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Contribution of photogrammetry and sensor networks to the energy diagnosis of occupied historical buildings

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ABSTRACT: The sustainable energy renovation of historical buildings is a challenge for all European countries. It is crucial for their conservation as well as for urban and rural development. Nonetheless, proposing adequate interventions requires appropriate investigation efforts. This paper presents a specific approach for performing the energy diagnosis of occupied historical buildings, developed under the constraints of several ongoing research projects. It is shown how photogrammetry and wireless sensor networks can be combined to produce rich datasets, while keeping disturbances for occupants at a minimum. Within this multi-disciplinary investigation program, the focus is also put on the production of input and validation data for implementing dynamic energy simulations. A case study is presented to illustrate the deployment of the proposed methodology. Only two site visits allowed to capture a large quantity of descriptive and performance information, which was valorized through clear protocols for sampling and formatting the data.

1 INTRODUCTION

1.1 *Energy retrofits of historical buildings*

In Europe, several research projects have recently focused on the issue of energy retrofitting of historical buildings and the identification of adequate intervention strategies (Martínez-Molina et al., 2016). Conserving built heritage does not mean 'freezing' it because that would make it unsuitable for present and future needs, in terms of use as well as from the perspective of comfort and performance (Fabbri, 2013). On the other hand, modifying ancient buildings to improve their energy performance cannot happen without questioning the application of standard solutions for energy optimization.

In Flanders, the project *ErfgoedEnergieLoket* (de Bouw et al., 2014) assists the architects specialized in architectural heritage regarding energy and comfort aspects. In Wallonia, the research project *P-Renewal* (Stiernon et al., 2017) aims to develop strategies for the sustainable retrofit of historical Walloon dwellings with heritage value and built before 1914. Within this latter project, whole-building dynamic energy models are used as flexible and exploratory tools to evaluate the relevance of different energy-related interventions. Nevertheless, calibrating building energy simulation (BES) tools is challenging, given the complexity of the underlying mathematical representations (O'Neill and Eisenhower, 2013) and uncertainty about the values of the input parameters.

1.2 *The building performance investigation in the 'digital era'*

In terms of energy efficiency and hygrothermal balances, it is well-known that traditional masonry buildings are specific: the indoor conditions are shaped by the high thermal inertia of walls and specific ventilation/infiltration patterns; their construction materials are the seat of complex coupled HAM (Heat Air and Moisture) transfers, which are not simple to model; the condition of these materials can influence the theoretical performance; the presence of building systems is often limited or outdated. Even if the final energy consumption is a central performance indicator in most building energy policies, this data alone is insufficient to grasp the building specificities and thus to propose adequate intervention strategies. The risk of accentuating existing pathologies or creating new ones is real. The biodeterioration of wooden beams subsequent to the internal insulation of a masonry wall is a classic example (Guizzardi et al., 2015).

For each retrofitting project involving a historical building, one crucial aspect is thus the implementation of a relevant multi-disciplinary investigation program, a hard and time-consuming task. It is aimed towards the characterization of the building 'as it is' and 'as it performs' through the mobilization of a range of sensing methods. Not only deficiencies and their causes are sought for, but also intrinsic qualities (*e.g.* natural comfort in some rooms) and values (*e.g.* building elements with heritage significance). The ultimate objective is to obtain organized information to judge the risks and benefits associated with a particular renovation measure, or a combination of measures. Studies on heritage buildings have encouraged the development of non-invasive technologies for such documentation and analyses (Troi et al., 2015).

A modern and systematic methodology was developed at the BBRI (Belgian Building Research Institute) to optimize the quality of the data collected in historical and occupied buildings, for exhaustive energy studies. It is based on state-of-the-art methodological approaches (Casanovas, 2008; Vieites et al., 2015) while integrating relevant and innovative digital tools and maximizing their potential of data production. Two non-destructive techniques (NDTs) are here used in a complementary way: multi-view photogrammetry and wireless sensor networks. The integration of those two key technologies into a methodological process was encouraged by specific constraints met during the *P-Renewal* project. This paper shows how they greatly benefit to the expert team to evaluate a building in terms of energy and comfort, with a view to its renovation.

