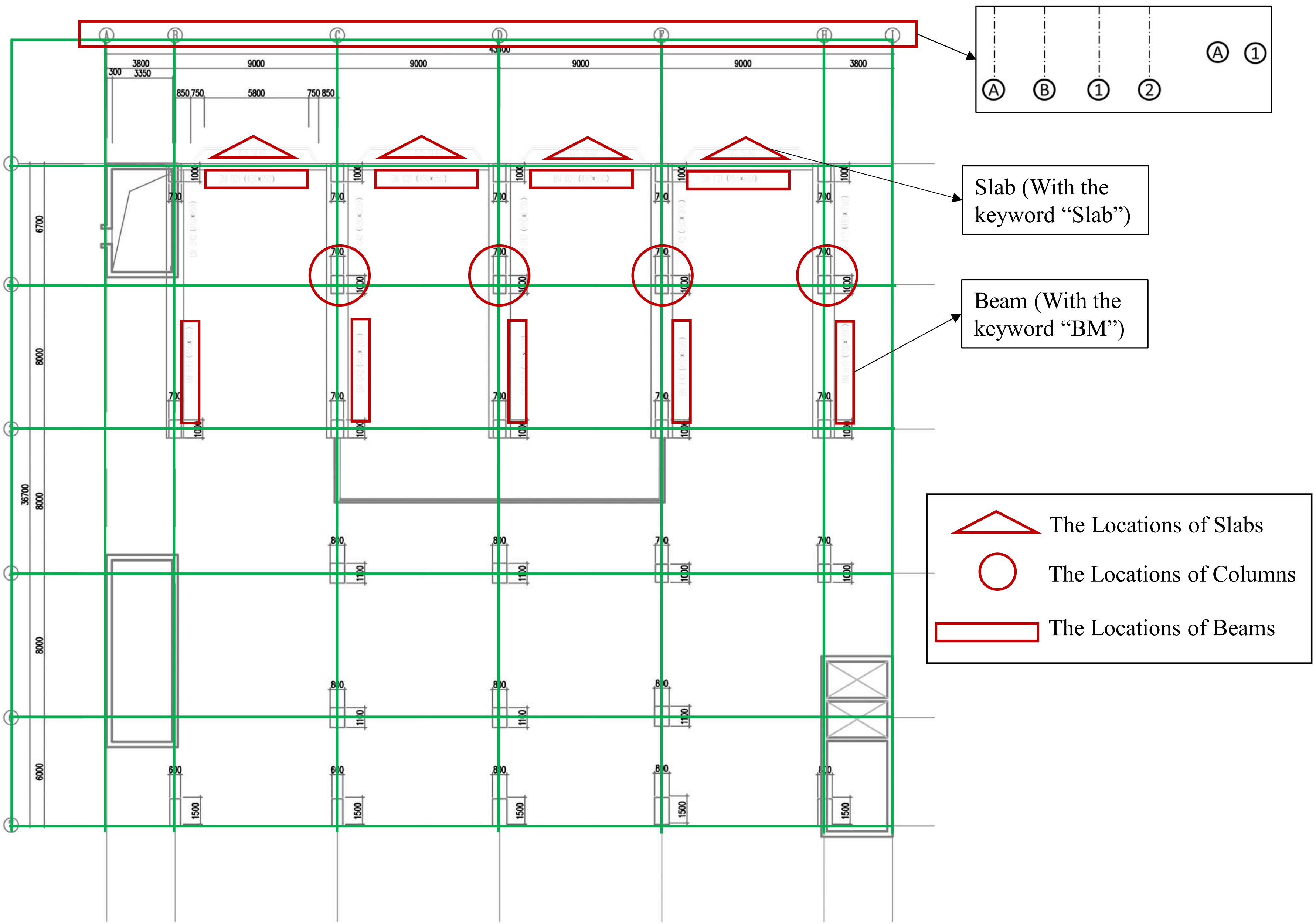

5000
5000
BM B42 (450×950)
6700
6700
700
BM B41 (450×950)
1000
5000
(1)
(2)
(3)
(4)
BM B42(450 X 950)
BM B41(450 X 950)
A
B
1
2
(a)
(b)
(c)
(d)


A
B
5000
5000
Case 3 (with incomplete information):
1
1
Case 1 (with keywords):
BM B42 (450×950)
6700
6700
BM B42(450 X 950)
Case 2 (with complete information):
700, 1000
700
BM B41(450 X 950)
1000
2
2
5000
A
B

