Journal of Building Engineering 2 (2015) 24–35

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Review: reconstruction of 3D building information models from 2D scanned plans

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ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form
8 April 2015
Accepted 9 April 2015
Available online 11 April 2015

Keywords:
Building Information Model (BIM)
3D building models
2D scanned plans
3D automatic reconstruction
Building model checking
IFC

ABSTRACT

3D digital modeling, Building Information Modeling (BIM) and numerical simulation are widely recognized as essential components of building design support tools, but require a significant amount of digital data to truly achieve their potential. Currently, they are mostly applied in the design and construction of new buildings but rarely in renovation projects, since few digital data are available for the majority of existing buildings. It is therefore urgent to devise reliable and effective approaches to the generation of 3D digital (BIM) models of existing buildings. This recognition is widely shared and has resulted in a substantial amount of research work and significant innovations in various fields: 3D laser scanning, images processing, etc. With the aim of bringing some significant contribution to this state-of-the-art, this paper provides a critical review of the methods and tools for generating 3D building models from 2D drawings, developing along two complementary lines: a wide-spectrum assessment of 3D generation techniques, and a more focused, in-depth review of 2D drawings-based approaches (from image processing to BIM creation and validation). The review follows a well-defined methodology and builds on the work of more than 100 relevant references. It includes substantial discussions to highlight the strengths, weaknesses and preferential applications of the reviewed research works, and provides a research agenda. The study particularly highlights that the state-of-the-art is fragmented: most research works focus on specific, limited steps of the 3D models generation process, but no solution has yet been able to tackle the whole generation chain. An additional conclusion is that the selection of the most effective approach largely depends on the intended application, and on project-specific constraints. Also, the study highlights that significant benefits could be drawn from combining existing approaches.

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http://dx.doi.org/10.1016/j.jobe.2015.04.002
2352-7102/

1. Introduction

The motivation for improving the effectiveness of renovation designs comes from three simple facts. The first is that building stocks increase slowly (by 1% every year) and are therefore mainly composed of constructions [1]. The second is that developed countries face several environmental challenges that require drastic measures to dramatically enhance energy efficiency. The third is that building energy consumption represents between 20% and 40% of the total energy use in Europe and as such, building energy efficiency is one of the main levers to significantly impact global energy efficiency [2]. The combined consideration of these factors leads to the conclusion that only through significant enhancement of the renovation practices will we be able to reach the challenging goals set by contemporary environmental issues. This view is widely acknowledged and some research works have already demonstrated that advanced support such as decision–support systems for renovation action selection and assessment can bring significant benefits in terms of cost and energy efficiency [3].

However, some hurdles remain, among which one stands out clearly: the lack of digital information for existing buildings and, especially, of computable data, which prevents any intensive use of ICT tools (CAD tools, numerical simulation) that are so beneficial to building design practices. Most existing buildings have been designed and built following paper-based, 2D approaches, which result in few, if any, digital data. This particularly applies to 3D digital models (and more widely to Building Information Models) that, despite their importance to ICT-enabled design, are rarely available for existing buildings. One critical short term research challenge is therefore to devise effective and reliable methods and tools to reconstruct 3D digital models of existing buildings.

This diagnosis is not new: numerous research works have attempted to deal with the creation of existing buildings' 3D digital models. For instance, a recent literature survey [4] classified techniques into two groups, namely: non-contact techniques such as photogrammetry, videogrammetry, laser scanning, tagging and the use of available information, and a second group based on contact techniques such as tape measures or calipers. An alternative technique is to redraw 3D models manually using 3D modelling software tools but, in any case, all studies highlight that, regardless of the method chosen, the 3D model creation is a complex (requiring advanced skills) and time-consuming task.

The corollary of the above consideration is the impossibility of creating 3D models at reasonable costs. This explains the relatively low take-up of BIM (Building Information Modeling) and numerical simulation in the scope of renovation design practices and highlights the importance of the research area considered in this paper. Relying on extensive BIM and simulation design–support is, at the present time, particularly detrimental to the effectiveness of renovation design and construction. Indeed, BIM is widely acknowledged as the basis of modern building design [5] and brings significant benefits, far beyond visualization and CAD-based design: BIM embeds most of the building technical information about the building being designed and allows for seamless design data flow and management. The main difference between BIM and sole CAD tools is that digital models do not only include 3D geometrical and topological information, but also structured and semantic data, allowing for advanced query and analysis of design options [6]. One issue, however, is that BIM translates into expended but also more complex digital information. In the case of existing building digital model creation, this generates additional difficulties and requires more reliable model checking and validation techniques on top of 3D model generation tools.

The motivation for writing this paper can therefore be summarized as follows: (a) renovation can have a major impact on building stocks global energy efficiency; (b) advanced software design–support (of which BIM is a key element) significantly enhances the building design effectiveness; (c) enabling BIM-based, ICT-supported renovation design processes call for an effective and reliable approach to create and generate existing buildings' BIMs.

With these issues in mind, the objective of this paper is to pave the way for cost-effective generation of 3D BIM models through three key contributions: (i) the first is a critical review of a wide spectrum of techniques to generate 3D BIM, which highlights their strengths, weaknesses related applications and potential synergies. One important conclusion of this analysis is that there exists no universal solution; i.e., choosing one approach over the other significantly depends on the intended application, and on project-specific constraints; (ii) a focus on 3D BIM generation approaches based on scanned paper plans, including a step-by-step study of the generation process (image processing, building elements recognition, BIM generation and validation). This focus shows that the research results in this area are substantial, but fragmented – only limited parts of the generation process are usually addressed, without any real attempt to provide an exhaustive approach; (iii) substantial discussion and a research roadmap outline the potential of combining existing 2D-drawing-based and 3D-model approaches with the available methods based on images-processing.

The paper is structured along the above objectives. Section 3 provides a critical review of the proposals in the literature that focus on creating 3D models of buildings. The strengths, weaknesses and preferential applications of each approach are highlighted and discussed. Then, the methods based on the automated processing of scanned paper plans are thoroughly reviewed in Sections 4–6. Section 4 focuses on image processing and geometric primitives recognition, Section 5 gives a detailed account of building element recognition methods and Section 6 addresses 3D model checking and validation. Finally, Section 7 provides a conclusive discussion and highlights the next steps to take in the area of 3D building model creation.

