An Integrated Scan-to-BIM Approach for Buildings Energy Performance Evaluation and Retrofitting

Enrique Valero*[1], Dibya D. Mohanty[1], Michal Ceklarz[1], Boan Tao[1], Frédéric Bosché[1], Giorgos I. Giannakis[2], Stefan Fenz[3], Kyriakos Katsigarakis[4], Georgios N. Lilis[4], Dimitrios Rovas[4] and Antonis Papanikolaou[2]

[1]School of Engineering, The University of Edinburgh, United Kingdom
[2]Hypertech SA, Greece
[3]Xylem Technologies, Austria
[4]Institute for Environmental Design and Engineering, University College London, United Kingdom

* Corresponding author: e.valero@ed.ac.uk

Abstract -

Energy retrofitting is paramount to reduce the use of energy in existing buildings, with benefits to the environment and people's economy. The increasing use of novel technologies and innovative methodologies, such as Terrestrial Laser Scanning (TLS) and Building Information Modelling (BIM), is contributing to optimise retrofit processes. In the context of energy efficiency retrofitting, complex semantic 3D BIM models are required that include specific information, such as second level space boundaries (2LSBs), material energy performance properties, and information of the Heating Ventilation and Air Conditioning (HVAC) system and their layout. All this information is necessary for energy analysis of the existing building and planning of effective retrofitting strategies. In this paper, we present an integrated (semi-)automated Scan-to-BIM approach to produce BIM models from point clouds and photographs of buildings by means of computer-vision and artificial intelligence techniques, as well as a Graphical User Interface (GUI) that enables the user to complete the models with information that cannot be retrieved by means of visual features. Information about the materials and their performance properties as well as the specification of the HVAC component is obtained from a database that integrates information from BAUBOOK, OKOBAUDAT and ASHRAE. The Scan-to-BIM tool introduced in this paper is evaluated with data from an inhabited two-storey building, delivering promising results in energy simulations.

Keywords -

BIM; Energy; Retrofit; Scan-to-BIM; TLS; Photogrammetry; HVAC

1 Introduction

Following the recast of the Energy Performance of Buildings Directive, the retrofitting of the building stock paves the way to energy savings and reduction in greenhouse gas emissions. To accurately predict the actual energy performance of existing buildings and evaluate the impact of potential energy retrofitting scenarios, Building Energy Performance (BEP) simulations are increasingly used. However, the preparation of the input data for simulation suffers from two major drawbacks: (1) it is a very time-consuming process, often requiring more time than is available within project deadlines, and (2) it is a non-standardised process that produces BEP simulation models whose results can significantly vary from one modeller to another.

Over the last decades, Building Information Modelling (BIM) has played a pivotal role on digitalising the Architecture, Engineering and Construction (AEC) industry. Considering the tangible benefits of BIM tools to facilitate communication, collaboration and information exchange between stakeholders, a number of national governments have actively promoted BIM and in some cases established BIM regulatory requirements [1]. As a consequence, the adoption and availability of Building Information Models have significantly increased. The extensive information compiled in BIM models has promoted this methodology as a key enabler to automate the generation of BEP models [2, 3, 4], contributing to the resolution of the aforementioned issues.

The generation of BIM models of existing buildings is challenging due to the complexity and diversity of building geometry. New technologies, such as Terrestrial Laser Scanners (TLS) or photogrammetry (PG), now enable the acquisition of dense and accurate 3D geometric data, in the form of point clouds. This data can be used as guidelines to define the geometry of the building components in the process called Scan-to-BIM [5, 6]. Although Scan-to-BIM is generally a manual process in current industrial practice, there is extensive research to develop algorithms to automatically extract geometric features from point clouds and define the geometry delimiting spaces in buildings [7] [8]. Other authors [6] have gone a step further, producing structural BIM entities (e.g. walls) from semantic information extracted from point clouds.

However, for robust modelling and simulation of the energy performance of existing buildings and designing of any retrofitting solution, more information is required than just geometry of the structural (i.e. 'primary') components of buildings (e.g. floors, ceilings, walls, openings). First, Second Level Space Boundary (2SLB) [9] geometry must also be inferred from this. Besides, material types (and energy performance properties), as well as the location of Heating Ventilation and Air Conditioning (HVAC) components and organisation of HVAC systems also need to be captured and modelled. These aspects have received comparatively less interest from the research community. Some works have been published on the detection of 'secondary' components, such as Mechanical (or HVAC), Electrical, and Plumbing (MEP) equipment [10, 11]. But, an important aspect is the integration and codification of structural and MEP information in unified models, ideally in the open IFC format [12], to provide interoperability (which is important as such information may then be employed by various software packages to conduct energy simulation and retrofitting design).

