Combining multi-view photogrammetry and wireless sensor networks when modelling the hygrothermal behaviour of heritage buildings

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Abstract – The construction sector has now entered the 'Digital era', and professionals are slowly getting familiar with many of these innovative technologies. This paper shows how such innovations improve the investigation phase when it comes to energy retrofits on heritage buildings. More specifically, multi-view photogrammetry and wireless sensor networks can facilitate the implementation and enhance the relevance of building hygrothermal and energy simulations: photogrammetry quickens up the reproduction of the building geometry whereas wireless sensor networks facilitate and enlarge the collection of data relative to the existing behaviour of an occupied building.

This paper explores the benefits of using those two technologies compared to more traditional solutions, regarding data quality and general workflow. In this purpose, two case studies from research projects ongoing in Belgium are briefly described.

Keywords – heritage buildings, energy efficiency, wireless sensor networks, multi-view photogrammetry, structure from motion, high definition surveying

1. INTRODUCTION

1.1 INVESTIGATING HERITAGE BUILDINGS IN THE 'DIGITAL ERA'

The rationalization of energy consumption in heritage buildings is a key step in making them more attractive – by reducing bills and improving the comfort [1]. Nevertheless, answering this challenge without harming the heritage values implies a well thought-out approach. If the specific hygrothermal behaviour of old dwellings is not taken into consideration, the risk of exacerbating existing pathologies is important. This implies that experts involved in the energy retrofits of heritage buildings need to be properly trained. Many research initiatives from the last years focused on providing guidelines for improving those competences [2]–[4].

For each energy retrofit project, one of the crucial aspects to deal with is the planning and implementation of a relevant investigation phase to characterize the building. It requires using the adequate sensing and modelling methods to guarantee a holistic grasp. Within the investigation, understanding the dynamic hygrothermal equilibria that take place in an ancient building is the key step in choosing the most appropriate interventions. For this purpose, the specific behaviour of the building can be described by numerical models that predict the response of the building or one of its components when submitted to different climatic conditions. In the context of the 'Industry 4.0' paradigm [5], many new numerical tools and technologies are becoming available to the heritage experts and enrich the well-establish traditional approaches. This paper shows how innovative 3D imaging and wireless monitoring solutions enhance the collection of input data for hygrothermal modelling.

1.2 MULTI-VIEW PHOTOGRAMMETRY

High-definition 3D digitization technologies revolutionized the building surveying and recording processes, which are crucial when working on heritage. Those mass data collection techniques [6] allow recording the surface of an object in a very precise way, with colour information and fine details transcription (Figure 1). Among the available methods, the 'Multi-View Photogrammetry' (MVP) is based on the automatic matching of several (digital) images: the three-dimensional topography of an object is rebuilt from different points of view of the object by means of an algorithm that combines 'structure from motion' and 'multi-view stereo' approaches. A clear overview of the underlying computational aspects can be found in [7]. The 3D point clouds or meshes stemming from HD surveying techniques not only offer a strong visualization and documentation support, but also serve as basis for many advanced numerical studies. In that respect, the handling and transformation of 'raw 3D models' into useful deliverables is more and more documented [8], [9].

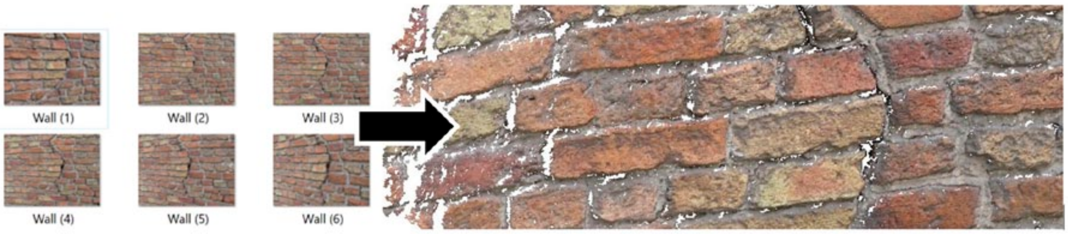

Figure 1. Point cloud generated from photographs of a wall with a MVP software.