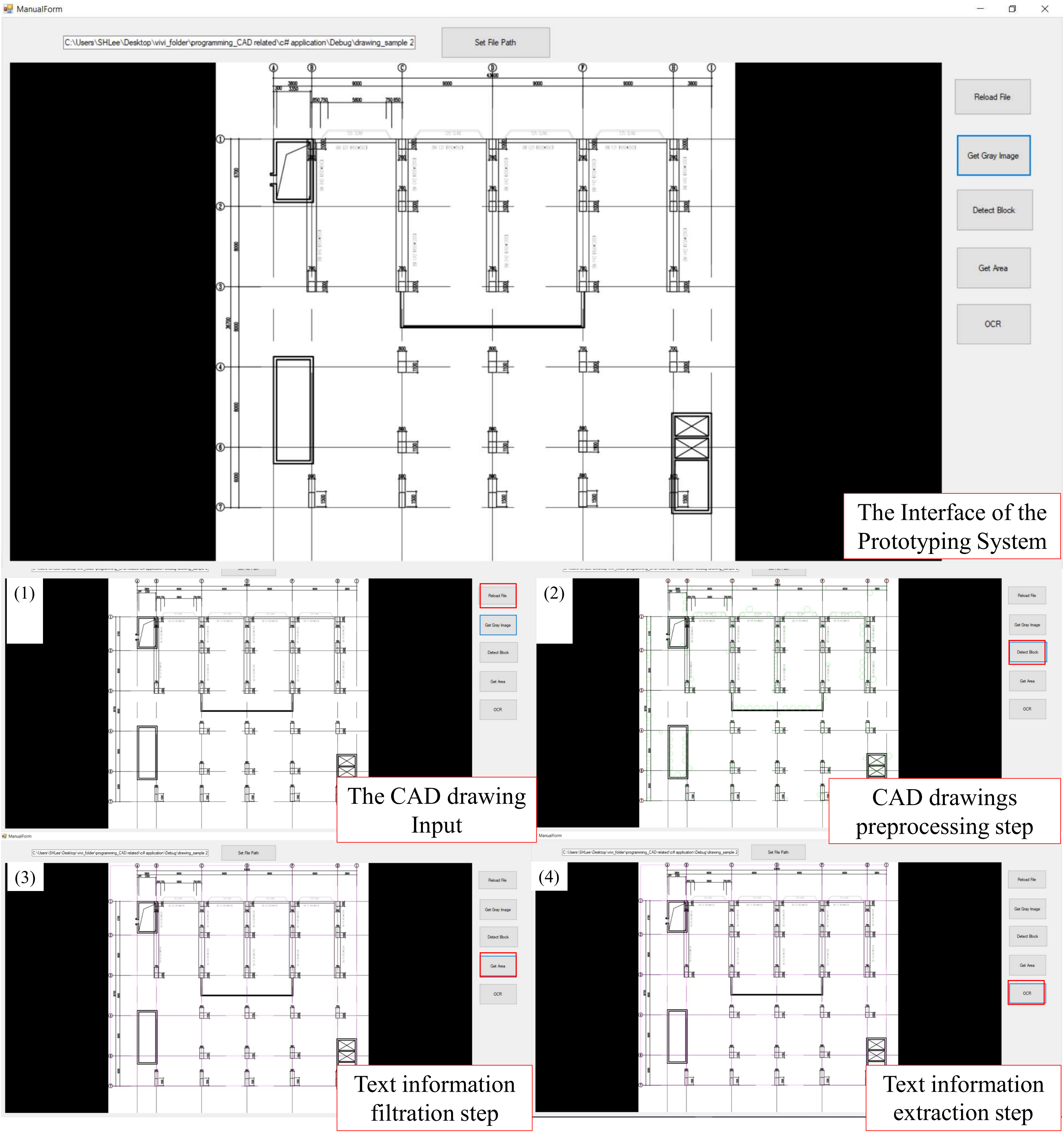

IfcProject
RelatingObject
LCST 4
IfcRelAggregates
RelatedObject
IfcSite
RelatingObject
LCST 3
IfcRelAggregates
RelatedObject
IfcBuilding
RelatingObject
LCST 2
IfcRelAggregates
RelatedObject
RelatedObject
......
IfcBuildingStorey
......
IfcBuildingStorey
......
RelatingStructure
LCST 1
IfcRelContainedI
nSpatialStructure
......
RelatedElement
IfcWallStandardCase
IfcDoorStandardCase
IfcWindowStandardCase
IfcColumnStandardCase
IfcBeamStandardCase
......