2 UPDATING THE ENERGY DIAGNOSIS APPROACH

2.1 *Facing specific constraints during research efforts*

Within the *P-Renewal* project, five buildings from pre-1914 were studied, each of them being representative of one major type of dwellings in Wallonia (Stiernon et al., 2017). It was necessary to obtain a holistic picture of each one of them, in terms of their environment, composition, condition, occupancy and performance, while keeping the cost of tests to a minimum. For several reasons, leading in-depth energy studies in historical and occupied buildings were particularly relevant but also very challenging.

As the evaluation of future intervention strategies required properly calibrated whole-building energy models, the task was even harder. Indeed, many input parameters were required, several of whom are, unfortunately, very case specific. Each material present in the building has its own specificities, which must be translated into standard parameter values in the model. In addition, some physical variables should be monitored, ideally over a long period of time to provide dynamic input (e.g. climatic boundary conditions) or validation data to the model. The monitoring equipment can be invasive, and the installation cost significative.

An exhaustive evaluation of heritage values was another important step in this project. Even if the considered buildings were not specifically listed, the goal was to pinpoint features of significance across the investigated areas and estimate their state of preservation. Such analyses require a proper documentation phase that traditionally goes through meticulous on-site observations.

All studied buildings being permanently occupied, any technique that would allow to drastically speed up the on-site investigation and limit the impact on the occupants' activities would be precious. A clear diagnostic methodology had to be developed, with an optimization of the 'efforts-to-results' ratio and a limitation of the invasiveness of tests.

2.2 *Which key data for a comprehensive energy diagnosis of historical buildings oriented towards dynamic modelling?*

The energy diagnosis approach is first defined by the key information to be collected, with respect to the objective and the extend of the analysis pursued. Here, the research is characterized by a high exhaustivity. The target information is divided into four main domains, as illustrated on Figure 1.

The first data category groups the information related to the history of the building, its place in the past and present context, its evolution from its creation, and cultural values associated to its different components. Then comes the anthropological domain, which is a complex matter. It covers the data related to the behavior of occupants and their perception of this behavior. Those are crucial aspects to interpret any indoor air measurement or energy consumption information. The way the people occupy the different indoor spaces or the way they use and program the available heating systems during winter are some examples of information that can hardly be guessed from direct observation. Indeed, they are related to complex social and comfort schemes and can vary according to daily, weekly or seasonal pattern. The second anthropological aspect is related to the significance of the building and its components for the occupants, which, more than likely, will vary from the opinion of the heritage expert.

For reasons of convenience, technical data can be organized according to the study scale, which ranges from the material scale up to the site scale, the HVAC systems forming a specific category. Then, at each scale, the target data are classified either in the architectural/geometric domain or in the physics/performance domain. The first category groups descriptive information, such has the type and function of the identified building elements. The second category forms a wider domain where the ongoing hygrothermal phenomena are translated into condi-