2. Review methodology

Research on automatic recognition and reconstruction of 3D building models of existing buildings started in the 1990s with the breakthrough of ICT tools in the construction sector. In 1992, Koutamanis [7] laid out the foundations of this research theme by describing the rationale for conversion of paper plans into digital plans. As shown in Fig. 1, the frequency of reviewed papers per year in this research theme increased in 2005 and has since kept the interest of the community.

In the literature, numerous reviews and surveys about digital plans reconstruction already exist. However, they usually focus on a given approach (e.g. images processing) but do not provide any insights about, or comparisons with other techniques. In addition, numerous contributions that deal with specific components of the 3D model generation process, like symbol recognition or building model checking are available. Unfortunately, no available literature review deals with all the steps of the 3D model generation process (as depicted in Fig. 3). According to our study, the last review paper about generation of 3D building models from architectural drawings was published in 2009. Considering the fast evolution of the technologies and practices, we believe that an update is useful.

From a methodological point of view, our review follows a three-step approach (from a broad spectrum to more specific research issues), spanning both academic and applied publications. The final bibliography includes more than 100 relevant references.

In the first step, we targeted the broadest spectrum of existing approaches to generate a 3D building model. The main search keywords were “automatic 3D reconstruction”, “3D

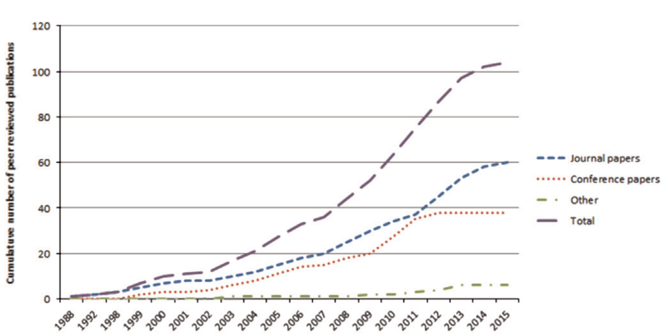

Fig. 1. Frequency of reviewed publications per year of publication.

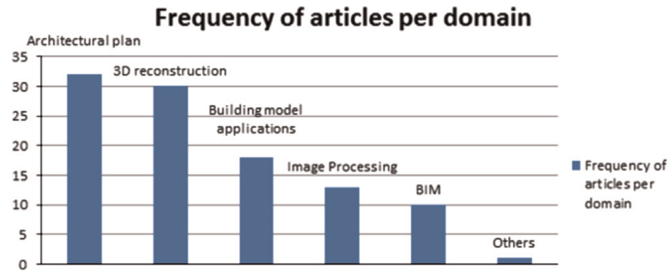

Fig. 2. Frequency of reviewed publications per domain.

reconstruction” and “existing building”. In the second step, we focused on 2D scanned plans and main keywords were “architectural floor plans”, “building recognition”, “floor plan analysis”. In the third step, we focused on the 3D building model and more particularly on model checking and validation. The main keywords were “BIM”, “checking”, “validation”.

We also studied the scopes of the journals from which the references were collected. This confirmed that the subject of interest is very wide and spans a large number of disciplines. As shown in Fig. 2, four main domains are represented: 3D reconstruction, architectural plan recognition, image processing and BIM and related applications.

3. An overview of building 3D model creation approaches

Various approaches have been devised [4,8] for the reconstruction of a 3D model of an existing building. Each brings its own strengths and weaknesses and, in this fast-moving technology area, it would be pointless to target a comparative ranking. However, one critical feature is worth being highlighted: type, breadth and source of building data that will be used to feed the 3D model generation, which, in our understanding, is a pivotal issue in 3D building model creation. A complementary issue is the level of information of the resulting 3D BIM (even if the latter can vary a lot depending on the requirements of the foreseen applications). There is actually no general answer about which information a 3D BIM includes and how it is modeled. However, it is widely acknowledged that a 3D digital model includes three components: geometry, topology and semantics. *Geometry* defines shape and dimensions, *topology* defines spaces and their relationships, and *semantics* describes additional characteristics, such as room functions, usually with dedicated attributes. Complete and valid building models can be generated only if these three kinds of information can be extracted from the input data of the generation process.

The two points above: (i) type, breadth and source of building data; and (ii) wealth of information in generated 3D BIM, underpin the study presented in the subsequent sections, where a large set of 3D model creation approaches are outlined and assessed. In particular, we focus on two kinds of approaches: those that rely on on-site data acquisition, and those that rely on building documentation.

3.1. 3D model creation based on on-site data acquisition

Many 3D model creation approaches are based on on-site data acquisition. Here we refer to those approaches that require dedicated building data collection, in order to bootstrap the model creation processes. Such approaches usually differ by the type of measurement device used (from light mobile devices to aerial cameras) and by the granularity of the collected data (from aerial photographs of large areas to a dense 3D cloud points of a room).

In this section, we give an overview of these approaches, emphasizing their specificities and related applications, differentiating between four main areas: aerial photographs, building ground pictures, laser scanning and mobile applications. The last subsection (Section 3.3) gives a summary and discussion, highlighting the motivation for our focus on 3D model creation from 2D scanned plans.

3.1.1. Aerial photographs

Many research works dealing with 3D reconstruction are based on aerial images [9,10]. These images of high-resolution are taken from an aerial vehicle (plane, UAV, satellite). The quality of the images is of utmost importance: weather and flight conditions can affect quality, for example by generating occlusions. The method to generate building images is to extract building footprints from a Digital Surface Model (DSM) composed of remotely sensed images. Large areas can be processed with little information (e.g. cities) in a very short time, and effectively enables the automatic identification and reconstruction of building roofs [11,12].