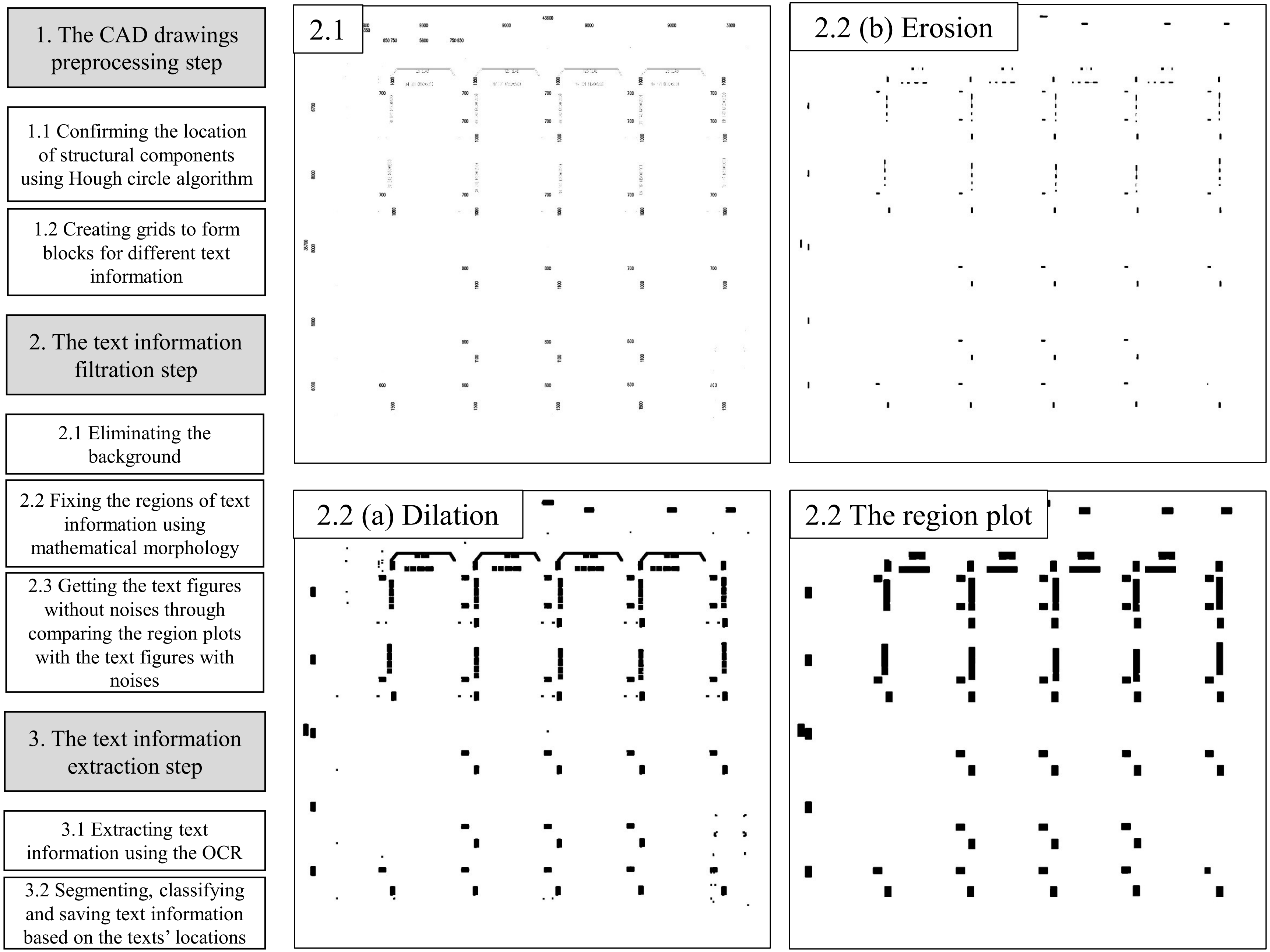


(1)
(2)
(3)
(4)
(5)
(6)
SLOW 慢駛
300
900
700
1000
800
1100
600
1500
8000
6000

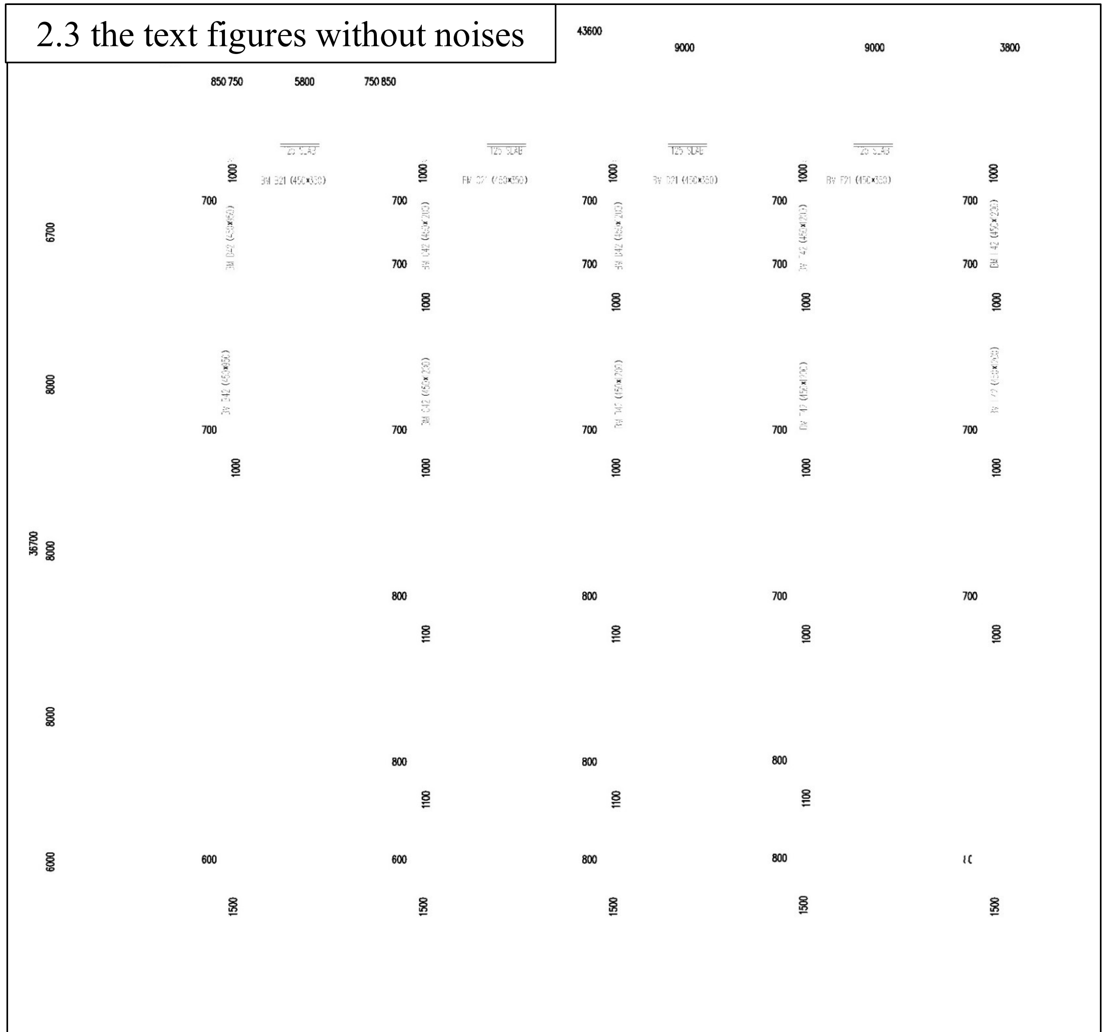


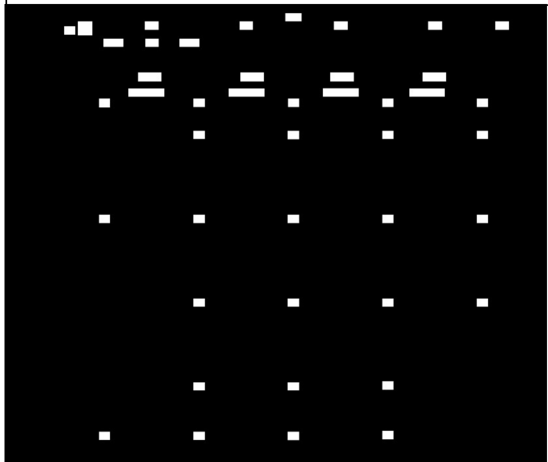
Slab (With the keyword "Slab")
Beam (With the keyword "BM")
The Locations of Slabs
The Locations of Columns
The Locations of Beams
43500
3800
9000
9000
9000
9000
3800
36700
6700
8000
8000
8000
6000


ManualForm
C:\Users\SHLee\Desktop\vivi_folder\programming_CAD related\c# application\Debug\drawing_sample 2
Set File Path
Reload File
Get Gray Image
Detect Block
Get Area
OCR
The Interface of the Prototyping System
(1)
The CAD drawing Input
(2)
CAD drawings preprocessing step
(3)
Text information filtration step
(4)
Text information extraction step


1. The CAD drawings preprocessing step
1.1 Confirming the location of structural components using Hough circle algorithm
1.2 Creating grids to form blocks for different text information
2. The text information filtration step
2.1 Eliminating the background
2.2 Fixing the regions of text information using mathematical morphology
2.3 Getting the text figures without noises through comparing the region plots with the text figures with noises
3. The text information extraction step
3.1 Extracting text information using the OCR
3.2 Segmenting, classifying and saving text information based on the texts' locations
2.1
2.2 (b) Erosion
2.2 (a) Dilation
2.2 The region plot