1.3 WIRELESS SENSOR NETWORKS

A holistic hygrothermal study of a building often implies to monitor physical variables to confirm hypotheses concerning its behaviour. The sensors and systems dedicated to this task are evolving constantly. Research-dedicated monitoring systems consisted first of specialized data-logging stations connected to various wired sensors. Battery-operated sensors with embedded logging capabilities naturally followed with the development of low power integrated circuits. Today the 'Internet of Things' is gaining popularity [10] and many innovative wireless communication protocols are being deployed, allowing data to be transmitted remotely using radio frequencies [11]. 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 [12], [13]. 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 [14]. The success of open-source development boards and the dynamic user's community should encourage heritage experts to develop more WSN solutions tailored for the study of traditional buildings.

2. COMBINING MVS AND WSN WHEN MODELLING THE HYGROTHERMAL BUILDING PERFORMANCE

When it comes to hygrothermal modelling, three physical fields can be described in a building, i.e. the heat, air and moisture fields, and three geometrical regions, i.e. the exterior air, the building envelope and the interior air regions [15], [16]. Various types of hygrothermal models exist and each category generally focuses on some of these domains [17].

Building Energy Simulation (BES) models are frequently used to assess the energy efficiency of entire buildings. Most are based on the assumption that the air of each room is well mixed and associated with a single temperature value (multi-zone models). Each zone is then described with a heat balance that includes all energy-related loads. The description of moisture transfers is often very simplified. *EnergyPlus* is a well-spread example of such tools. Other models focus on the detailed description of the transient and coupled transfers in specific envelope parts. Most of the time they are simply referred to as Heat, Air and Moisture (HAM) models, but we prefer the denomination Building Element HAM (BEHAM) simulation tools [18] to avoid confusion with the other types of hygrothermal models. *Wufi* and *Delphin* are two popular commercial BEHAM software examples.

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. Even if an initial parameter estimation is crucial, only well-thought monitoring campaigns will effectively support the model calibration phase. Any method that allows increasing the quality of the initial input data or the calibration material is then precious. Figure 2 shows how MVP and WSN intervene in multiple points of the modelling workflow.

The geometry of heritage buildings is complex by nature. Advanced survey techniques such as MVP could capture this complexity and speed up the creation of the whole-building energy models. Photo-based 3D reconstructions are also very rich in textural information that can help the visual analysis of walls composition.

Collecting relevant hygrothermal data through monitoring systems is a hard task. Especially when it implies to instrument an occupied building. Typical monitoring systems are either too invasive (e.g. cables running through the house, large central data logger) or too restrictive (e.g. commercial battery-operated sensor with local storage of data). The development of WSN tends to miniature and polyvalent solutions that are deeply desirable. For the expert, it is a chance to multiply the type of variables that can be monitored and the number of sensors that can be implemented in a building without disturbing the occupants. In particular, 'hybrid' sensor networks that combine commercial and open-source hardware seem to be a powerful solution.