In this paper, we present a Scan-to-BIM approach that is able to: (1) automatically model structural and MEP components, by processing point clouds and photographs of buildings, (2) enables the manual editing of materials and MEP properties using a large online repository of actual components and materials, and (3) outputs the semantically-rich model in standard-compliance IFC format with all the required information for robust energy analysis and design of the retrofitting strategy.

2 Methodology

The approach presented in this paper, illustrated in Figure 1, can be divided into three sub-components:

1. Structural Scan-to-BIM (Subsection 2.1), where structural elements are extracted from a point cloud and an initial BIM model is produced in IFC format;
2. Mechanical, Plumbing and Electrical (MEP) Scan-to-BIM (Subsection 2.2), in which MEP components are detected in pictures and added to the BIM model; and
3. Scan-to-BIM Editor (Subsection 2.3), which is used for manually populating the BIM model with information that cannot be extracted from visual features (e.g. material layers and properties, as well as MEP component properties).

2.1 Structural Scan-to-BIM

The objective of the Structural Scan-to-BIM sub-component (delimited in green in 1) is: the detection in the input point cloud of the main structural components of buildings, their parameterisation, and the codification of the delivered information into an IFC-SPF file. This tool is divided into a number of tasks (or algorithms), which analyse the building from general to specific and are summarised in the following.

- **Storey identification**: The first stage of the Scan-to-BIM process consists in the segmentation (i.e. labelling) of the point cloud (Figure 2a) into storeys. The proposed approach for this operation is based on the analysis of point density along the vertical axis. Similarly to the strategy followed in previous works (e.g. [13], [14]), a histogram is generated and ceilings and floors are extracted. Then, these are used for defining the storeys, and points with a z-value between z_{floor_i} and $z_{ceiling\_i}$ are labelled as being part of storey i, as illustrated in Figure 2b.

- **Structural component detection**: Each segmented point cloud representing a storey of the building is processed to model the slabs (Figure 2c) and to extract the wall boundaries.

  The points corresponding to the ceiling of each storey are first extracted and subsequently voxelised and segmented into clusters using the Euclidean Cluster Extraction algorithm [15], since no ceiling points are found inside walls. Each of the resulting clusters delimits a space (i.e. room) (Figure 2d).

  The boundary of the ceiling of each space is modelled as a boundary representation (B-Rep) and, assuming that walls are vertical, the points defining the visible surface of each wall are searched and labelled accordingly (their projections onto the plane defined by the ceiling lie on the vicinity of the segments).

  As a result, the point cloud corresponding to each storey is segmented into polygons that define the Boundary Representation (i.e. 1LSB) for each space.

  Finally, these polygons are analysed to define the geometry of walls. This is carried out by matching sets of parallel vertical polygons with opposite normal vectors. If a wall surface remains without any matching plane, then, an artificial surface is created to fully define the wall. The outcome of this process is the set of 3D walls for the given storey (see Figure 2e).

- **Opening detection**: Opening elements (e.g. doors and windows) are then detected in walls by processing point clouds representing both sides of each wall.