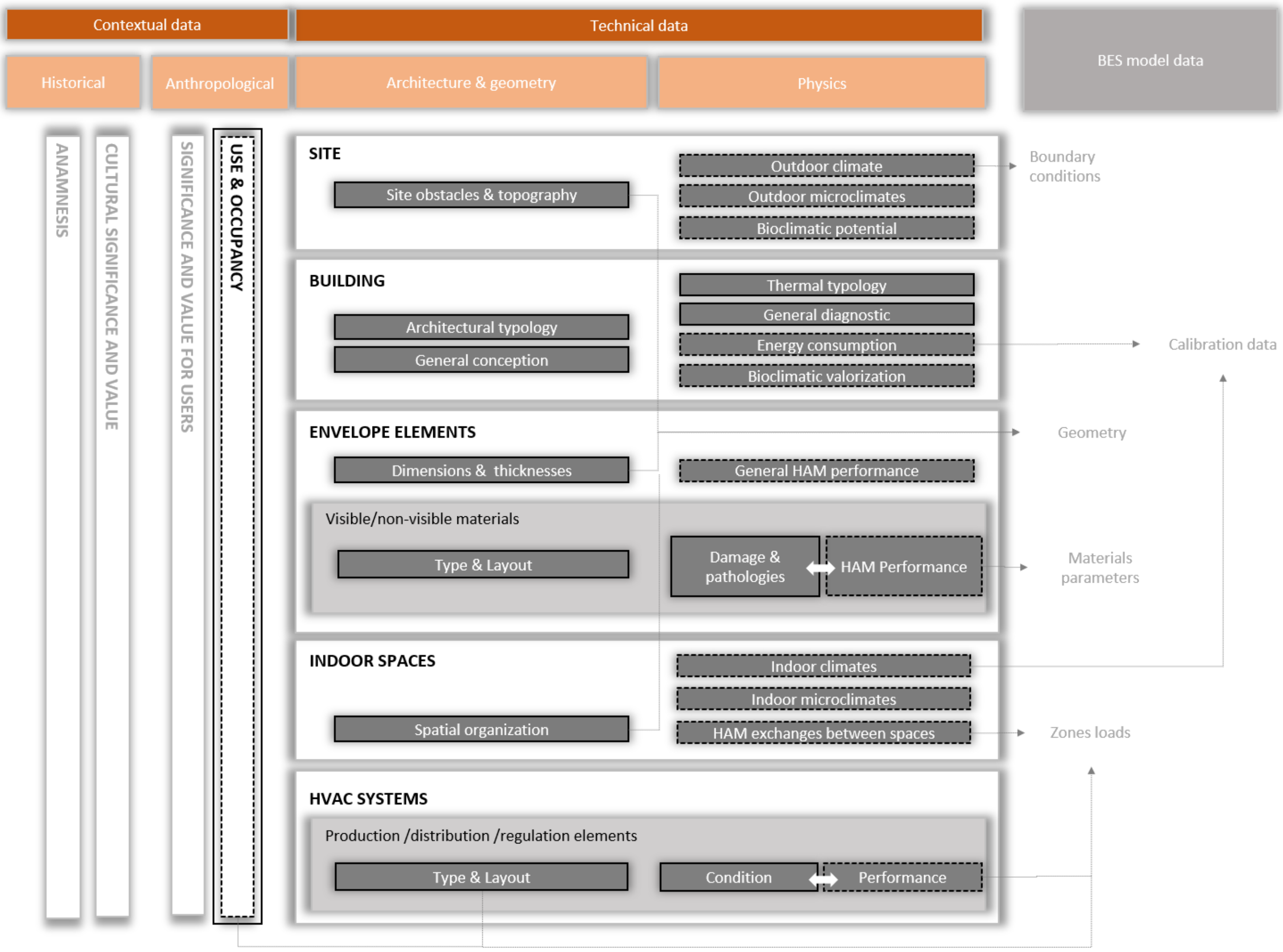

Figure 1. Data to be collected during the energy diagnosis of a historical building, with possible use as BES model input. Framed in solid black line, the aspects where 3D photogrammetry can facilitate on-site data collection; framed in dashed line, the aspects where wireless sensor networks provide a way of improving the investigation process. In grey letters, the contextual data that is often set aside from energy studies on existing buildings but are essential to propose heritage-compatible interventions through an adequate value assessment

tion-oriented aspects (e.g. a damage on the surface of a material) and performance-oriented aspects (e.g. the U-value of an envelope element).

As shown on the synthetic figure, part of the investigation data can be translated into input parameters for dynamic energy models. Each instance of a hygrothermal model requires a series of inputs: the geometry of the modelled region(s), the hygrothermal parameters of each material forming those regions, the hygrothermal conditions at their boundaries, and zone loads for BES simulations (e.g. occupancy conditions, heat sources). The impact of renovation or restoration interventions can only be evaluated once the model is properly calibrated. Such models are highly demanding and the confidence in simulation results is dependent on the quality and completeness of data.

2.3 *Collecting and processing data*

Once the key target data is identified, the appropriate diagnosis tools must be selected and their deployment organized, considering the occupation of the building and constraints in terms of access. Operationally, the energy diagnosis approach is divided into several phases.