This method is successfully used by Geographic Information Systems (GIS) such as Google Maps.[1] However, one main limitation is the Level of Details (LoD), which is usually quite poor: the resulting models only include data about outdoor walls, roofs, and no information about outdoor openings and indoor elements. Such models, which only represent building envelope, possibly completed with a textural image on facades, correspond to low LoD (1 to 2) in the CityGML standard [13]. To summarize, these approaches are characterized by a high cost-effectiveness but a low granularity.

3.1.2. City building images

These images are usually taken at the street-level from different angles. They are mainly used for two applications: (a) in order to reconstruct a 3D picture of the building from several images and (b) in order to process façade images to identify and differentiate building envelope elements (e.g. openings, balconies). In the first case, the process is to take a set of images [14–16] that are then calibrated and oriented in order to retrieve 3D coordinates to model the scene [17]. This process can be automated, but the search of similar points between images is usually a critical point. Such approaches only allow the reconstruction of the envelope of the building. Indoor spaces have to be modeled differently.

In the second case, only the façade image of the building is processed in order to extract building elements such as doors, windows and their relative positions and dimensions. A critical issue, given the large variety of architectural patterns, is to reliably and accurately segment the façade images and to identify the façade elements. These approaches are therefore more relevant in the case of repetitive geometrically basic architectural patterns (e.g. large residential buildings from the 1970s). However, automated façade semantization is very relevant in combination with other methods, in order to enrich 3D models [18–20] and to reach higher levels of details (CityGML LoD 3).

3.1.3. 3D laser scanning

A lot of 3D building model reconstruction techniques are based on purely geometric 3D data, like 3D cloud points [21,22]. In order to create an "as-built" building information model (BIM), these techniques advocate the acquisition of dense 3D cloud points thanks to laser scans from key locations around (or inside) the building. Millions of points can be collected in a very short time to characterize both the building shape and its interior spaces. One drawback is that the quality of the generated data highly depends on the environment of the building, and on the design of its interior, which can both result in significant noise.

The general procedure to convert the 3D point cloud into a BIM consists of three main steps: data collection, preprocessing and modeling [23]. This process is for the most part performed manually, and in some cases may be time-consuming, subjective and error-prone [24]. According to the literature, depending on the size of the building and on the targeted granularity of the model, several months can be required to achieve the full 3D model creation process. However, laser scanning remains the most reliable and accurate reconstruction approach, and is worth being used in some cases despite its limitations. The state-of-the-art is also fast evolving and it is likely that cost-effective semi-automated laser-scanning approaches will be available in the near future [25–27].

The most critical limitation of laser scanning is that the models generated from cloud points only include geometric data (from which the topology can be deduced). More abstract information, like semantics, requires further processing or additional data. For instance, Li et al. [28] describe an approach to generate detailed (IFC) 3D models from 3D point cloud. Additional devices used in combination with laser scanning, like cameras, also allow us to enrich the semantics of the 3D model, by analyzing point colors [29]. In the same scope, other researches combined terrestrial photographs and 3D cloud points to generate BIM façades semi-automatically [30].

3.1.4. Mobile applications

The emergence of mobile technologies has led to the development of many applications specifically dedicated to "computer-assisted" plan reconstruction using mobile phone cameras (*MagicPlan*[2] is an example of such applications). These solutions are low-cost in that they only require a cheap mobile device for data acquisition, which is guided step by step. However, if the generation of the 2D plan is partially automated, many tasks are still done manually. For instance, model fine-tuning, such as rooms assembling and merging, still requires manual work. Also, these approaches do not target the generation of professional quality 3D models, but rather of rough 2D plans. They can therefore be useful to the larger public, but can only be considered in combination with more advanced techniques for professional use.

3.2. 3D-model generation from building documentation

Unlike the approaches introduced previously, which require on-site data collection, the ones outlined in this section rely only on documents. These documents mainly include design documentation like 2D architectural plans. An obvious advantage is that this information is readily available in most cases. One drawback, however, that the information is scarcely up-to-date. Most of the documents are usually issued at design phase and few (if any) updates are performed after commissioning. Three types of building documentation have been considered in our study: sketches, 2D scanned paper plans and CAD plans.

3.2.1. Building architecture sketches

Sketches are used to illustrate design concepts in the first steps of design and the related level of details is often low. Sketches can be drawn with paper and pencil or directly on a pad [31,32]. In the first case, 2D plans are processed offline. Once the drawing is achieved, it is processed as an image [33,34]. In the latter case, the

[1] https://maps.google.com.
[2] http://www.sensopia.com/english/index.html.

drawings are performed online on a digital pad and result in time-series instead of images. The movements are therefore analyzed by the software which can also perform automated drawing corrections relying on optimization algorithms [35–38].

3.2.2. 2D scanned paper plans

Scanned 2D paper plans are obtained from building paper plans which are scanned by an optical imaging scanner that transforms the plans into digital images. Additional processing may be required depending on the scanner quality and on the digitalization method. These plans are often complex and contain a large amount of information (various coastlines, measures, texts, etc.), which can generate significant noise in the resulting images. Therefore, the first processing phase is usually to clean images to delete the useless information. Then, the aim is to extract meaningful and structured information: geometric primitives, text, etc. As mentioned before, a general issue with scanned plans is that drawing errors and inaccuracies can generate significant inconsistencies (topological and geometric problems), which can hinder recognition and reconstruction tasks [39].

3.2.3. CAD plans

CAD plans are in vector format i.e. they are composed of geometric primitives, like lines and polylines, instead of mere pixels. A CAD plan is organized in layouts, each layout being related to specific types of drawing elements. Layout configuration may vary depending on the designers' requirements and constraints. There exist some solutions to convert CAD plans into 3D building models [40], but they require some actions to be performed manually. For instance, complex door and window geometries have to be simplified by the user. One of the advantages of CAD-based drawings is that the resulting lines are crisp and precise. They also contain more information than sketches [41]. The main weakness of a CAD plan is that it is not usually available for old buildings.