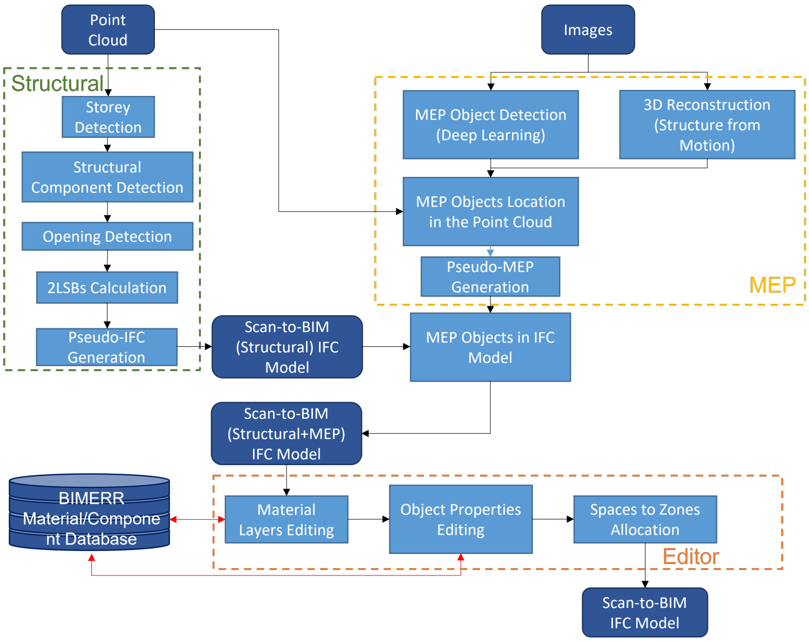

Figure 1. Pipeline of the proposed strategy for the (semi-)automatic generation of BIM models.

Bounding boxes are calculated for all empty areas within the wall surfaces, applying a hole detection strategy similar to that proposed in [16]. Openings are then detected based on the size of the bounding box and the overlap between pairs of bounding boxes on both sides of the walls. The result of this process is illustrated in Figure 2e).

- **Calculate 2^{nd}Level Space Boundaries (2LSBs)**: Once structural entities, including openings, are parameterised, the relationships between spaces and surfaces, and subsequently the 2LSBs, are automatically determined (Figure 2f). As discussed earlier, 2LSBs are important for energy simulation and analysis (more specifically to calculate heat transfers). In contrast to the approach of Lilis et al. [9], our process is able to exploit the geometric information and the semantics extracted from the point cloud instead of extracting that information from an existing IFC file.

- **IFC generation**: Geometric and semantic information extracted for the structural entities using the above-described method are codified into a BIM model, following the IFC standard [12].

2.2 MEP Scan-to-BIM

The objective of the MEP Scan-to-BIM sub-component (delimited in yellow in Figure 1) is the detection and localisation of some MEP components (e.g. HVAC systems) in images of the environment, and subsequent codification of these entities into the IFC-SPF file outputted by the Structural Scan-to-BIM sub-component.

The MEP Scan-to-BIM process encompasses the following steps:

- **MEP object detection**: The first step of the MEP Scan-to-BIM process is the detection of different MEP components in the input images – here principally heating and cooling system components. The algorithm used is based on deep learning and it is structured as follows. First, a Faster Regional Convolutional Neural Network (Faster R-CNN) [17] is trained using a dataset of images labelled with MEP components. The Faster R-CNN uses Neural Architecture Search Net (NASNet) [18] as a feature extractor and has been previously trained on the Microsoft Common Objects in Context (MS-COCO) [19] detection dataset. Then, the trained model is tuned through a cycle of validation and optimisation to achieve the best possible performance on the dataset.

- **3D reconstruction**: In parallel to the previous step, the input images are loaded into a PG Structure-from-Motion (SfM)-based solution to generate a 3D point cloud of the environment [20]. This point cloud is used as a bridge between the images, where the objects are detected, and the TLS point cloud, in whose coordinate system the MEP entities are subsequently modelled. The registration of the PG point cloud to the TLS coordinate system is carried out manually in CloudCompare [21] by selecting four pairs of