First, the preliminary study, which aims to provide a general 'picture' of the building as it is and compile the first hypotheses about its composition and performance. It consists in a general documentary investigation completed by one single preliminary visit, where the expert should try to optimize the quantity of collected data. As existing plans and photographs are often lacking, or only provide an incomplete image of the building, solely on-site observations will generate reliable information about its geometry. This geometric documentation is a crucial upstream step, as it will provide the basis to provide a context to any other information. The first visit is also an opportunity to briefly analyze the condition of the building, possibly by using handy noninvasive methods. Moreover, meeting the tenants of the building is always an extremely rich source of information. From the preliminary visit, the initial descriptions and hypotheses regarding the current hygrothermal behavior are compiled in an initial synthetic report.

In a second stage, a multidisciplinary testing program is deployed to enhance the information that was gathered during the preliminary study. This 'in-depth studies' phase also focuses on the validation of initial composition and performance hypotheses. It combines on-site testing (*e.g.* blower door test, thermography) and monitoring campaigns, which extend over different time periods. Given the occupied status of the considered buildings, the number of visits is limited to a strict minimum. A synthesis phase closes the investigation where a final report compiles all the collected data and is communicated to the energy simulation specialist.

At those different stages, the expert relies on different investigation and communication tools. The more precise the description of a building must be, the more building visits are typically needed. There is thus a conflict between the need for exhaustive studies and the will to limit the investigation impact on occupants. On-site experts would thus benefit from any technique that allows to optimize the quantity of data collected in a given period. In the next sections, it is shown how photogrammetry and wireless sensor networks perfectly answer this need. However, the large amount of data they provide must be properly handled, transformed and synthetized, otherwise there is a risk of missing the initial objectives.

3 INTEGRATING INNOVATIVE DIGITAL TOOLS

3.1 *Photogrammetry as a multi-purpose and multi-scale tool to produce descriptive data*

When it comes to geometry, recent high-definition technologies have revolutionized the building surveying and recording processes (Guarnieri et al., 2006; Remondino, 2011; Yastikli, 2007), which are crucial when working on heritage. The documentation process is now benefiting from an extremely high level of details offered by such automatic 3D digitalization technologies. Among the available methods, 'Multiview Photogrammetry' (MVP) (Furukawa et al., 2015) is very promising as a multi-scale and multi-purpose tool, not only for descriptive analysis but also for performance estimation. As its name suggests, the technique is based on the automatic processing of photographs in a software: the three-dimensional shape of an object is estimated from overlapping pictures with varying points of view. The recording process of heritage building studies can be greatly enriched by the level of details that MVP offers for highly textured objects.

From the raw 3D data that is produced from photographs, i.e. point clouds or triangular meshes, many useful deliverables can be produced. It includes 1D deliverables (e.g. roughness profile of the point cloud along a line), 2D deliverables (e.g. vectorized cross sections, 2D CAD drawings, screen captures, orthomosaïcs), 2.5D deliverables (e.g. planarity maps, distance maps, *cloud-vs-cloud* maps), 3D deliverables (e.g. textured meshes, cross sections of point clouds, 3D CAD drawings, annotated 3D PDF's, BIM models), or simple figures or statistics. Deliverables can also be differentiated according to whether they focus more on geometric information or color information. In summary, the raw geometric and radiometric data stemming from MVP can be used for many building studies. This data transformation process is theoretically infinite and needs to be strictly supervised regarding the objective of the study.

Here, the MVP is proposed as a 'multi-purpose' tool for supporting the energy diagnosis of the building. So far, it seems that the potential of the technology has not been sufficiently exploited. In Figure 1, the key technical data that can be inferred from MVP through appropriate processing and analysis in clearly highlighted. Nonetheless, the difficulty for the energy diagnosis expert is rightly to determine how to transform the 3D information and, further upstream, how to collect the data in an appropriate way.

In the proposed approach, the technique is mobilized during the preliminary visit to capture the building completely and benefit from the data early in the project. The field team captures the whole building from the inside and the outside, producing two or more point clouds that are registered with ground control points. The capture distance is chosen to get a typical 'ground sample distance' of 2.5mm on the resulting photos, which provides a good balance between acquisition time and final model resolution. The different resulting point clouds are then processed to end up with the set of standard deliverables as illustrated in Table 1.