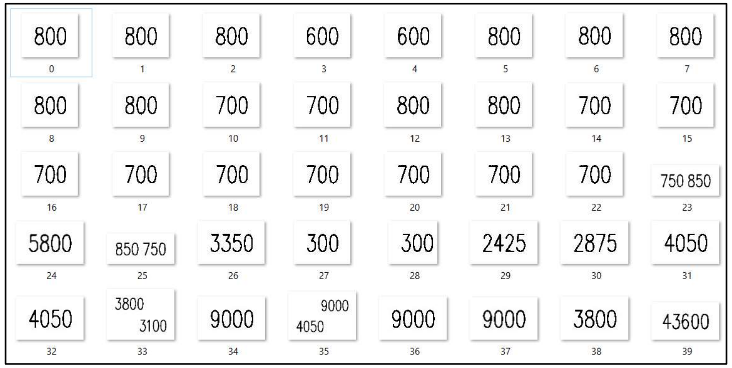
2.3 the text figures without noises



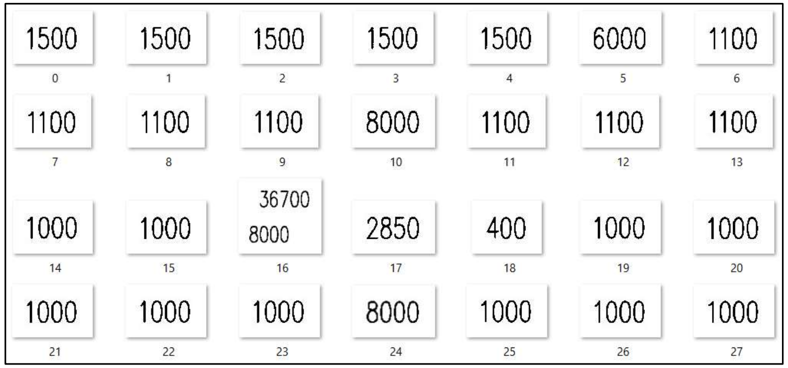


3.2 The horizontal region plot

3.2 The vertical region plot

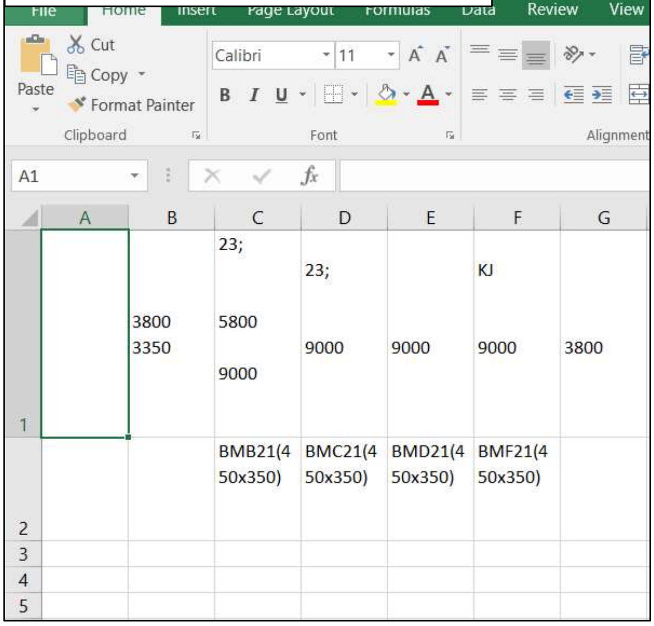


Horizontal Texts

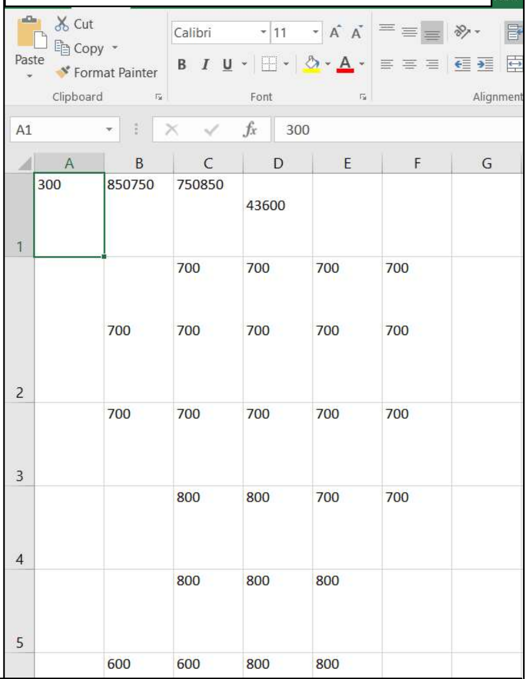


Vertical Texts

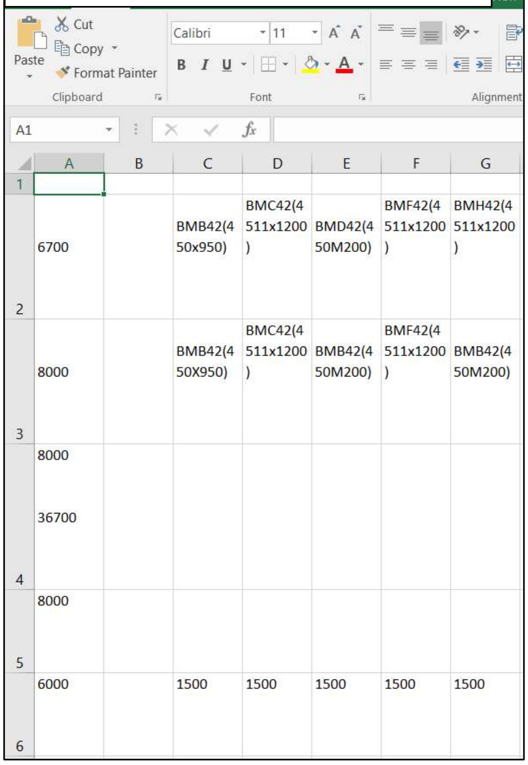
<u>The Excel File:</u> Horizontal 1



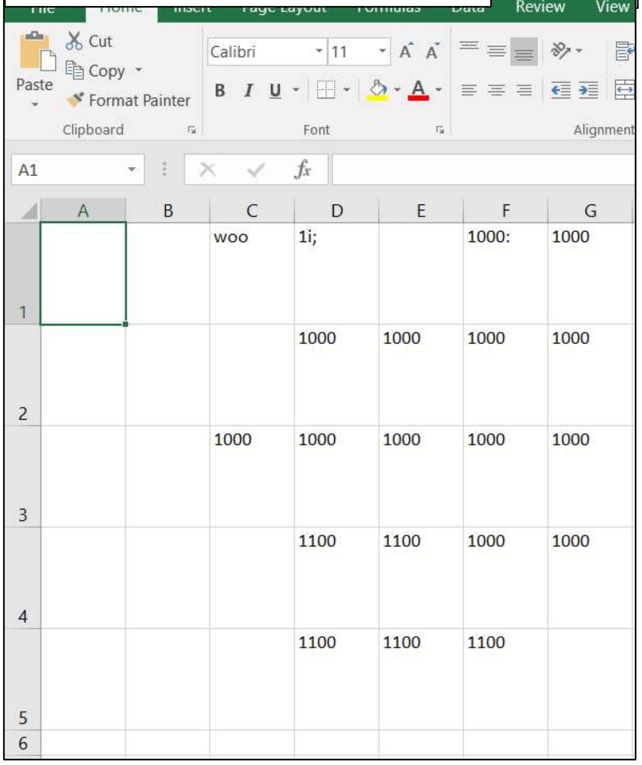
<u>The Excel File:</u> Horizontal 2

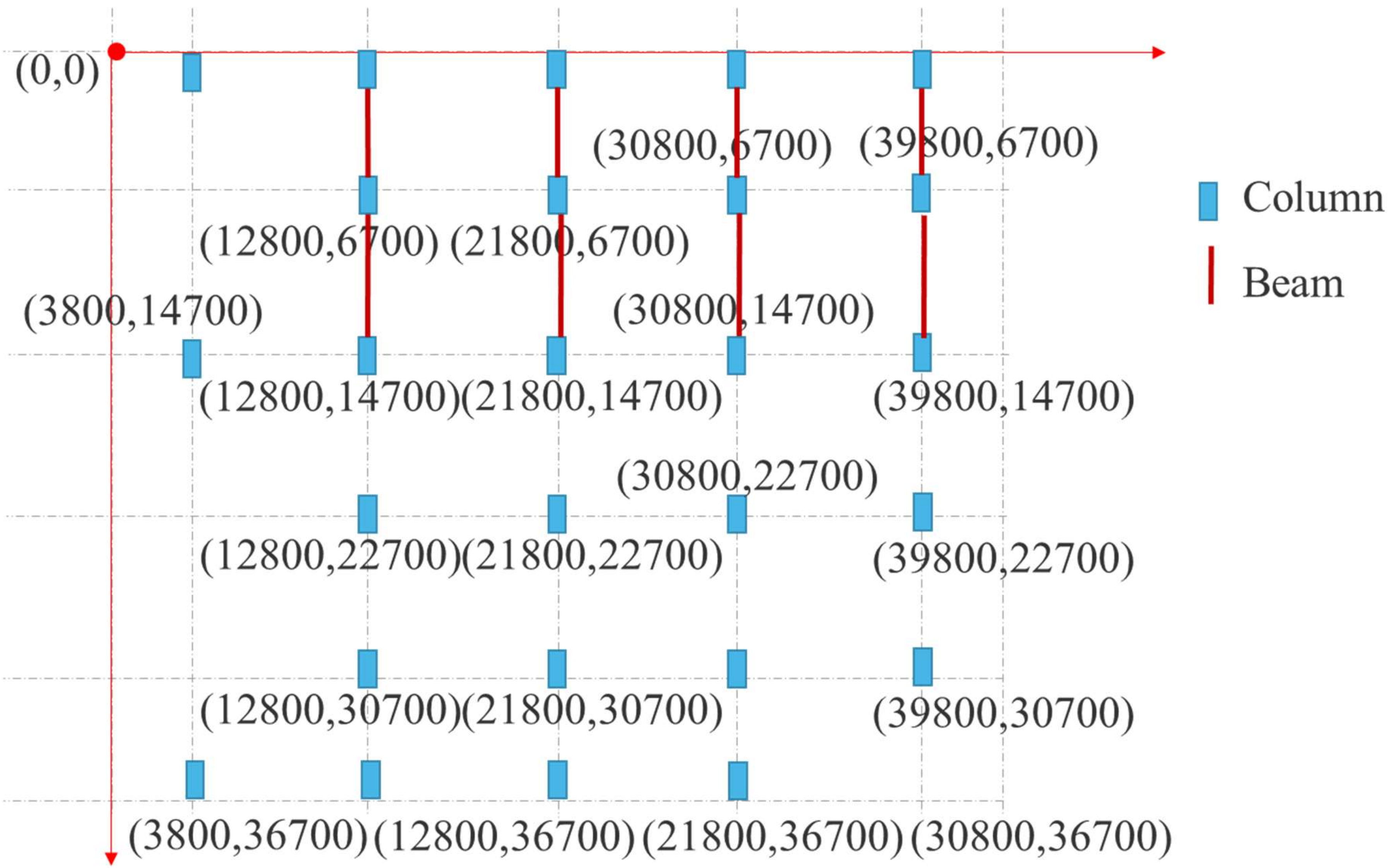


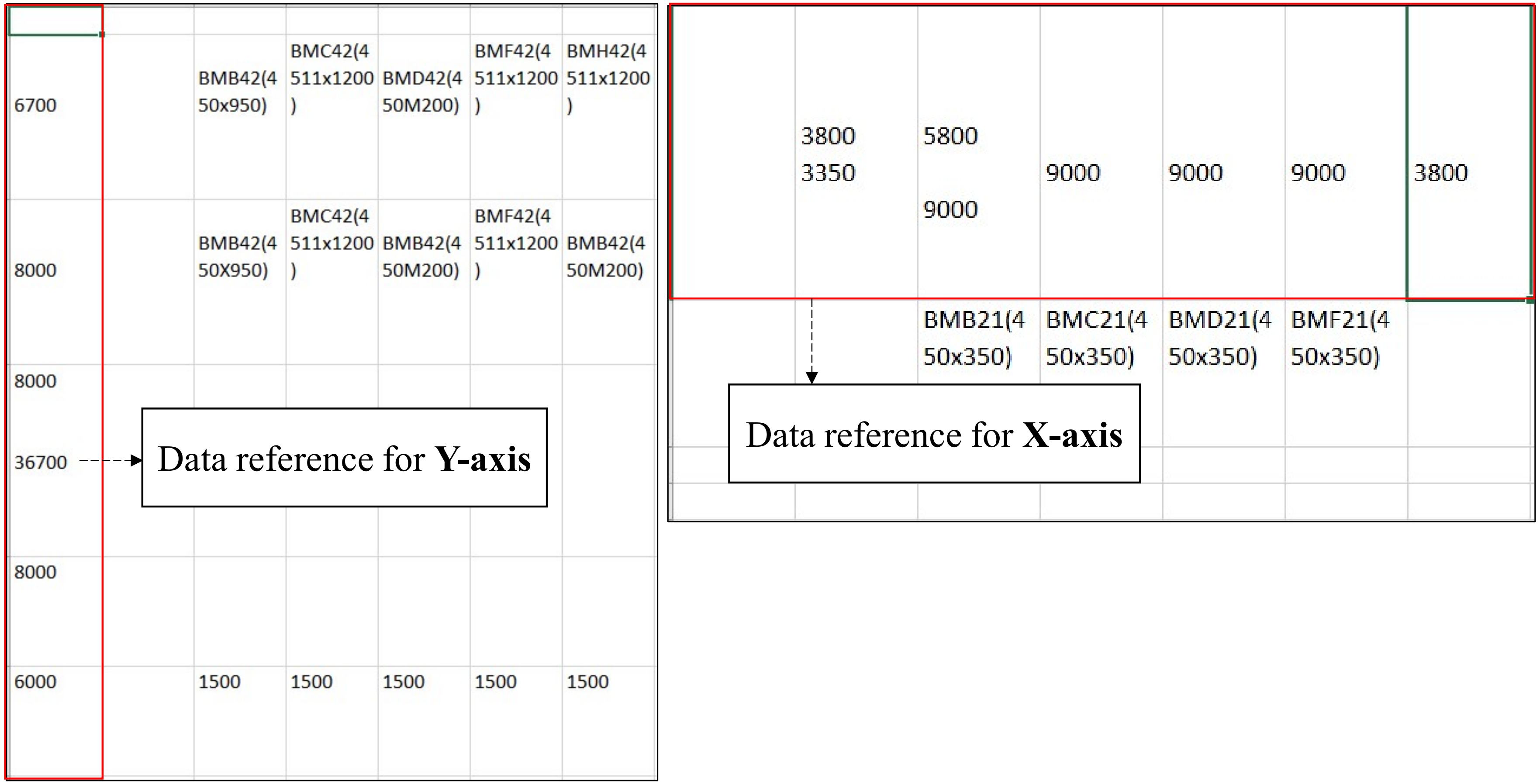
<u>The Excel File:</u> Vertical 1