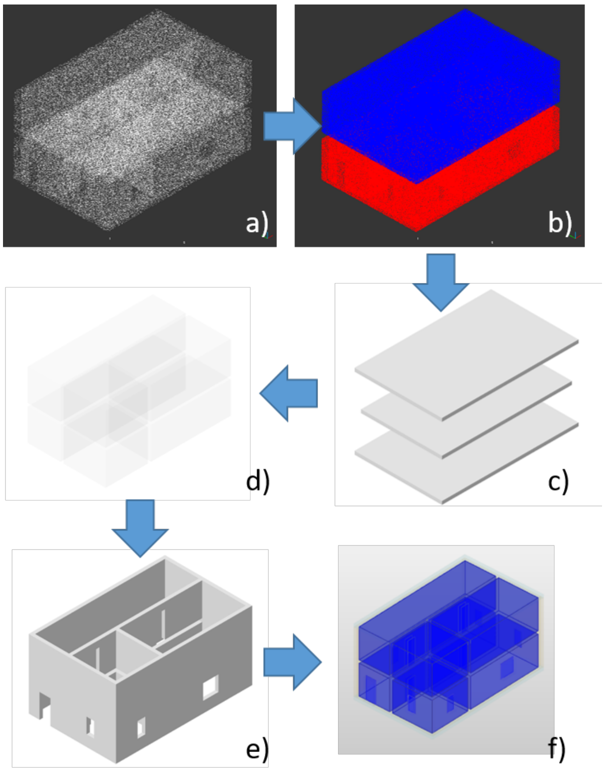

Figure 2. Intermediate results of the Structural Scan-to-BIM process. a) Point cloud; b) Point cloud divided into storeys; c) Slabs; d) Spaces; e) Structural elements with openings; and f) 2^{nd} level space boundaries.

corresponding points in the two clouds. This operation, performed only once per PG model, delivers the transformation matrix between coordinate systems.

- **Locate MEP objects in the semantic model**: The inputs for this process are: the image MEP detection bounding boxes from 'MEP Object Detection', the PG reconstruction of the scene (including the external calibration matrices of the camera images), the intrinsic matrix of the camera, the PG-TLS transformation matrix, and the point cloud delivered by the laser scanner. The PG-TLS transformation enables the localisation (location and orientation) of the camera images in the coordinate system of the TLS point cloud and therefore the 3D model (IFC) outputted by the Structural Scan-to-BIM. The internal calibration matrix is then used to reproject the detected MEP objects into the 3D model.

- **Model MEP objects in the IFC model**: The information (i.e. the type of detected MEP object and the projected 3D bounding box coordinates) is coded and added into the IFC model file of the Structural Scan-to-BIM model.

2.3 Scan-to-BIM Editor

The purpose of the Scan-to-BIM Editor (see Figure 3a), is to enable the user to add information to the generated Scan-to-BIM IFC model that cannot possibly be detected from the input point cloud and images. This includes information about wall layers and materials, material properties, as well as MEP properties. The inputs to this tool are: an IFC file containing structural components (see Subsection 2.1) and MEP components (2.2); and information on materials and MEP entities, which is stored in an online database and harvested by the Editor.

This database, called the Building Material & Component Database, contains data about 1,198 building materials originating from the third-party databases Baubook Vorarlberg Energy Institute and IBO GmbH [22], Ökobaudat German Federal Ministry of the Interior, Building and Community (BMI) [23], and ASHRAE [24]. Each material is assigned to a class within a unified classification schema, covering the used third-party data schemes and thereby enabling the user to efficiently retrieve material information across all data sources.

The operations that can be performed with the Scan-to-BIM Editor include:

- **Creating and editing material layers**: After selecting a structural component (i.e. slab or wall) in the Editor, multiple layers can be defined and populated with materials from the Building Material & Component Database. An example is presented in Figure 3b).

- **Populating material information in entities located in openings**: In as similar way, after selecting doors or windows in the Editor, material information can be added to these entities. For example, this enables specifying the type of glazing for the windows, which is important for energy analysis.

- **MEP object properties**: For heating and cooling systems, properties related to power, relationships between elements (e.g. boiler feeding a radiator), and other characteristics (i.e. type of machine) can be provided and edited. Alternatively, an MEP object in the model can be matched to an MEP component in the Building Material & Component Database, thereby providing all relevant properties.

- **Assigning spaces to zones**: Finally, the Editor enables the user to create zones (codified as ifcZones) and link spaces (i.e. ifcSpaces) to them, as illustrated in Figure 3c. This information is necessary to perform the thermal zoning, or spatial discretisation, in which the building is divided into thermal zones (i.e. groups of spaces), representing nodes with averaged values of thermal parameters.