A first category of deliverables includes files that are directly generated from the reconstructed point cloud data and are called 'intermediate' deliverables. From those, secondary deliverables are created and shared to the involve expert team within the project. Those final files are all images, in order to facilitate the collaboration and ensure and optimal access to the desired data. In the future, the development of BIM (Building Information Modelling) should encourage the direct exchange of 3D information.

Table 1. A standard set of deliverables produced from the photogrammetric study and adapted for a holistic energy diagnosis. The data is ultimately processed in the form of images to facilitate the collaboration between the involved experts. See Figure 3 for a concrete example from a case study.

3D reconstruction data		Processed data (intermediate)		Processed data (final)	Use
Point cloud of indoor spaces (cleaned and registered)	→	I1. Distance map(s) of selected floor(s) and/or ceiling(s) compared to reference planar surfaces	→	I1-1. Orthoviews of the distance map(s)	*Evaluating the condition of floors and ceilings*
Point cloud of the envelope (cleaned and registered)	→	E1. Distance map of each façade compared to reference planar surfaces	→	E1-1. Orthoviews of the distance maps	*Evaluating the condition of walls*
	→	E2. Textured mesh of the envelope	→	E2-1. Orthomosaïc photos of all façades	*Materials/pathologies identification and mapping (through image analysis and machine learning)*
Merged point cloud of the envelope and the interior spaces (cleaned and registered)	→	M1. Cross-sectioned point cloud	→	M1-1. Isometric views of the sectioned model	*Illustrating the internal organization of the building*
	→	M2. 0.1m thick cross sections every 0.5m along main building axes	→	M2-1. Orthoviews of the sections	*Encoding the building geometry and the thickness of envelope elements in whole-building energy models*

3.2 *Wireless sensor networks as a key facility to grasp the dynamic phenomena*

A holistic hygrothermal study of a building often implies the monitoring of physical variables. Whatever the quality of a photogrammetric survey, it will only give an ‘instant’ image of the building. The specificities of the hygrothermal behavior of an old building are profoundly dynamic: inertia and thermal comfort, for example, cannot be evaluated in a static way.

The sensors and systems dedicated to the monitoring phase are evolving constantly. Traditionally, research-oriented monitoring systems consisted of specialized data-logging stations connected to various wired sensors. Battery-operated sensors with embedded logging capabilities naturally succeeded with the development of low-power integrated circuits. Today the ‘Internet of Things’ is gaining popularity (Atzori et al., 2010) and many innovative wireless communication protocols are being deployed, allowing data to be transmitted remotely using radio frequencies (Gubbi et al., 2013). As a result, ‘Wireless Sensor Networks’ (WSN) were developed. In their simplest form, they combine sensor nodes and gateways for the end-transmission of data to the user (Bhattacharyya et al., 2010; Mottola and Picco, 2011). With WSN, all sensor measurements are more easily accessible because they are gathered in a single location in the building, and even stored on cloud servers. Parallel to the diversification of sensor communication schemes, the development of hardware and software based on an open-source approach has gained much attention (Fisher et al., 2015). The success of open-source development boards and the dynamism of user communities should encourage heritage experts to develop more WSN solutions tailored for heritage building studies.

During the multidisciplinary testing phase of the proposed methodology, wireless sensor networks (WSN) are valorized as flexible tools for remote data collection over long periods of time and for multiple buildings. Such networks can be easily deployed on many parallel sites and open-source microcontrollers allow custom-made solutions to be developed. For example, carbon dioxide, temperature and humidity can be monitored in multiple rooms, and heat fluxes on multiple surfaces. As summarized on Figure 1, WSN can improve the assessment of physical phenomena, energy consumption and building use.

4 CASE STUDY

4.1 *The building*

A traditional farm located in Enghien (Wallonia) is proposed here as a brief illustration to the systematic energy diagnosis approach (Fig. 2). This XVIIIth

Figure 2. A traditional farm where the energy diagnosis approach was tested

century building was studied within the *P-Renewal* project. It is now used as a single-family dwelling, permanently occupied by three people. Several retrofit interventions have already taken place, including the replacement of some windows, the insulation of part of the attic floor and the installation of a thermostatic control of the central oil heater.