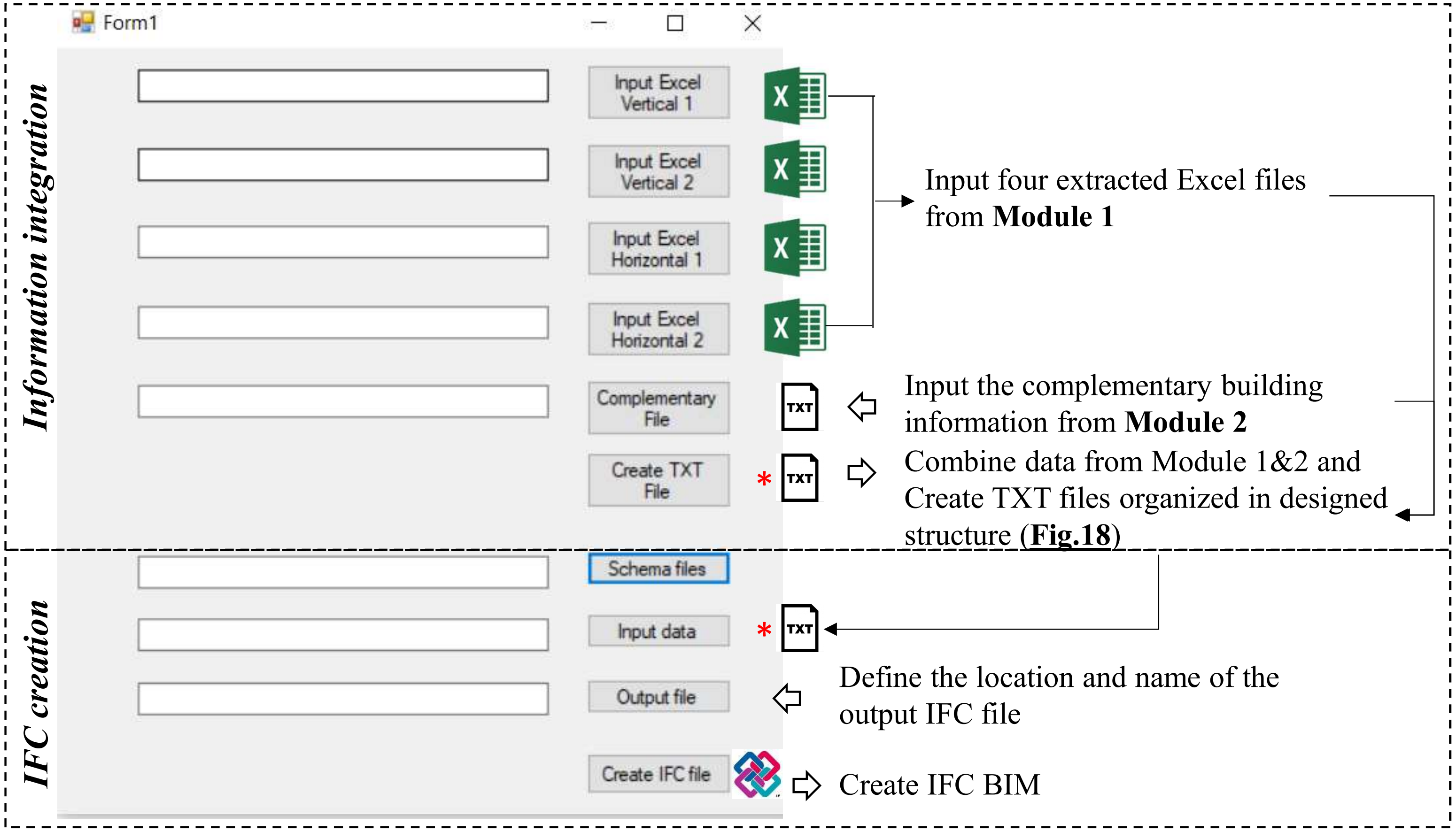


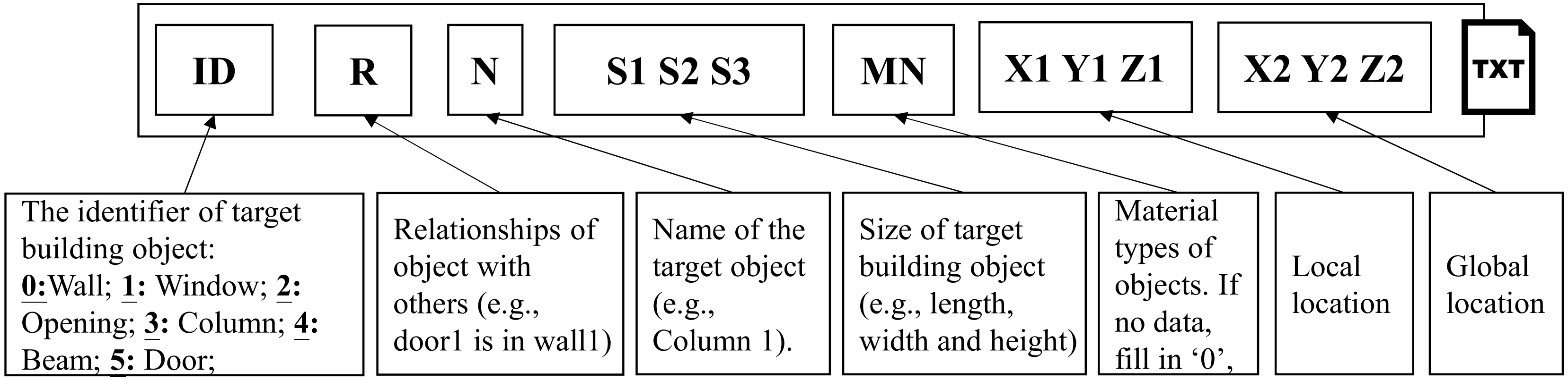
<u>The Excel File:</u> Vertical 2

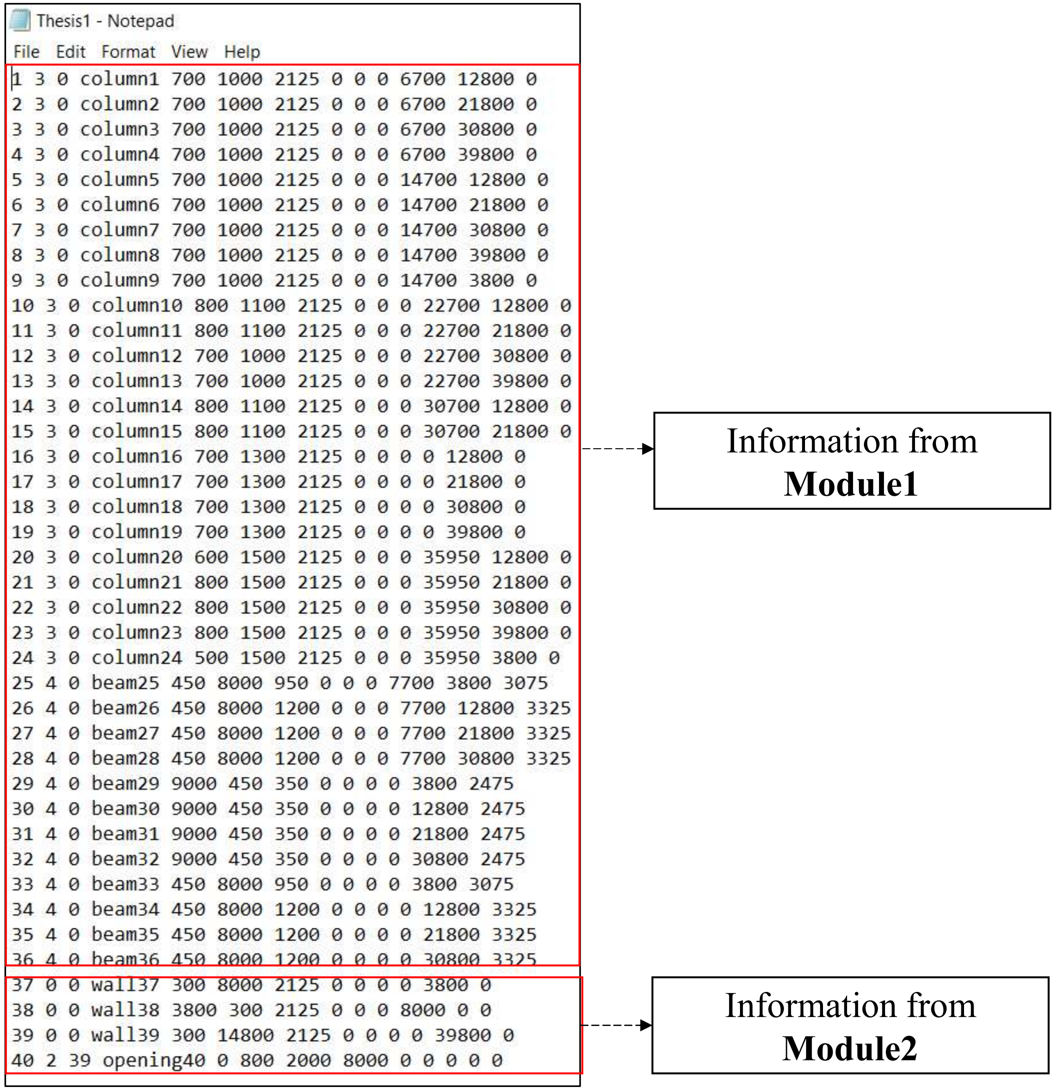



(0,0)
(30800,6700)
(39800,6700)
Column
Beam
(12800,6700)
(21800,6700)
(3800,14700)
(30800,14700)
(12800,14700)
(21800,14700)
(39800,14700)
(30800,22700)
(12800,22700)
(21800,22700)
(39800,22700)
(12800,30700)
(21800,30700)
(39800,30700)
(3800,36700)
(12800,36700)
(21800,36700)
(30800,36700)


6700
BMB42(450x950)
BMC42(4511x1200)
BMD42(450M200)
BMF42(4511x1200)
BMH42(4511x1200)
8000
BMB42(450X950)
BMC42(4511x1200)
BMB42(450M200)