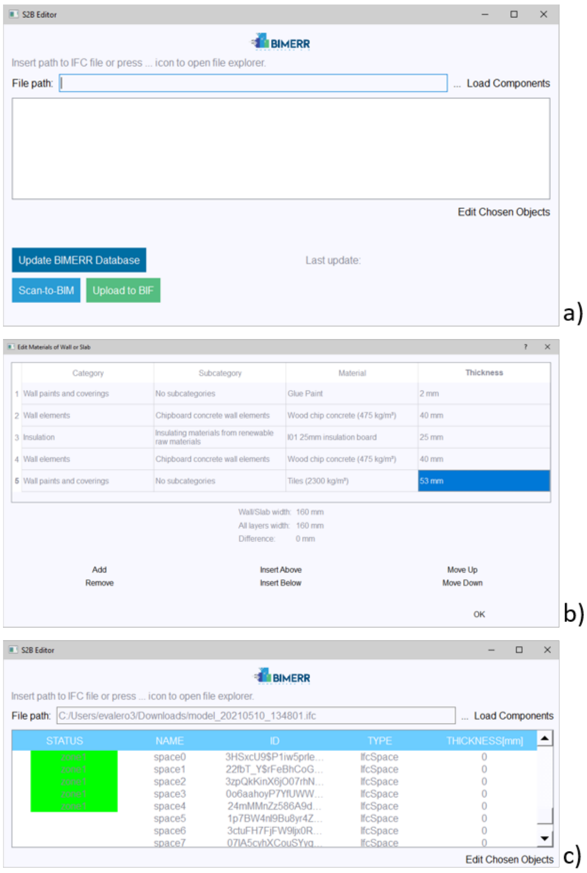

Figure 3. Scan-to-BIM Editor. a) Main window; b) Materials and layers for a wall; c) Zone annotation.

3 Application to a Pilot Site

The approach presented in the previous section has been preliminary tested in one of the pilot sites for the Horizon2020 -funded BIMERR project (`http://bimerr.eu`), called the 'Kripis House'. This is a two-storey building, located in Thessaloniki (Greece). It is a smart home, equipped with one reception, three working spaces, two living rooms, three bedrooms, three toilets and one bathroom. The house has many rooms, including toilets with lower suspended ceilings, and HVAC devices are installed across the building.

3.1 Generation of a BIM model with the Scan-to-BIM tool

A total of 69 scans were taken from strategic locations, both indoors and outdoors, with a Faro Focus 150s Terrestrial Laser Scanner. An unstructured coloured point cloud containing 16M points, with a density of $1pt/cm^2$, was delivered after pre-processing and sub-sampling the data (see Figure 4).

Figure 4. Coloured point cloud of Kripis House.

Besides, a total of 4,080 images were collected of the indoors with a mobile phone camera. The images were then sampled and used for 3D reconstruction and MEP object detection. Figure 5 shows some sample images.

Figure 5. Sample images of the Kripis House.

Following the approach presented in Figure 1, the Structural Scan-to-BIM tool took the point cloud shown in Figure 4 as input and delivered a BIM model in IFC format. As illustrated in Figure 6a, the model is aligned to the point cloud. The main structural entities were detected and modelled in the BIM model: slabs, walls and openings (see Figure 6b), as well as spaces. Finally, the 2LSBs were calculated as shown in Figure 6c.

In parallel to the Scan-to-BIM structural process, the images taken from the Kripis house were used to simultaneously:

- produce a 3D photogrammetric reconstruction (i.e. coloured point cloud) of the rooms (Figure 7a); and

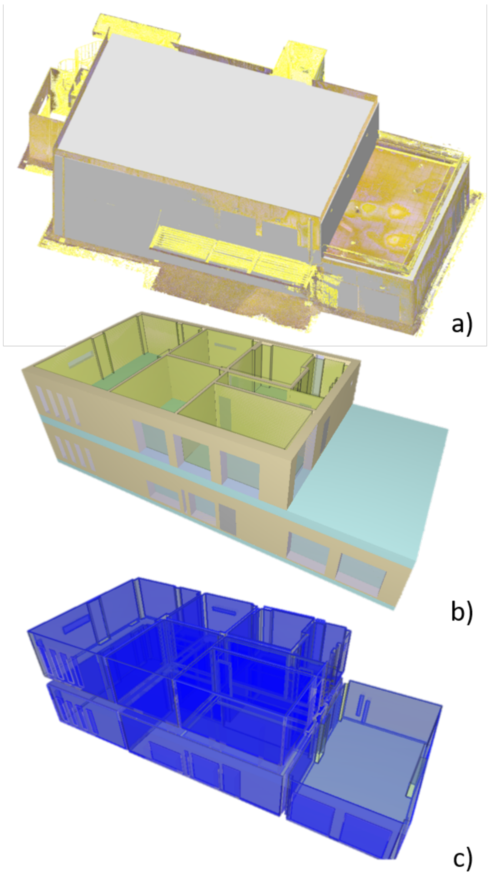

Figure 6. Results of the Structural Scan-to-BIM process for the Kripis house. a) Model aligned to the point cloud; b) Model including structural elements, openings and spaces; and c) 2^{nd} level space boundaries.