3.3. Summary and discussion on building 3D models creation approaches

Choosing from the different approaches outlined above depends on specific criteria such as (i) the building environment, which can be an obstacle to the use of some methods; (ii) the budget allocated to the project and the required level of investments, both in terms of equipment and workload; (iii) the level of details required for envisioned applications. Only the knowledge of the combination of these three parameters allows determining the most suitable method. Tables 1 and 2 summarize the advantages and disadvantages of each approach. Mobile applications are not included in this summary because they are better suited to public consumers' needs than to professional purposes.

Approaches that use aerial photographs or city building images provide models that contain poor semantic information and do not include indoor space information. These methods are relevant for applications that simply require building footprints such as electrical design assessment or realistic environment simulation for video games, but they prove to be insufficient for more advanced applications, such as indoor navigation simulation [42,43]. In this case, the building model has to include more detailed information about its internal elements and additional semantic information, such as room function or wall materials types and properties.

Laser scanning approaches allow the generation of accurate and reliable models, which can be easily imported into BIM software. These approaches are clearly way above average when it comes to precision and reliability. However, they also require an extensive range of equipment and a significant workload. They are fully relevant in the scope of heavy, high end renovation projects, but can be too expensive in the case of massive renovation actions, implemented over large buildings stocks.

Approaches based on building documentation (sketches, 2D scanned plans, CAD plans) can be relevant in some cases. They have significant advantages, the main being that the required information is available at no cost. However, as the methods that rely on aerial or ground-level photographs, these approaches can result in incomplete or inaccurate models, since their effectiveness heavily depends on the reliability and completeness of the documentation.

The paragraphs above confirm that the selection of a method

Table 1
Comparison of methods to generate 3D building model when data are acquired on-site. Some of themes and results are extracted from [4].

Themes	Aerial images	City images	Laser scanning
Data acquisition			
1. Cost	High	Medium	High
2. Time	Medium	Medium	High
3. Influence of size and complexity of the scene	High	High	High
4. Influence of environmental conditions	High	High	Medium
5. Equipment portability	Low	High	Medium
6. Equipment durability and robustness	High	High	High
Data characteristics			
7. Data type	Remotely sensed images	Images	3D cloud points
8. Level Of Detail(LoD)	Poor (0–2)	Medium (0–3)	High (0–4)
9. Data volume	High	Medium	High
Data processing			
10. Time of processing	Medium	Medium	High
11. Degree of automation	Medium	High	Low
12. Complexity of the processing	Medium	Medium	High
Accuracy of the resulting model			
13. Geometry	Medium	Medium	High
14. Topology	Medium	Medium	High
15. Semantic	Low	Medium	Medium

Table 2
Comparison of methods to generate 3D building model when data are already available. Some of themes are extracted from [4].

Themes	Sketches	CAD plans	2D paper plans
Data acquisition			
1. Availability	Low	Medium	High
2. Quality	Medium	High	Variable
3. Up-to-date	Low	Medium	Medium
Data characteristics			
7. Data type	Image	Vector format	Image
8. Level Of Detail(LoD)	Low	High	High
9. Data volume	Low	Medium	Low
Data processing			
10. Time of processing	Medium	Medium	Medium
11. Degree of automation	Medium	High	Medium
12. Complexity of the processing	Medium	Medium	Medium
Accuracy of the resulting model			
13. Geometry	Medium	High	High
14. Topology	Low	High	High
15. Semantic	Low	High	High

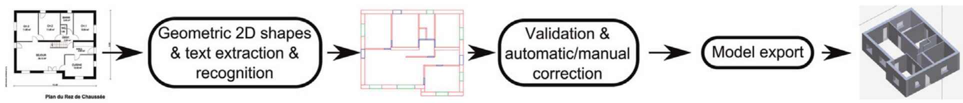

Fig. 3. General process to convert 2D plan into 3D building model.

will highly depend on the end users objectives and constraints. It is also obvious that synergies can be found: where some approaches can be too expensive but more reliable, some others are very cost-effective but can result in incomplete or inaccurate models. Using a combination of the existing methods could therefore achieve more potential than each approach individually. In particular, if the aim is to ensure the widest impact possible, approaches that rely on available information and do not require any on-site data collection are probably the most (cost-)effective. Their limitations are known and can possibly be balanced by relying on complementary methods. One promising option is to combine the 3D building models generated from 2D scanned plans, and then, to complete and update the model through additional focused data acquisition and processing: e.g. façade photographs, or targeted 3D cloud points of specific building parts generated by laser scanning. In such an approach, a critical component is the generation of (initial) 3D building model from 2D plans. We therefore provide, in what follows, a step-by-step study of the generation process represented in Fig. 3.

4. Recognition of geometric primitives and preprocessing

The generation process starts with some preprocessing, in order to clean the data and reach the quality level required for the subsequent phases. Architectural plans actually contain a large quantity of heterogeneous information, but not all this information is useful at each step of the recognition process. Two kinds of elements are then recognized: lines that define building elements and text labels that give miscellaneous information (e.g. surface areas or room names).

Scanned plans require intensive image processing to clean images and extract all useful information. Distortions may occur, which can negatively impact the precision of the generated model metrics and geometry. Cleaning essentially aims at removing the noise caused by scanning itself [44], but also by some image elements (e.g. a background grid, a title, etc.). The process usually includes binarization of the image, text extraction and line detection. To decrease processing time, scanned plans can be split to process each area separately, and then combine the results [45].

4.1. Binarization and text extraction

The first preprocessing step deals with image *binarization*. The aim is to minimize the quantity of available information while preserving useful information. This treatment allows removing the noise from the image. Binarization results in a black and white image (only two classes of pixels), which facilitates subsequent treatments. Ghorbel [46] distinguishes three binarization types: *global binarization* where the threshold is unique for the image, *local binarization* where the threshold depends on the pixel and local information and *dynamic binarization* where the threshold of a pixel depends on the neighboring pixels.

After binarization, *text extraction* isolates text information from the background. The related state-of-the-art is substantial [47] and shows that one of the main difficulties is to automate the process, because of the heterogeneity of images (e.g. color variations).