BMF42(4511x1200)
BMB42(450M200)
8000
36700
Data reference for Y-axis
8000
6000
1500
1500
1500
1500
1500
3800
3350
5800
9000
9000
9000
9000
3800
BMB21(450x350)
BMC21(450x350)
BMD21(450x350)
BMF21(450x350)
Data reference for X-axis

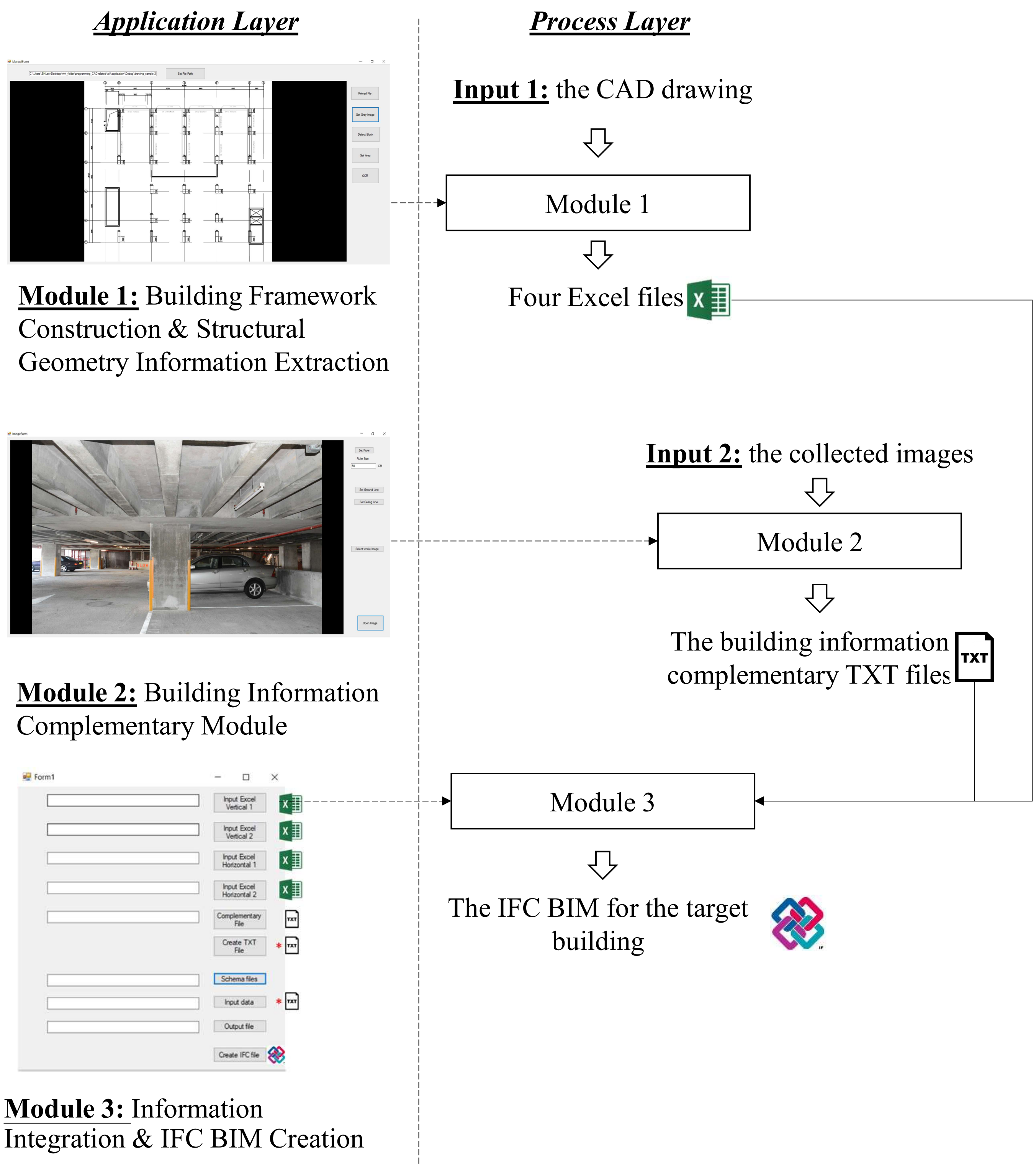

Form1
Information integration
Input Excel Vertical 1
Input Excel Vertical 2
Input Excel Horizontal 1
Input Excel Horizontal 2
Complementary File
Create TXT File
Input four extracted Excel files from **Module 1**
Input the complementary building information from **Module 2**
Combine data from Module 1&2 and Create TXT files organized in designed structure (**Fig.18**)
IFC creation
Schema files
Input data
Output file
Create IFC file
Define the location and name of the output IFC file
Create IFC BIM


ID
R
N
S1 S2 S3
MN
X1 Y1 Z1
X2 Y2 Z2
TXT
The identifier of target building object: 0:Wall; 1: Window; 2: Opening; 3: Column; 4: Beam; 5: Door;
Relationships of object with others (e.g., door1 is in wall1)
Name of the target object (e.g., Column 1).
Size of target building object (e.g., length, width and height)
Material types of objects. If no data, fill in '0',
Local location
Global location