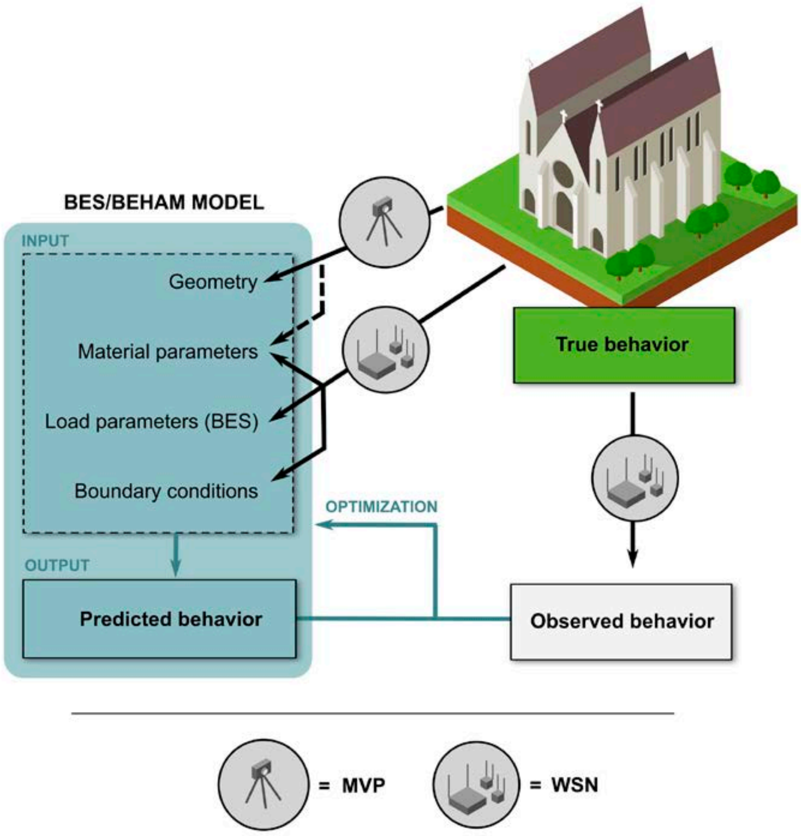

Figure 2. Complementarity of Multi-View Photogrammetry and Wireless Sensor Network to improve the hygrothermal modelling of heritage Buildings.

3. RESEARCH PROJETS AND CASE STUDIES

The combined use of MVP and WSN techniques is currently analysed in two on-going projects that are led by the *Belgian Building Research Institute* in Belgium. Both projects focus on proposing adequate solutions to improve the energy efficiency and comfort of heritage buildings. In Flanders, the project *ErfgoedEnergieLoket,* spanning from 2014 to 2021, focuses on answering the need for energy consultants specialized in architectural heritage. The key measure is the elaboration of a training program intended for restoration architects. The teaching material was enriched through an investigation program carried out on protected buildings [19]. In Wallonia, the research project *P-Renewal,* extending from 2017 to 2021, aims to develop a methodological tool providing strategies of energy refurbishment and sustainable retrofit of historical Walloon dwellings with heritage value and built before 1914.

Figure 3 and 4 show the two case studies chosen here as illustration. Building A is a one-storey 18th century detached house located in Mellier. Building B is a one-storey 20th century villa located in Tervuren. The energy efficiency and the comfort of both buildings needed to be assessed in order to propose and evaluate adequate retrofitting strategies. It implied to create a BES model for each of them.

Figure 3. Building A: a case study in Mellier. Photo: Samuel Dubois.

Figure 4. Building B: a case study in Tervuren. Photo: Samuel Dubois.

Building A was surveyed with the MVP technique, using 918 photographs for the interior spaces reconstruction and 146 photographs for the exterior walls. *Agisoft Photoscan* software was used to generate dense clouds for the two domains. The interior and exterior models were aligned with control points, which were surveyed with a *Leica S910* laser distance measurer. Finally, the *CloudCompare* software was used to further process the point clouds.

The long-term monitoring system implemented in building B is a hybrid network (Figure 5) that combines commercial and tailored components. Commercial *Monnit* sensor nodes allow the monitoring of a wide range of ‘standard’ variables, such as the temperature and relative humidity of indoor air (Figure 6). Those ‘ready-to-deploy’ nodes are useful to deploy a monitoring basis, with a typical 15 min heartbeat interval. The various battery-operated nodes communicate their data to a proprietary gateway using 868 MHz radio frequency. In parallel, a tailored-made signal-processing unit was deployed to monitor heat fluxes through walls (Figure 7). An *Arduino*-based platform collects the analogic signal from a heat flux meter (Figure 8). Afterwards, it transforms the analog data into digital information and transmits it to a *Monnit* serial data bridge: this particular node from the commercial WSN system is the key here to the ‘hybridisation’ process. Once the bridge node gets the heat-flux data from the Arduino, through

RS232 wire communication, it transfers it to the *Monnit* gateway. Upstream of the network, a 3G router ensures that the *Monnit* gateway can communicate with internet, and reaches the cloud servers where all nodes data is stored.