The QGAR Project led at LORIA (France) [48], focused on graphic recognition and document analysis. During this project, free software was developed including basic graphics analysis and recognition tools. The project stopped in November 2008 and the software has not been updated since then, but many functions are still available. The QGAR approach consists of splitting the plan into two layers: one for the text and the other for graphical objects [49,50]. This algorithm has the advantage to be independent from text font, size and orientation. To evaluate their results, a comparison was performed between the number of characters manually recognized in each image and the number of characters automatically recognized by the method. The study showed that reliability highly depends on image quality: up to 92% of recognition for a good image quality, but only 22% for a very bad quality image, in which only 7 of 31 characters were found. This method can be applied when text and graphical elements overlap, which often occurs in 2D architectural plans.

Even if this step is complex and depends on image quality, it is essential to the recognition stage. In particular, text is important to extract semantic information from 2D plans (e.g. room functions). Moreover, binarization and text extraction remove noise or elements that can hinder subsequent recognition tasks.

4.2. Line detection

Line detection is performed only once text information has been filtered out, since text pixels can cause errors during recognition or even be confused with walls or others elements. A selection of line detection methods is outlined in what follows.

Vectorization is a process that converts raster data into vector data: sets of pixels are transformed into geometric primitives such as lines, polylines, or curves. This field of research is well known, and a recent survey classified existing methods into six categories [51]: Hough transform-based, thinning-based, contour-based, run-graph-based, mesh-pattern-based, and sparse-pixel-based. The main evaluation criterion is that an effective vectorization method should preserve information related to the shape including line width, geometry and intersections. According to this study, sparse-pixel-based vectorization is the most promising approach: time complexity is linear and shape information is preserved.

In the more specific scope of architectural drawings, a number of methods have been implemented and tested. For instance, Dori and Lieu [52] applied the Sparse Pixel Vectorization (SPV) approach, in which only medial axis points are selected to decrease computing time. Su et al. [53,54] also proposed an algorithm – called Global Line Vectorization (GLV) – that does not rely on skeletonization in order to optimize lines width preservation. This latter point is very interesting because width is usually correlated to wall types.

Potrace [55], which stands for "polygon tracer", is another automatic vectorization solution that is used in popular software such as Inkscape (a free vector drawing software).[3] Here, the resulting image is composed of a set of polylines (continuous lines composed of many line segments). This requires additional processing to sort out the polylines and to detect plain lines.

OpenCV is a popular open source computer vision library which includes a lot of basic image processing functions, including

[3] https://inkscape.org.

vectorization.[4] The OpenCV vectorization module is based on Hough methods and allows more effective recognition of image segments. Tests performed on floor plans show that for the same 2D architectural plan, Potrace provides a set of 250 lines composed of 4600 segments while OpenCV Hough vectorization results in a set of 420 segments.

Some of the methods reviewed advocate the separation of thin and thick lines into two layers, for instance using mathematical morphology [56]. This step is not mandatory but the advantage is that the vectorized image will be composed of fewer entities and recognition will be simplified.

5. Recognition of building elements

After the extraction of geometric primitives, building element recognition takes place. The aim is to characterize building elements along three components: geometry, topology and semantics. Topology and geometry are linked and concern essentially walls, openings and rooms. Semantics can be determined thanks to element shapes, but also deduced from text and symbol recognition.

5.1. Walls and rooms recognition

Our review shows that wall and room recognition is a widely addressed topic. This step is actually critical to the recognition stage, particularly to determine the building footprint. One of the main difficulties is that small lines can introduce artifacts during recognition. To sort out walls, some authors propose sorting criteria (wall typologies), like Choi et al. [57], who differentiate between normal walls that can contain openings (e.g. doors and windows) and virtual walls (e.g. rails and open walls). In the following, we summarize the three main methods for wall and room recognition.

The first method (method 1 in Table 2), is based on edges resulting from a previous vectorization. The rationale is to choose an edge representing a wall and to follow it to reconstruct rooms and spaces. This method was first proposed by Lewis and Sequin [40] in 1998. It can be improved using edge thickness between two parallel lines to check whether this edge represents a wall [58,59]. An analysis based on thickness allows the recognition to be faster because the set of possible walls is reduced. Conversely, the risk of missing a wall is higher.

The second method (method 2 in Table 2), proposed by Macé et al. [60], consists in line detection and is based on the coupling of Hough Transform and Image Vectorization. Three steps are necessary: first, lines that are both parallel and close to each other are selected as potential walls, then, the texture between the two lines is analyzed, and finally, wall connections are checked.

The last method (method 3 in Table 2) [61,62] relies on a patch-based, pixel-level, segmentation approach. The floor plan image is separated into patches, which are small areas of the image. Further processing assigns a label to each patch using a learned vocabulary, and the probability for each patch of belonging to each object class. This method is used to detect walls in architectural floor plans.

These three methods were tested on the same architectural plan database containing 90 images for walls and rooms detection. The results, given in Table 3 (extracted from [62]), suggest that methods 1 and 3 are the most effective.

[4] http://opencv.org/.

Table 3
Wall and room detection results. The table is extracted from [62]. Wall detection results are not available for the method 2.

Detection rate (%)	Method 1 (%)	Method 2 (%)	Method 3 (%)
Wall detection	90.00	X	97.00
Room detection	94.88	85.00	94.76

5.2. Symbol recognition

Symbol recognition is also an important part of building plan processing. In architectural plans, a symbol is defined as a set of pixels that is neither part of a geometric primitive nor of a text element. Two symbol types may be differentiated: prototype-based symbols (doors, windows) and texture-based symbols (hatching or tilling representing walls). In particular many research works have focused on recognizing freehand-drawn diagrammatic sketches [63]. Regarding the architectural plans, the recognition process is generally complex and time-consuming due to the lack of symbol standardization. Related methods are usually sorted into two groups: statistical symbol recognition based on characteristics of pixels, and structural symbol recognition in which symbols are partitioned. Most symbol recognition methods rely on rule databases [64,65], which can be dynamically adapted when new symbols are discovered [66–68].