- automatically detect the MEP objects installed in the building (Figure 7b).

All the MEP objects detected in the pictures are then reprojected onto the cloud (see Figure 7) and BIM model, and added to the BIM model.

Finally, the Scan-to-BIM Editor is executed to enable the user to provide the structural entities with material information and the MEP objects with additional properties. This additional information is delivered by the BIMERR Building Material & Component Database – the online repository described earlier.

Once the IFC file is completed, further processes are executed in order to evaluate the energy performance of the building and subsequently plan an effective retrofitting. This approach is detailed in the following sections and illustrated in Figure 8.

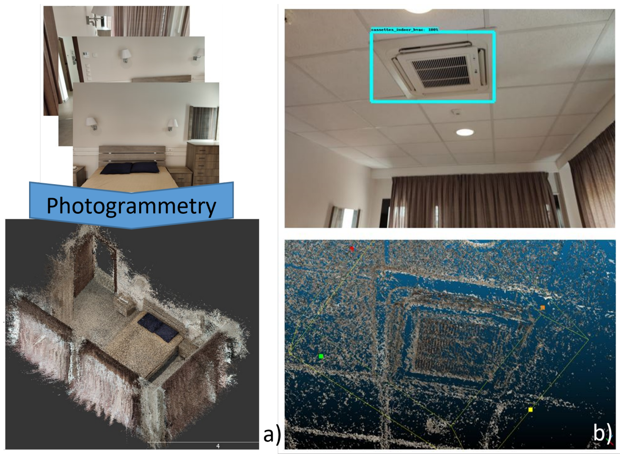

Figure 7. Initial MEP Scan-to-BIM processes for the Kripis house. a) Photogrammetric reconstruction of a room; b) Reprojection of detected MEP components to point cloud.

3.2 Data quality checking

The IFC file automatically generated by the Scan-to-BIM sub-components may contain some errors (e.g. geometric inaccuracies, missing semantic links or missing/incomplete components) that need to be checked and corrected before being used as input to the BEP model generation processes.

To identify and correct these errors, the produced IFC file is used as input to two of the BIM Management Platform (BIM-MP) [25] online services: *MVD completeness* and *geometric correctness checking* [26]. These tools deliver a report, highlighting the required modifications, which will be used by a BIM modeller to amend the IFC file. This iterative modification of the BIM model is performed in the ArchiCAD [27] BIM authoring tool until a faultless IFC file is produced.

3.3 Use of the BIM model for energy simulation and retrofit design

The final IFC model is used to produce an Input Data File (IDF), which is the main input to the EnergyPlus simulation engine [28]. The IFC to IDF mapping process is automatically performed by means of the Building Energy Performance Module's IDF Generator. The resulting file contains information about the building and the HVAC system to be simulated and it is used together with an EnergyPlus Weather (EPW) file as inputs to EnergyPlus in order to perform the simulation. Results of each EnergyPlus simulation are post-processed to estimate predefined energy Key Performance Indicators (KPIs) used as input to the Renovation Decision Support System (RenoDSS). The RenoDSS, in turn, illustrates the renovation options for the building, evaluates their impact on the building's performance, and guides the user through various alternatives towards the optimal choice for given boundary constraints (such as size of intervention, budget, target energy savings, etc.).