4.2 *Preliminary visit and MVP study*

After studying the available building documentation, which did not include any plans, and initializing contacts with the owners, the team prepared the first site visit. Once there, a MVP survey was led, both from the inside and from the outside of the building, where 857 and 111 photos were taken respectively. All photos were captured within a 3-hour time period with a Canon EOS 5D mark III equipped with a fixed 20mm Sigma lens and mounted on a tripod. The chosen diaphragm aperture was f/8, and the iso value of the sensor was set to a minimum of 100.

The resulting pictures were processed in *Agisoft Metashape*, ultimately forming two dense point clouds: 46 million points for the exterior photoset, 520 million for the interior photoset. All the rooms in the house were rebuilt without any significant alignment problems. Walls with a very uniform color, especially on the first floor, were reconstructed with less precision than the most 'textured' walls (such as the exposed brick walls in the attic). Six ground control points allowed the 'rigid' registration of both point clouds, with an average reconstruction error of 1.3cm on those control points.

Parallel to the photogrammetric survey, a brief humidity diagnosis was performed, using a protimeter to localize problematic zones within the envelope. Samples of salt efflorescences were also collected as part of the traditional prediagnosis assessments. Finally, the owner agreed to answer a standard interview, which provided basic information regarding the use of the building, the felt thermal comfort and observable pathologies.

From the collected information, the team responsible for the energy diagnosis could synthetize initial hypotheses regarding the building condition, its energy performance and the indoor comfort.

4.3 *Second visit and installation of the WSN*

As already mentioned, the in-depth studies focus on validating the initial composition and performance hypotheses by implementing an adequate testing program. The second site visit was targeted towards the realization of relevant complementary tests and the installation of a WSN. The latter was designed to capture the actual long-term hygrothermal variation within different rooms of the building. The used *Monnit* sensor nodes allow the monitoring of a wide range of 'standard' variables, such as the air temperature, but also the development of tailor-made sensors (based on a serial communication protocol bridge or standard voltage/current nodes).

Seven temperature/humidity sensors were implemented in different rooms of the farm and one outside to monitor the outdoor climate. Those battery-operated nodes communicate their data every 15 minutes to a gateway using 868 MHz radio frequency. Upstream of the network, a 3G router ensures that the gateway can communicate with internet and reach the cloud servers where all data is stored.

The complementary performance tests consisted first in a blower-door evaluation of air infiltration, with varying control volumes to estimate air transfer schemes between parts of the building. Thermographic images were also taken from inside and outside of the building to highlight local air infiltration patterns or envelope defects. The humidity diagnosis was continued with some calcium carbide tests.

4.4 *Valorization of MVP and WSN data*

All the deliverables defined in Table 1 were generated from the photogrammetric reconstructions of the farm, as shown on Figure 3. As expected, those output files made it possible to address many aspects of the energy diagnosis. On the architectural level, the geometry of the building was adequately transcribed which allowed to properly contextualize all observations and tests. Using the 10cm thick cross sections through the whole building point cloud, not only floor plans could be inferred but also the thickness of all envelope elements. The connections of rooms and constructive elements appeared clearly, and many hypotheses could be put forward.

The great additional benefit of using MVP is the quality of color rendering it offers. In this matter, orthomosaïc photos were precious to complement the cross sections information. They served, for example, as basis for the listing of openings size and the mapping of pathologies.