Some authors propose further improvements to this general scheme. For example, the so-called “repeat mode” introduced in [69] only retrieves fully identical symbols. It can be useful when symbols include repetitive patterns (e.g. stairs). In addition, Valveny and Marti [70] introduced two types of deformable templates to extend the recognition spectrum, namely: global deformation that includes translation, rotation and scaling, and local deformation of lines.

5.3. Semantic information

Semantic refers here to all the information attached to an element excluding those concerning topology and geometry. For example, semantic information for a room can be its function, or the maximum number of people allowed in the room. Extracting this information is necessary to complete the model and to reach a better understanding of its structure.

Since most semantic information is contained in the text, a lot of methods rely on character detection and recognition. Some methods are manual [71] or semi-automatic. For instance, in [54], the user points to a text item and the system detects automatically the corresponding word from a mapping between strings and a dictionary. In [72], text recognition is used to label rooms automatically in order to determine their functions.

5.4. Graph based recognition

Some research works advocate relying on graph-based approaches during the recognition process [73–75]. For instance, Dominguez et al. [76] used a wall adjacency graph (WAG) to detect walls and openings and to search for intersection points between walls in a CAD document. Nuchter and Hertzberg [21] also used graphs constructed from 3D models to generate maps for mobile robots. These maps consist in constraints networks, in which nodes represent different planes types (wall, floor, ceiling, door, no feature) and edges represent different relationships (parallel, orthogonal, equal-height). These graphs do not contain only building elements but also topological and geometrical relationships.

Other approaches apply more advanced techniques from the graph theory in order to extract internal layout (rooms and other internal building elements). For instance, Huang et al. [39] use the concept of loops and the graph theory to identify spaces in the building. The rationale is to check for specific patterns (loops) in the graph built from the plans, which map to specific building elements (e.g. columns, rooms). Zhi et al.[77] follow a similar approach in order to obtain the topology and geometry of the building to generate evacuation plans.

6. 3D building model checking and validation

Regardless of the technique chosen, the final step is always to check, correct and validate the generated model. In this respect, the literature emphasizes two main objectives. The first is to perform general-purpose validation and checking, for instance to assess compliance with a standard or to check for geometry, topology and semantic correctness. The second is to check model for application-specific purposes. In the latter case, one usually assumes that the building model has beforehand gone through the general-purpose validation and checking phase.

6.1. Overview of the checking and validation process

In 2009, Eastman et al. [78] identified four main checking and validation steps: (1) Rule interpretation, (2) Building model preparation, (3) Rule execution, (4) Rule check reporting. Rule interpretation (1) consists in translating rules into a computer-processable language. The subsequent step (2) consists in checking the model for its completeness and can be performed automatically or manually. Then, rules are applied on the model (3) and finally, a report, which lists all errors found in the model according to the rule base, is generated (4). The report is often linked with a model viewer and corrections can be performed through the viewer interface.

Checking building models may be time-consuming and expensive, because it requires specific skills, knowledge, and significant manual intervention. This is the reason why many research works have aimed at automatizing this task, with little success until now .

The format in which building models are expressed is also a critical point. Software solutions allowing us to draw 3D models manually, such as Sketchup,[5] Blender[6] or Sweet Home 3D,[7] often use specific proprietary formats. Some open standards have also emerged. The most popular is probably the Industry Foundation Classes (IFC) from BuildingSmart international. The IFC standard is widely used for 3D building modeling and a lot of tools provide export/import functions. CityGML from the OGC (Open Geospatial Consortium) [13] is another well-known GIS (Geographic Information System) standard, but which relates more to city scale. The wide variety of BIM formats and software may result into *interoperability* issues [79]. Interoperability is the ability to safely and reliably share and exchange information. It is recognized as a challenge and a limitation that hinders BIM take-up and that results in significant costs for architects, engineers, general contractors and building owners [80,81]. Most of the authors, for instance Greenwood et al. [82], argue that open standards like IFC should be favored. However, IFC and other available formats do not include all information required for checking and additional data usually have to be added before running model-checking tools. Also, IFC does not solve all interoperability issues as shown by [83–85].

6.2. General-purpose building model checking

This subsection focuses on building model checking against standards and general rules common to all buildings.

Horna et al. [86] proposes to check 2D plans before 3D reconstruction. The aim is to obtain a correct 2D plan without errors and inconsistencies. For the semantic part, only room names are checked and users have to give semantic information when an element is not named.

In a similar way, Niemeijer et al. [87] propose a system that checks automatically an IFC model against predefined configurable rules. This system is used for mass customization in the housing sector. An architect designs a plan for clients who can subsequently change the design without the architect's help. Constraints on the building like “Every window must be less than 1200 mm high” are edited thanks to pre-defined and configurable rules. Some solutions also propose to use additional information sources, e.g. a separate database with missing information, or to extend the IFC standard [88], or even to devise a new standard tailored for constraints checking.

Borrmann et al. [89] propose an approach to enforce spatial constraints during the design process. The context is collaborative design, where one team member can issue a rule that applies to a set of objects. Then, the rule will be automatically enforced in order to prevent any modification that could violate it. A challenge during checking is that rules are only written and accessible by experts of the domain. As a consequence, an intermediate level of abstraction is proposed, which lies between building geometry stricto sensu and more intuitive, human spatial reasoning.

Software solutions also exist, such as the Solibri Model Checker, which has been developed by the Solibri company to allow the analysis of BIM models for “integrity, quality and physical safety” [90]. This tool allows checking IFC models validity and correctness. The model is checked against a pre-defined set of rules including building structure, component types, spaces, etc.

6.3. Application-specific models validation

After the general-purpose checking phase introduced in the previous section, additional validation activities can be performed in order to check the models against application and user-specific requirements.

For example, Casella et al. [91] check safety criteria in a building, and more particularly emergency paths, by relying on building sketches. In a similar way, but with a wider scope, Ding et al. [92] work on a solution for configurable automatic checking of building models (DesignCheck), in which checking is possible at different levels during design and construction: sketch design, detailed design and documentation.