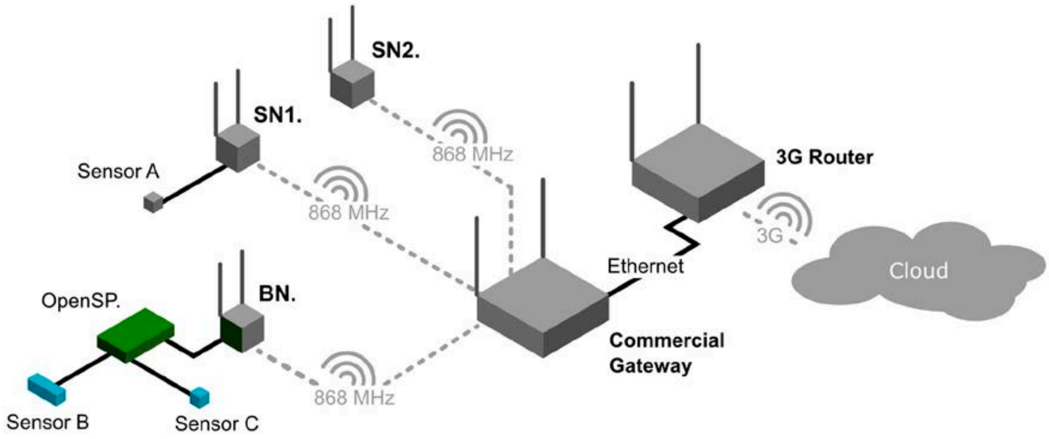

Figure 5. The flexibility of the 'hybrid' WSN system for the monitoring of heritage buildings. SN1 = Commercial sensor node with external sensor; SN2 = Commercial sensor node with internal sensor; BN = Commercial bridge node; OpenSP = Open source signal-processing unit.

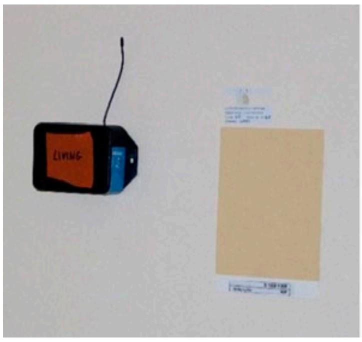

Figure 6. A temperature and humidity sensor node (commercial system) mounted on an interior wall in building B.

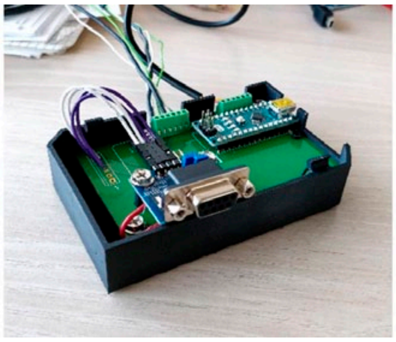

Figure 7. A tailored signal processing unit (open-source) to allow the measurement of heat flux.

Figure 8. A heat flux meter and temperature sensor integrated in the hybrid-WSN solution.

4. RESULTS AND DISCUSSION

Figure 9 shows the combined interior-exterior model generated from photographs of Building A. When performing cross-sections through this 'whole building' point cloud (Figure 9b), we obtain precious input for the geometric modelling of BES. All rooms are well delimited and the combination of their geometry with the exterior envelop provides the thickness of all walls. Orthomosaic photos, easily created from the exterior scan, also provide a strong modelling support (Figure 9c). They allow the drawing of windows or the recognition of material configurations, for example.

The benefits of the approach have to be balanced against some drawbacks. First, the workflow around high-definition 3D reconstructions remains very demanding in terms of computational power. Another important remark concerns the privacy of occupants, which has to be guaranteed throughout the study. Working with photographs is not easy in that respect. Finally, the intrinsic limitations of multi-view photogrammetry (e.g. the object to be reconstructed should not have a uniform colour), as well as the requirements in terms of input image quality should not be underestimated. That imposes to adequately prepare the photographic mission and take measures to validate the accuracy of the 3D reconstruction. In that respect, obtaining accurate and complete 3D models by photogrammetry requires some competences that can only be acquired by experience or proper training. Moreover, not all buildings are necessarily adapted to MVP studies.

Figure 10 shows a portion of the monitoring data collected with the hybrid WSN installed in Building B. More specifically, the heat flux going through one of the exterior walls is provided for a two-week period, together with the temperatures of the adjacent air spaces. Those three variables allow estimating the U-value of the wall, here with a dynamic prospect. The potential of the system was validated as all this data was obtained at a lower cost and with less clutter compared to a traditional logging solution. Advanced heat-flux measurement nodes could thus easily be multiplied within a single occupied building, without bothering the inhabitants too much. In fact, many types of advanced sensors could be deployed in a similar way. The remote access to data offered by this cloud-based WSN was also very useful, for communication purpose (measurements can be showed directly on a smartphone) or to intervene quickly in case of a system failure. An important attention point concerns the risk of losing data due to some miscommunications between the nodes and the gateway or from the gateway to internet.