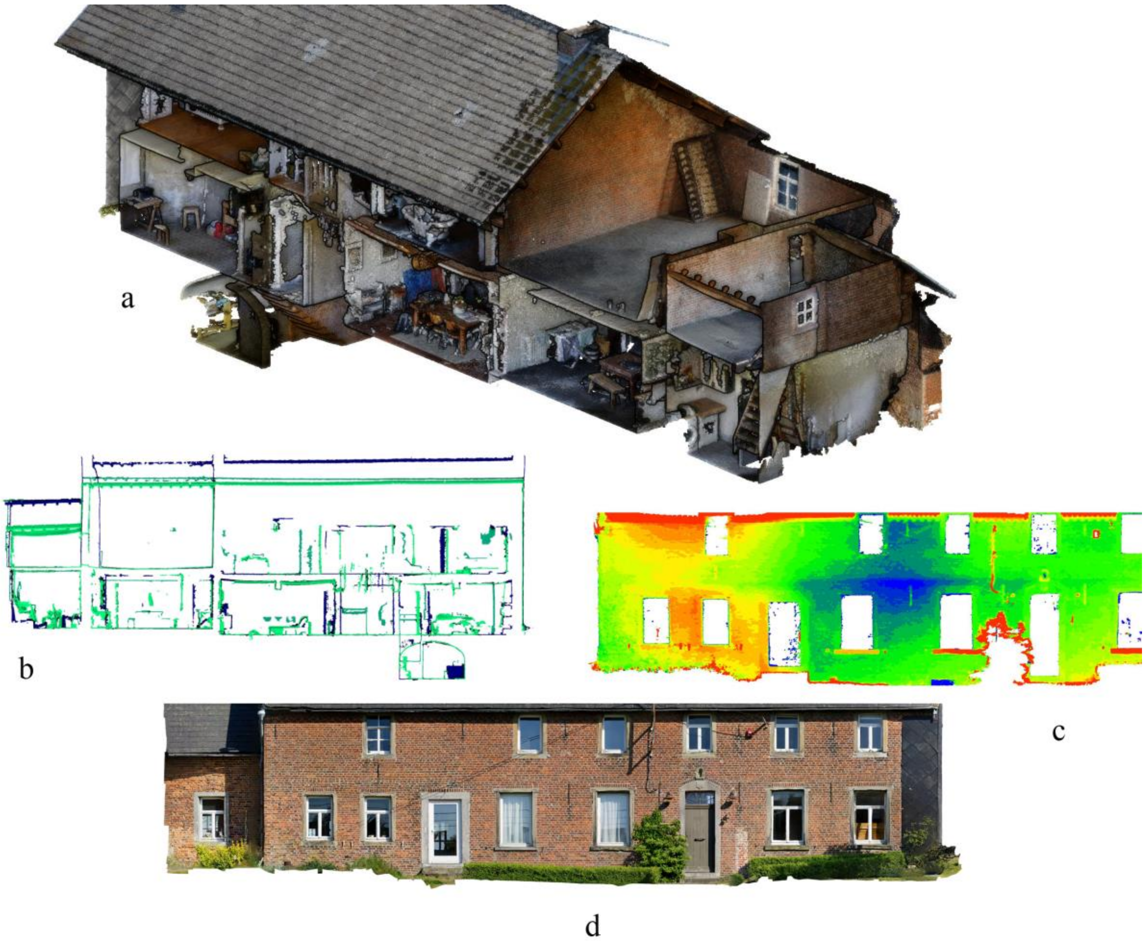

Figure 3. Some of the standard deliverables used for the energy diagnosis and modelling, generated with MVP for the reference case study. (a) Deliverable M1-1 : isometric view of the merged point cloud with key cut sections; (b) Deliverable M2-1 : orthoview of 10 cm thick cross sections along the X axis; (c) Deliverable E1-1 : orthoview of a planarity map of the main façade; (d) Deliverable E2-1 : orthomosaïc photo of the front façade, generated from a textured mesh.

In summary, the visual quality of the 3D point clouds, their geometrical resolution, and the overall geometric accuracy provided a strong base for conducting analyses and for presenting the results. For decision-making purposes, such data can be easily valorized in a BES software. In this study, *Openstudio* was specifically used to test various retrofitting strategies. The geometry of the model was created in *Sketchup* using a combination of cross sections images and orthomosaïc photos of the façades.

On the other hand, the WSN installation allowed to properly capture the inside and outside climatic conditions. The main benefit for the researchers was the permanent access to data. There was no need any more to plan building visits only to collect the sensor measurements. However, the multiplication of sensors and monitored sites led to a profound transformation of how the data is processed. For diagnostic purposes, each data set was traditionally analyzed manually, and graphs of interest were generated based on the observations. This time-consuming task is incompatible with the big data era. The development of specific *Python* scripts has thus been initialized to format the rich monitoring data offered by WSN. Those scripts focus on an automatic creation of relevant graphs and statistics for the studied period (Figure 4).