Thesis1 - Notepad

File Edit Format View Help

```
1 3 0 column1 700 1000 2125 0 0 0 6700 12800 0
2 3 0 column2 700 1000 2125 0 0 0 6700 21800 0
3 3 0 column3 700 1000 2125 0 0 0 6700 30800 0
4 3 0 column4 700 1000 2125 0 0 0 6700 39800 0
5 3 0 column5 700 1000 2125 0 0 0 14700 12800 0
6 3 0 column6 700 1000 2125 0 0 0 14700 21800 0
7 3 0 column7 700 1000 2125 0 0 0 14700 30800 0
8 3 0 column8 700 1000 2125 0 0 0 14700 39800 0
9 3 0 column9 700 1000 2125 0 0 0 14700 3800 0
10 3 0 column10 800 1100 2125 0 0 0 22700 12800 0
11 3 0 column11 800 1100 2125 0 0 0 22700 21800 0
12 3 0 column12 700 1000 2125 0 0 0 22700 30800 0
13 3 0 column13 700 1000 2125 0 0 0 22700 39800 0
14 3 0 column14 800 1100 2125 0 0 0 30700 12800 0
15 3 0 column15 800 1100 2125 0 0 0 30700 21800 0
16 3 0 column16 700 1300 2125 0 0 0 0 12800 0
17 3 0 column17 700 1300 2125 0 0 0 0 21800 0
18 3 0 column18 700 1300 2125 0 0 0 0 30800 0
19 3 0 column19 700 1300 2125 0 0 0 0 39800 0
20 3 0 column20 600 1500 2125 0 0 0 35950 12800 0
21 3 0 column21 800 1500 2125 0 0 0 35950 21800 0
22 3 0 column22 800 1500 2125 0 0 0 35950 30800 0
23 3 0 column23 800 1500 2125 0 0 0 35950 39800 0
24 3 0 column24 500 1500 2125 0 0 0 35950 3800 0
25 4 0 beam25 450 8000 950 0 0 0 7700 3800 3075
26 4 0 beam26 450 8000 1200 0 0 0 7700 12800 3325
27 4 0 beam27 450 8000 1200 0 0 0 7700 21800 3325
28 4 0 beam28 450 8000 1200 0 0 0 7700 30800 3325
29 4 0 beam29 9000 450 350 0 0 0 0 3800 2475
30 4 0 beam30 9000 450 350 0 0 0 0 12800 2475
31 4 0 beam31 9000 450 350 0 0 0 0 21800 2475
32 4 0 beam32 9000 450 350 0 0 0 0 30800 2475
33 4 0 beam33 450 8000 950 0 0 0 0 3800 3075
34 4 0 beam34 450 8000 1200 0 0 0 0 12800 3325
35 4 0 beam35 450 8000 1200 0 0 0 0 21800 3325
36 4 0 beam36 450 8000 1200 0 0 0 0 30800 3325
37 0 0 wall37 300 8000 2125 0 0 0 0 3800 0
38 0 0 wall38 3800 300 2125 0 0 0 8000 0 0
39 0 0 wall39 300 14800 2125 0 0 0 0 39800 0
40 2 39 opening40 0 800 2000 8000 0 0 0 0 0
```


Application Layer
Process Layer
Input 1: the CAD drawing
Module 1
Four Excel files
Module 1: Building Framework Construction & Structural Geometry Information Extraction
Input 2: the collected images
Module 2
The building information complementary TXT files
TXT
Module 2: Building Information Complementary Module
Form1
Input Excel Vertical 1
Input Excel Vertical 2
Input Excel Horizontal 1
Input Excel Horizontal 2
Complementary File
Create TXT File
Schema files
Input data
Output file
Create IFC file
Module 3
The IFC BIM for the target building
Module 3: Information Integration & IFC BIM Creation

```
#773 = IFCCOLUMNSTANDARDCASE('0mk90SwqZKk4iX$1GucPia', #5, 'column10', 'Description of Column', $, #774, #779, $,
.STANDARD.);
#774 = IFCLOCALPLACEMENT(#37, #775);
#775 = IFCAXIS2PLACEMENT3D(#776, #777, #778);
#776 = IFCCARTESIANPOINT((22700., 12800., 0.));
#777 = IFCDIRECTION((0., 0., 1.));
#778 = IFCDIRECTION((1., 0., 0.));
#779 = IFCPRODUCTDEFINITIONSHAPE($, $, (#802, #803, #823));
#780 = IFCCOLUMNTYPE('1A9Owcbi$ClKPB9a8klY$C', #5, 'column10', 'Description of Column Type', $, $, $, $, $, .STANDARD.);
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#791 = IFCQUANTITYLENGTH('Length', 'Length', $, 800., $);
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#793 = IFCQUANTITYAREA('GrossSideArea', 'GrossSideArea', $, 1.7, $);
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#795 = IFCQUANTITYLENGTH('Height', 'Height', $, 2125., $);
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#798 = IFCMATERIALLAYERSETUSAGE(#799, .AXIS2., .POSITIVE., -400., $);
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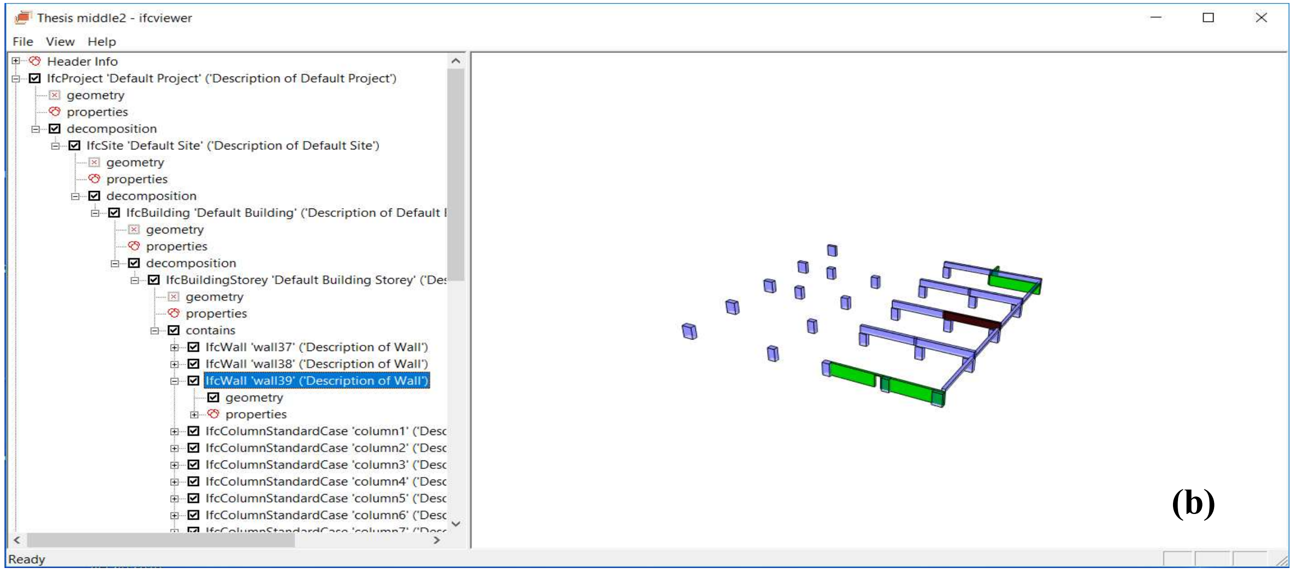
(a)



(b)