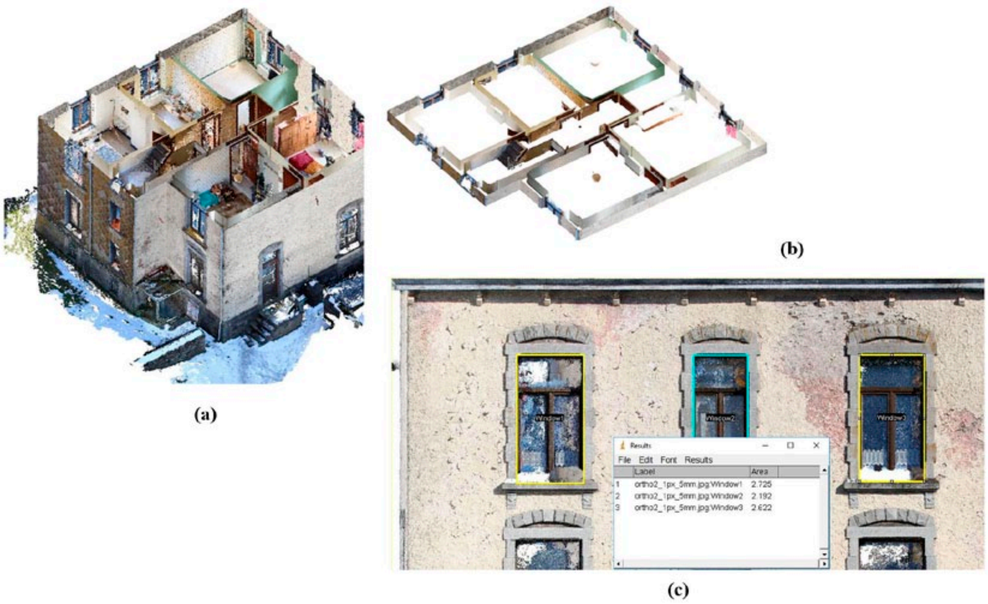

Figure 9. Building A surveyed with MVP: (a) model obtained by combining the interior and exterior reconstructions; (b) a cross-section through the whole-building 3D model; (c) drawings and measurements using an orthomosaic photo as support.

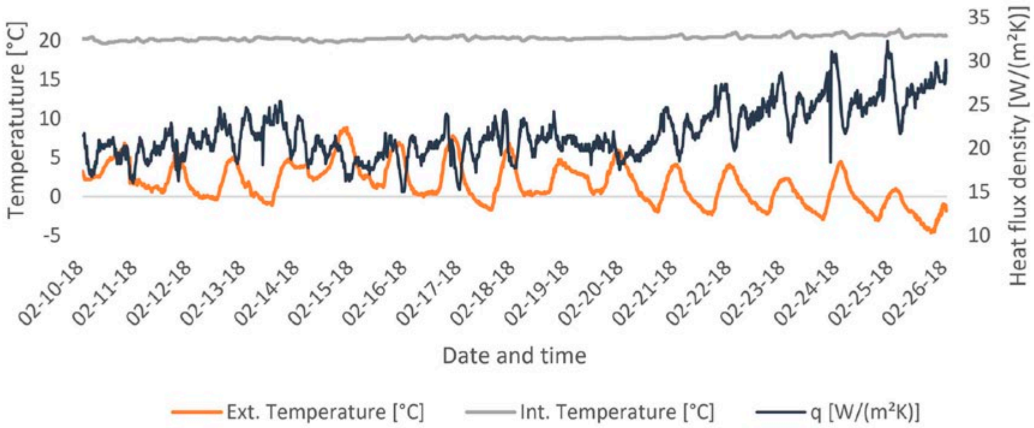

Figure 10. The hybrid WSN system makes it possible to monitor advanced variables remotely, such as the heat fluxes through walls.

5. PERSPECTIVES AND CONCLUSIONS

This paper showed how advanced digital solutions are revolutionizing the work of heritage experts. When it comes to implementing high quality energy retrofits, it is clear that numerical technologies cannot be put aside. We showed that MVP and WSN both improve the hygrothermal and energy modelling workflow, which is a critical stage when investigating potential energy-related interventions. MVP mainly improves the completeness of the geometrical input data. High-quality interior and exterior 3D reconstructions were created with a simple equipment. Combined, the two point clouds provide a holistic geometric dataset. A practical and direct use of this data is the creation of the geometry within a multi-zone building energy simulation. In parallel, WSN proved to be extremely interesting to enlarge the hygrothermal monitoring possibilities in occupied buildings, without causing too much disturbance for occupants. Hybrid systems, which combine ready-to-use sensor nodes and gateways with tailored solutions, open the way to advanced studies at a low cost.