The WSN data was also transformed for incorporation as input data in the BES model. Again, *Python* scripting allowed to automatize the process. For example, the climatic boundary conditions were constituted as a combination of WSN on-site measurement

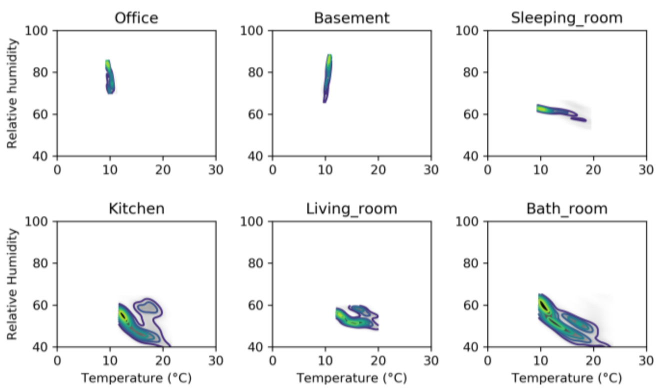

Figure 4. Automated charts creation: here, scatter plots are generated for 6 of the monitored rooms for one typical winter week.

and satellite data for radiation, wind and atmospheric pressure.

5 DISCUSSION

Digital technologies have enormous potential to improve the study of old buildings. Today, it is necessary to develop new diagnostic methodologies that fully incorporate them, with clear protocols for data transformation, valorization and archiving. Indeed, the digital era also means the data era. A bad definition of data handling could mean, at the end, no use of this incredibly rich data at all.

The case study showed that precise and very high-density 3D surveys can be created only from photosets. It offers great opportunities for the energy diagnosis. First, the method is nondestructive (remote sensing) while providing large possibilities in terms of analysis and reducing disturbances for occupants when working in 'real life' case studies. The method is also multi-scale. Depending on the type of photographic lens used and the typical capture distance, objects ranging from the microscopic up to the terrain scale can be digitalized. Because the method is UAV-compatible, large, inaccessible or dangerous areas are also becoming easily diagnoseable.

MVP has however some noticeable pitfalls. Many factors can affect the quality of the 3D reconstruction and the protocol followed to capture the interest object has a major impact on the results. If the computational principles and the inherent limits are not properly understood, there is a risk of creating erroneous or incomplete data. Nonetheless, historical buildings that have undergone little transformation are good candidates for MVP campaigns. In this study, the use of photogrammetry alone on several case studies has proven that an absolute geometric error in the centimeter range is achievable. However, such mean value should not hide the fact the method can show some local drop in precision. On the overall, this level of confidence seems compatible with the required accuracy of dynamic energy models. Modern materials, with the predominance of synthetic and texture-less surfaces, are somewhat unsuitable for the proposed approach. There, when it comes only to 3D geometrical restitution, the terrestrial laser scanner is more reliable as it is less dependent on the operator skills. However, its color restitution is much less advanced than MVP. A combination of both techniques would bring the best to any study but is not always realistic from a cost point of view.

The WSN must be considered as an innovative infrastructure to collect dynamic data over long periods. The reduction of installation cost, the diminution of cable constraints and the remote access to data make them perfect for studying occupied buildings.

6 CONCLUSION

The proposed diagnostic methodology has already been successfully applied on several Belgian case studies, confirming clear benefits in terms of efficiency for the building energy diagnosis, especially when dynamic energy models are implemented to explore retrofitting scenarios and support the decision making. For the presented case study, it allowed producing a large quantity of data, from only two actual visits and minimum impacts to the occupants.

At the root of this approach, photogrammetry quickens up the reproduction of the building geometry, with a high level of detail. The combination of inside and outside surveys has proven to provide precious information regarding the architecture and performance of the building, and ultimately for implementing BES models. Not only the envelope geometry is easily transposable but cross sections through the 3D point clouds allows to infer the configuration of indoor spaces and the thickness of walls. Here, the exploitation of the colour information also plays a central role. It provides a strong basis for qualitative analysis (*e.g.* material identification, pathology diagnosis). On their side, wireless sensor networks facilitate and enlarge the collection of data relative to the dynamic behaviour of an occupied building. With an appropriate data processing scheme, both techniques are complementary and allow to rapidly implement accurate and exhaustive energy studies.

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