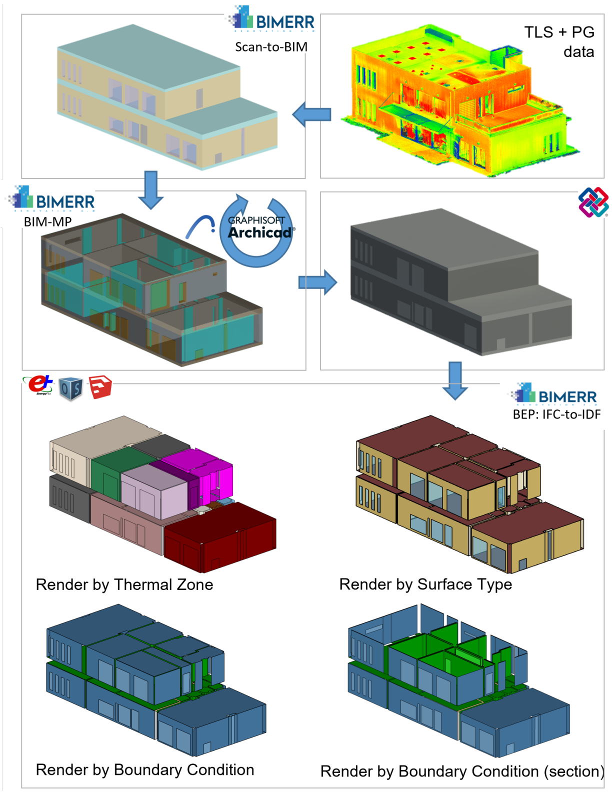

Figure 8. Processes and tools employed for the generation of an IDF of Kripis House.

4 Conclusions

This paper presented an integrated Scan-to-BIM approach for energy performance evaluation and retrofitting of buildings. The proposed tool comprises three subcomponents to create BIM models from point clouds: Structural Scan-to-BIM, to identify and model the structural entities; MEP Scan-to-BIM, to detect and model MEP components; and Scan-to-BIM Editor, to complete the BIM model with additional non-visible features (e.g. materials and properties) and classify spaces into zones. The tool is also integrated within a broader process that includes a BIM Management Platform (BIM-MP) that checks the geometric correctness and completeness of the generated IFC file, as well as the Building Energy Performance Module. The latter, invoked by RenoDSS to estimate the energy performance of the building, it initially receives the IFC file, automatically transforms it to proper simulation input data files and launches EnergyPlus to calculate predefined KPIs.

The Scan-to-BIM tool, as well as the broader process, was validated in a two-storey building. This showed the quality of the BIM model produced by the Scan-to-BIM tool, which saves time during the modelling phase. Nonetheless, future work remains to increase the robustness of the Scan-to-BIM tool, especially to identify openings more accurately and detect a larger range of MEP objects.

Acknowledgements

This work was conducted as part of the BIMERR project that received funding from the European Commission's Horizon 2020 research and innovation programme under grant agreement No 820621. The views and opinions expressed in this article are those of the authors and do not necessarily reflect any official policy or position of the European Commission.

References

[1] H.M. Government. Building information modelling. industrial strategy: government and industry in partnership. `https://cutt.ly/JQpdeaw`, London, 2012.

[2] G.I. Giannakis, K.I Katsigrakis, G.N. Lilis, and D.V. Rovas. Workflow for Automated Building Energy Performance Model Generation Using BIM Data. In *Proceedings of the 16th IBPSA Building Simulation Conference*, pages 504–511, 2015. Rome, Italy,2-4 September 2019.

[3] A. Andriamamonjy, D. Saelens, and R. Klein. An automated ifc-based workflow for building energy performance simulation with modelica. *Automation in Construction*, 91:166–181, 2018.

[4] R. Wimmer, J. Cao, P. Remmen, T. Maile, J. O'Donnel, J. Frisch, R. Streblow, D. Müller, and C. van Treeck. Implementation of advanced bim-based mapping rules for automated conversions to modelica. In *Proceedings of the 14th IBPSA Building Simulation Conference*, pages 419–426, 2015. Hyderabad, India, 7-9 December 2015.

[5] F. Bosché, M. Ahmed, Y. Turkan, C. T. Haas, and R. Haas. The value of integrating scan-to-bim and scan-vs-bim techniques for construction monitoring using laser scanning and bim: The case of cylindrical mep components. *Automation in Construction*, 49:201–213, 2015. doi:https://doi.org/10.1016/j.autcon.2014.05.014.

[6] M. Bassier and M. Vergauwen. Unsupervised reconstruction of building information modeling wall objects from point cloud data. *Au-*

tomation in Construction, 120:103338, 2020. doi:https://doi.org/10.1016/j.autcon.2020.103338.

[7] C. Thomson and J. Boehm. Automatic geometry generation from point clouds for bim. *Remote Sensing*, 7(9):11753–11775, 2015. doi:10.3390/rs70911753.

[8] S. Nikoohemat, A. Diakité, S. Zlatanova, and G. Vosselman. Indoor 3d modeling and flexible space subdivision from point clouds. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-2/W5:285–292, 2019. doi:10.5194/isprs-annals-IV-2-W5-285-2019.