6. REFERENCES

[1] M. de Bouw, S. Dubois, L. Dekeyser and Y. Vanhellement. Proceedings of International Conference on Energy Efficiency in Historic Buildings, 2016. [Online]. Available: https://www.eechb.eu/wp-content/uploads/2016/12/Proceedings_EECHB.pdf

[2] A. Troi, Z. Bastian. Energy Efficiency Solutions for Historic Buildings – A Handbook. Basel: Birkhäuser, 2014.

[3] A. Martínez-Molina, I. Tort-Ausina, S. Cho, and J.-L. Vivancos. “Energy efficiency and thermal comfort in historic buildings: A review,” in Renew. Sustain. Energy Rev., vol. 61, pp. 70–85, 2016.

[4] P. Eriksson, C. Hermann, S. Hrabovszky-Horváth and D. Rodwell. “EFFESUS methodology for assessing the impacts of energy-related retrofit measures on heritage significance,” in Hist. Environ. Policy Pract., vol. 5, no. 2, pp. 132–149, 2014.

[5] M. Brettel, N. Friederichsen, M. Keller, and M. Rosenberg. “How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective,” in Int. J. Mech. Ind. Sci. Eng., vol. 8, no. 1, pp. 37–44, 2014.

[6] D. Barber and J. Mills. “3D laser scanning for heritage: Advice and guidance to users on laser scanning in archaeology and architecture”. English Heritage, 2007. [Online]. Available: https://historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage/ [February 26, 2018].

[7] Y. Furukawa and C. Hernandez. Multi-View Stereo: A Tutorial. Delft: now Publishers, 2016.

[8] S. Dubois, M. de Bouw, and Y. Vanhellemont. “Innovation Paper: le relevé géométrique à haute définition – La numérisation 3D à l’heure du BIM”. CSTC-WTCB-BBRI. [Online]. Available : www.cstc.be/homepage/index.cfm?cat=services&sub...InnovationPapers [January 20 2018].

[9] J. Bedford. “Photogrammetric Applications for Cultural Heritage – Guidance for good practice”. Historic England, 2018. [Online] -. Available: https://historicengland.org.uk/images-books/publications/photogrammetric-applications-for-cultural-heritage/ [February 28 2018].

[10] L. Atzori, A. Iera, and G. Morabito. “The internet of things: A survey,” in Comput. Netw., vol. 54, no. 15, pp. 2787–2805, 2010.

[11] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami. “Internet of Things (IoT): A vision, architectural elements, and future directions,” in Future Gener. Comput. Syst., vol. 29, no. 7, pp. 1645–1660, 2013.

[12] L. Mottola and G.P. Picco. “Programming wireless sensor networks: Fundamental concepts and state of the art,” in ACM Comput. Surv. CSUR, vol. 43, no. 3, p. 19, 2011.

[13] D. Bhattacharyya, T. Kim, and S. Pal. “A comparative study of wireless sensor networks and their routing protocols,” in Sensors, vol. 10, no. 12, pp. 10506–10523, 2010.

[14] R. Fisher, L. Ledwaba, G. Hancke, and C. Kruger. “Open hardware: A role to play in wireless sensor networks?,” in Sensors, vol. 15, no. 3, pp. 6818–6844, 2015.

[15] A. Janssens, M. Woloszyn, C. Rode, A. Sasic-Kalagasidis, and M. De Paepe. “From EMPD to CFD–overview of different approaches for Heat Air and Moisture modeling in IEA Annex 41,” IEA ECBCS Annex 41, pp. 9–20, 2008.

[16] D. Costola, “External coupling of building energy simulation and building element heat, air and moisture simulation,” Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2011.

[17] S. Dubois. “Modelling the hygrothermal behaviour of crop-based construction materials” PhD Thesis, Gembloux Agro-Bio Tech, 2010.

[18] H. Hens. “Modelling, Heat Air and Moisture Transfer in Insulated Envelope Parts,” Final Rep. IEA-Annex, vol. 24, 1996.

[19] M. de Bouw, S. Dubois, S. Herinckx, and Y. Vanhellemont. “Specialized energy consultants for architectural heritage,” in Proceedings of International Conference on Energy Efficiency in Historic Buildings, 2014.