Some other works focus on safety at construction phase [93,94]. The aim is to check a BIM model against safety rules to detect safety problems that could occur on the construction site and to inform construction engineers and managers. It is a critical field of research because the majority of accidents occurring on construction sites are due to inappropriate or insufficient safety measures.

Another field of research relates to the compliance with regulations promoted by governments or other authorities. In this

[5] http://www.sketchup.com.
[6] http://www.blender.org/.
[7] http://www.sweethome3d.com.

scope, Yurchshyna et al. [95] propose a semi-automatic checking of construction projects against applicable regulations that relies on domain experts for rule interpretation and checking report generation. Hjelseth and Nisbet [96] also worked on automatic model checking based on semantics. Their approach relies on an ontology and aims at analyzing the probability of risk of moisture in buildings.

An important remark is that these application-specific model checking and validation approaches require detailed and focused information that has to be extracted from building models. Once again, the choice of the 3D building model format is a big challenge to be able to easily extract all required information.

7. Discussion

For the last 20 years, research teams have been working to improve both recognition performance and computation time of 3D model generation tools. Significant advances have been achieved in the area of symbol recognition and image processing. The introduction of BIM has also resulted in enhanced building modelling and representation capabilities.

However, this literature review has also highlighted strong limitations. First of all, no available solution enables the full-fledged generation of 3D models from 2D plans. A number of methods exist to deal with specific steps of the process. Image processing methods (text and graphic separation, line detection, symbol recognition), or 3D building model validation and checking are for instance extensively addressed. But to the best of our knowledge, no research work addresses the whole reconstruction process in an integrated way. Another issue is that the involvement of multiple, heterogeneous software components and files into the 3D building model generation process can result in interoperability issues. For example, model validation and checking activities may require information that cannot be represented in the format chosen for the 3D models. Even though the introduction of international open standards like IFC certainly helps, this research issue remains open.

Another outcome is the lack of information in source plans, which generally results in less reliable recognition and in incomplete 3D models. Actually, information about the third dimension and about the materials used to construct the building is in practice not included in 2D plans. This issue is further discussed in Section 7.1.

In the remainder of this discussion, we will focus on two issues, which seem particularly critical to future advances: the improvement of the reliability and the completeness of generated 3D building models using additional information sources, and the enhancement of underlying 3D data building model to facilitate 3D reconstruction and to ensure compliance to standards.

7.1. Limitations of existing methods

In this section, we present the two main limitations of existing methods. The first is the difficulty to identify and generate automatically some building elements. The second is the lack of information in generated 3D models from 2D scanned plans.

7.1.1. Building element identification limitations

One main issue is that many elements are still not recognized automatically. For instance, it is difficult to identify and model stairs because they have no universal and standard representation in 2D plans. The corresponding 3D shape is also not trivial to generate. Stairs are usually represented in the 2D floor plan by their footprint and no information is given about their shape, railing system, and all related measurements such as step height.

Due to the complexity of symbol identification, in most of the cases stairs are simply not recognized and removed from plans. Roofs, also, are scarcely included in 2D plans; they can in some cases be represented by thin lines, which are not easily recognized and cannot be isolated from other elements. The automatic generation of a roof is therefore a complex task, whose reliability depends on various factors, namely: the shape of the building, the way the roof is represented, and the quality of the source plans.

Also, furniture is not well recognized and not even considered during the process, despite the fact that it could bring additional semantic information and could help in completing or checking models (for instance, identifying a sink could indicate that the corresponding room is a kitchen).

7.1.2. 3D model incompleteness

Generated building models usually include limited semantic information. In the literature, as far as semantics is concerned, recognition focuses on room name recognition, in order to label spaces. Generally, characters are well recognized and text bounding boxes are also reliably extracted. However, it would be beneficial to extend label extraction and recognition in order to enrich generated models to reliably recognize complex elements like stairs.

The third dimension (height) is also critical. Existing approaches only allow for 2.5D: height is either set by default or configured by end users. The same goes for windows and their vertical placement in the wall. This information cannot be deduced from the 2D plans and therefore the generation of complete 3D building models, which could be used for advanced checking or simulations, is beyond the reach of existing approaches.

To summarize, the main limitations of existing 3D model generation approaches are (i) the difficulty to integrate all processes into a complete process due to interoperability issues; (ii) the lack of information in the source plan such as the third dimension, which results in incomplete 3D building models; and (iii) the difficulties to identify and generate automatically some building elements, such as stairs or roofs; (iv) the strong dependency to input images quality and completeness.

7.2. Toward augmented models

We outline in this section two types of upgrades that could significantly enhance the generation of 3D building models: (i) relying on complementary data sources and (ii) enabling for iterative, user-in-the-loop models validation.

7.2.1. Complementary data sources

In order to overcome the intrinsic limitations of 2D floor plans, it is necessary to rely on additional complementary data sources. Actually, some other solutions exist to create BIM from existing data [4], one of which is to use different views of the building (front, side, top) to reconstruct it [97,98]. Drawing our inspiration from this approach, we propose to supplement 2D drawings based methods with easy-to-collect on-site data, like building façades photographs.

Façade images actually bring a lot of useful information. For instance, Ok et al. [19] parsed building façade images to deduce various building characteristics: height of the building, numbers of windows, level or window positioning. Using such information would be very useful in order to enhance and check generated 3D models. This would allow us to reliably evaluating the height of the building (height of walls as well as window positions in the wall) but would also be useful to check the generated model, by comparing the number of outdoor openings and their type (window or door). An image can also bring additional semantic information about outdoor building wall composition. In a similar

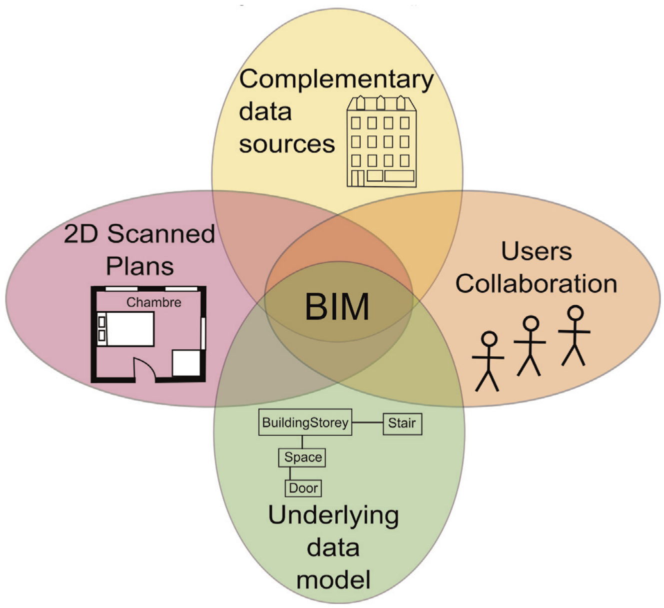

Fig. 4. Potential topics for future research.

way, aerial photos can also be used to automatically update and validate roofs generated from the 2D plans information [99].