[9] G. N. Lilis, G. I. Giannakis, and D. V. Rovas. Automatic generation of second-level space boundary topology from ifc geometry inputs. *Automation in Construction*, 76:108–124, 2017. doi:10.1016/j.autcon.2016.08.044.

[10] B. Quintana, S. A. Prieto, A. Adan, and F. Bosché. A methodology to automatically generate geometry inputs for energy performance simulation from IFC BIM models. In *Proceedings of the Joint Conference on Computing in Construction (JC3)*, pages 29–36, 2017. July 4-7, 2017, Heraklion, Greece.

[11] A. Corneli, B. Naticchia, A. Cabonari, and F. Bosché. Augmented reality and deep learning towards the management of secondary building assets. In Mohamed Al-Hussein, editor, *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC)*, pages 332–339, Banff, Canada, May 2019. doi:10.22260/ISARC2019/0045.

[12] ISO/TC 59/SC 13. Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — part 1: Data schema. Standard, International Organization for Standardization (ISO), 2018.

[13] B. Okorn, X. Xiong, B. Akinci, and D. Huber. Toward automated modeling of floor plans. In *Proceedings of the symposium on 3D data processing, visualization and transmission*, volume 2, 2010.

[14] E. Valero, A. Adán, and F. Bosché. Semantic 3d reconstruction of furnished interiors using laser scanning and rfid technology. *Journal of Computing in Civil Engineering*, 30(4):04015053, 2016. doi:10.1061/(ASCE)CP.1943-5487.0000525.

[15] R. B. Rusu. Semantic 3d object maps for everyday manipulation in human living environments. *Künstliche Intelligenz*, 24:345–348, 2010. doi:10.1007/s13218-010-0059-6.

[16] X. Xiong, A. Adan, B. Akinci, and D. Huber. Automatic creation of semantically rich 3d building models from laser scanner data. *Automation in Construction*, 31:325–337, 2013. doi:10.1016/j.autcon.2012.10.006.

[17] S. Ren, K. He, R. Girshick, and J. Sun. Faster r-cnn: Towards real-time object detection with region proposal networks. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 39(6):1137–1149, 2017. doi:10.1109/TPAMI.2016.2577031.

[18] B. Zoph, V. Vasudevan, J. Shlens, and Q. V. Le. Learning transferable architectures for scalable image recognition. In *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 8697–8710, 2018. doi:10.1109/CVPR.2018.00907.

[19] T.-Y. Lin, M. Maire, S. Belongie, J. Hays, P. Perona, D. Ramanan, P. Dollár, and C. L. Zitnick. Microsoft coco: Common objects in context. In *Computer Vision – ECCV 2014*, pages 740–755, Cham, 2014. Springer International Publishing.

[20] C. Wu. VisualSFM: A visual structure from motion system. `http://ccwu.me/vsfm/`, 2011.

[21] CloudCompare. CloudCompare v2.10.2 [GPL Software], 2021. URL `http://www.cloudcompare.org/`.

[22] Vorarlberg Energy Institute and IBO GmbH. Baubook GmbH. `https://www.baubook.at/?SW=6&lng=2`, Vienna, 2018.

[23] German Federal Ministry of the Interior, Building and Community (BMI). ÖKOBAUDAT datasets. `https://www.oekobaudat.de/en.html`, Berlin, 2021.

[24] Veronika Földváry Ličina et al. Development of the ashrae global thermal comfort database ii. *Building and Environment*, 142:502–512, 2018. doi:10.1016/j.buildenv.2018.06.022.

[25] K. Katsigakis, G. N. Lilis, and D.V. Rovas. A cloud IFC-based BIM platform for building energy perform simulation. In *Proceedings of the European Conference on Computing in Construction*, pages 164–171, Rhodes, Greece, 2021.

[26] G. N. Lilis, G Giannakis, K Katsigarakis, and DV Rovas. A tool for IFC building energy performance simulation suitability checking. In *eWork and eBusiness in Architecture, Engineering and Construction*, pages 57–64. CRC Press, 2018.

[27] Graphisoft Inc. ArchiCAD 24, 2020. URL `https://graphisoft.com/solutions/archicad`.

[28] U.S. Department of Energy (DOE). EnergyPlus v. 9.5.0, 2021. URL `https://energyplus.net`.