7.2.2. User-in-the-loop interactive 3D models generation

Making a system fully automatic is usually not achievable because plans contain too many heterogeneous elements. As a consequence, it is necessary to devise semi-automatic approaches; i.e., a way of relying on users in the recognition process that does not require specific expert skills. Conversely, another issue is to minimize the time spent by human operators. The aim is therefore to identify, during the recognition process, inconsistencies or potential mistakes and to generate warnings that will be taken into consideration in on-site survey preparation. Applications presented in Section 6 allow us to generate a report containing errors in the 3D building model but to the best of our knowledge, no application is available that would interactively support end users in identifying potential errors at recognition phase.

Another promising route would be to devise a BIM-based collaborative system to help with the correction of the errors occurring during the recognition. Such a system would leverage the collaboration between many human actors and would efficiently contribute to the improvement of the model. Such an approach could rely on studies that have been conducted on BIM collaboration and more particularly on related user requirements [100]. Tools also exist, like Active3D [101] or a.SCatch [102], in order to improve data exchange and collaboration. However, such collaborative approaches would require a very high level of interoperability to be reached. In order to collaborate, a unique data format would be necessary to avoid the loss of information by converting data to be readable and used by all participants.

7.3. BIM data model

As already mentioned, the choice of the BIM model used for 3D models generation process is a critical point. In this scope, two main trends may be highlighted. The first is to rely on a straightforward, flexible, light model like a graph. Using graphs as an underlying model actually brings several benefits. They include the three geographic components that are necessary to building modeling: topology, which is deduced from links in the graph, geometry, which can be defined by nodes coordinates and semantics, which is expressed thanks to node attributes. Corrections can be achieved directly on the graph during recognition, by continuously monitoring graph construction. After recognition, it is possible to export graphs in any standard format. Processes are therefore independent from standard format modifications because only the process to convert the graph into the standard format would be impacted.

The second trend is to rely on more exhaustive data models, fully dedicated to building modelling. This choice is the most frequent in the scope of building model checking. In this case, buildings are modeled using a BIM standard format and most of the proposals rely on the IFC (Industry Foundation Classes). Actually, the numerous classes available allow for various ways of expressing the same relationship [103], and therefore can make building model reconstruction more difficult. IFC is quietly an active specification, of which new versions come out regularly (the last was released in March 2013). This requires continuous updates to remain compliant with the standard.

A conclusion is that IFC is one of the most complete building models, which allow describing a building during all its lifecycle, and the only one to be an international standard. For specific applications such as indoor navigation or energy simulation, IFC can be extended to add specific information necessary to the simulation [104]. A relevant approach could be to devise a simplified building modelling format that would be natively compatible with standard formats such as the IFC data model. This would both facilitate iterative real-time building model reconstruction, and ensure straightforward translation of the resulting model into the selected standard format. Last but not least, the issue of semantic modelling has to be carefully considered. In this scope, both graphs and BIM standards fall short in expressing sufficiently rich semantic information and more advanced knowledge modelling approaches could be required [105].

The roadmap illustrated in Fig. 4 summarizes the discussion and highlights potential topics for future works.

8. Conclusion

This paper gives a review of the results achieved over the last 20 years in the area of 3D building model reconstruction from 2D scanned plans, relying on a well-defined methodology and an extensive bibliography. The review covers all stages of the 3D reconstruction process, from raw data to high level models, or in other words, from on-site data collection to 3D building information model (BIM) export and validation, including image preprocessing and feature extraction.

The review shows that there is no universally applicable solution to generate 3D models of existing buildings: each approach comes with specific strengths and weaknesses, and selecting one or the other heavily depends on project and user-specific requirements. However, the study also highlights promising synergies between existing approaches and the potential benefits of moving from comparison to combination.

As regards approaches for 3D model generation from 2D drawings, the related state-of-the-art is substantial but fragmented. Most researches tend to focus on specific, limited steps of the 3D generation process, but none managed to tackle the whole process. This is partly a consequence from interoperability issues that hinder the seamless propagation of information all along the generation process. Standard BIM data models, like BuildingSMART IFC, have a major role to play here, to allow for the combination of the various components into an integrated system. In addition, further improvements are required in building elements recognition: complex elements, such as stairs or roofs, are still poorly processed or, even simply ignored.

The main conclusion of this review is that combining existing approaches could be the most effective way to overcome the identified limitations. In particular, the combination of 2D drawings-based approaches with focused, on-site, data acquisition and processing (e.g. façade photographs or targeted laser scanning) could lead to significant improvements. The aim would be to rely as much as possible on low-cost methods (2D drawings based generation, façade image segmentation) to generate initial 3D models that would then be enhanced and completed by detailed, on-site data acquisition (targeted photographs and laser scanning) and assisted user intervention. This way, a good trade-off between cost-effectiveness on one side, and reliability and accuracy on the other side, would certainly be reached.

Acknowledgments

The work presented in this paper was supported by the European Community's Seventh Framework Programme under Grant Agreement no. 609138 (Project HOLISTEEC). We would like to warmly thank our referees for their insightful comments on earlier versions of this paper. We are also grateful to Dr. Hassan Sleiman from CEA LIST and Shaun Howell from Cardiff University for their revisions and comments.

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