INTEGRATING STATISTICAL DATA AND THERMOGRAPHIC SURVEY FOR ASSESSING ENERGY RENOVATION POLICIES: A REVIEW

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Abstract

Despite extensive energy renovation policies implemented across Europe, the tangible improvement in housing energy performance remains slow, particularly evident in Wallonia, Belgium, used as a case study. Identified challenges include mismatches between existing renovation support mechanisms and target demographics, as well as discrepancies between diagnostic tools like the Energy Performance Certificate (EPC) and actual construction realities. This paper is a reminder of two established methodologies to explore their potential synergies in addressing these issues. Leveraging large-scale databases enables the assessment of the building stock's composition and the socio-economic characteristics of residents. Concurrently, thermographic surveys offer rapid identification of atypical cases. Cross-referencing these methodologies reveals their compatibility and complementarity, suggesting a promising avenue for future research to test their combined efficacy in addressing energy renovation challenges.

Keywords

behavior, energy audit, Wallon region,

Abbreviations

AI, Artificial Intelligence; BEM, Building Energy Model; EPC: Energy Performance Certificate; EN, European Norms; GPR, Ground Penetrating Radar; HFM, Heat Flux Meter; IRT, InfraRed Thermography; ISO, International Organization for Standardization; IoT, Internet of Things; LiDaR, Light Detection and Ranging; NDT, Non-Destructive Techniques ; TPC, Thermal Point Cloud; UBEM, TWIR, Through Wall Imaging Radar; Urban Built Energy Model; UHI, Urban Heat Island

Introduction

The need to renovate Europe's built stock to meet climate targets (Renovate Europe, 2020) is a widely shared consensus. This is all the truer given the many other advantages of energy renovation (Thuvander et al., 2012). Long focused on new buildings, legislation is taking an increasing interest in this significant part of the built stock (Directive 2010/31/UE on Energy Performance of Building, 2010; Directive 2012/27/EU on Energy Efficiency, 2012). Numerous strategies are being tested: incentives (Dubois & Allacker, 2015), tax incentives (Villca-Pozo & Gonzales-Bustos, 2019), rent controls (Bertoldi, Economidou, et al., 2021), the massification of programs (Brown et al., 2019), simplification of supply (Bertoldi, Boza-Kiss, et al., 2021), and so on. Despite these numerous and sometimes costly programs, the rate of energy renovation is not reaching the expected levels (Filippidou et al., 2017).

When we look at the reasons why a household decides to undertake energy renovation work, we can see that this choice depends on two main aspects, among others. On the one hand, the best way to renovate largely depends on the technical characteristics of the building (Nielsen et al., 2016), its basic condition, its dimensions, its organization, the physical characteristics of the materials used, etc. While it is possible to improve the energy performance of any building, the fact remains that the techniques to be adopted, and therefore their cost, vary drastically depending on the base case. On the other hand, the socio-economic conditions of its occupants and owners (Friege & Chappin, 2014) will largely define the actions that can be envisaged. Occupancy status (rental, shared ownership, sole ownership) (Ástmarsson et al., 2013) and income, which determine the risk of falling into fuel poverty (Meyer et al., 2018), the ability to invest and knowledge of subsidy mechanisms (Baek & Park, 2012) are essential determinants of the decision to act. However, these two aspects are still relatively compartmentalized, both in the scientific literature and in the initiatives targeting one or the other. If we look at Belgium, the articles that have been able to study them together (Anfrie et al., 2021; Ruellan et al., 2021) are still very patchy. The state of the energy efficiency of the built stock suffers from very fragmented, old knowledge that is subject to many approximations and which is not representative of the actual use of the building (Monfils & Hauglustaine, 2016).

This brief introduction leads us to the following research question: How can we gain a better understanding of the built stock based on both the physical characteristics of the building and the socio-economic characteristics of its occupants?

To answer this question, we will first look at how our laboratory's previous studies in the Walloon region have enabled us to establish the existence of correlations between these different criteria and the possibility of proposing a mixed socio-technical model of the housing-occupant relationship.

Then, based on a review of the literature on infrared thermography, we will analyze the way in which such a technique could potentially enable us to validate hypotheses about this dwelling-occupant pairing with a view to better guiding building renovation strategies.

Finally, we will discuss the possible implementation of such a scan to validate the various hypotheses and identify the strategies best suited to the various cases encountered.

Building/Inhabitant couple: data crossing

It is reasonable to ask what correlations exist between the different technical and socio-economic characteristics that are decisive in the decision to renovate. To this end, we have previously (Ruellan et al., 2021) used different independent databases representing the criteria we were interested in for the Walloon Region. Two databases were compiled to represent the geometry of the building (detached, semi-detached, attached, flat) and its energy efficiency based on the EPCs. Two other databases were compiled to represent household income and occupant status (owner or tenant). The correlations between the distribution of these characteristics in the various Walloon municipalities were studied using statistical tools (Spearman correlation, linear regression, multiple linear regression), some of the results of which can be seen in Figure 1. It has already been possible to observe that flats were, on average more efficient due to their compactness and, even though they were mostly occupied by tenants on lower incomes. Paradoxically, the increase in income is accompanied by a relative decrease in energy efficiency.

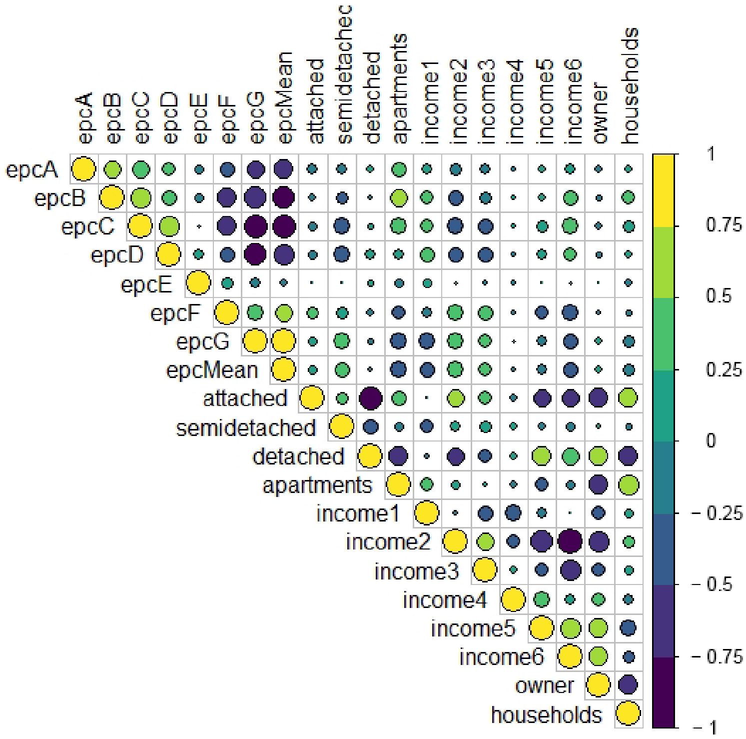

Figure 1. Spearman correlation between technical and socio-economic characteristics of the Walloon built stock (Ruellan et al., 2021).

Based on these initial results, it was possible to propose a clustering approach (Ruellan et al., 2025). Without going into detail - which is the subject of a dedicated article currently being submitted for peer review - the databases studied were weighted to take account of their representativeness. More specific statistical algorithms were then used to establish the correlations between these factors as accurately as possible. These correlations made it possible to construct statistically representative clusters of the different building/inhabitant pairs existing in Wallonia (Figure 2), composing a new model of the built stock capable of better anticipating the effectiveness of different building energy renovation strategies.

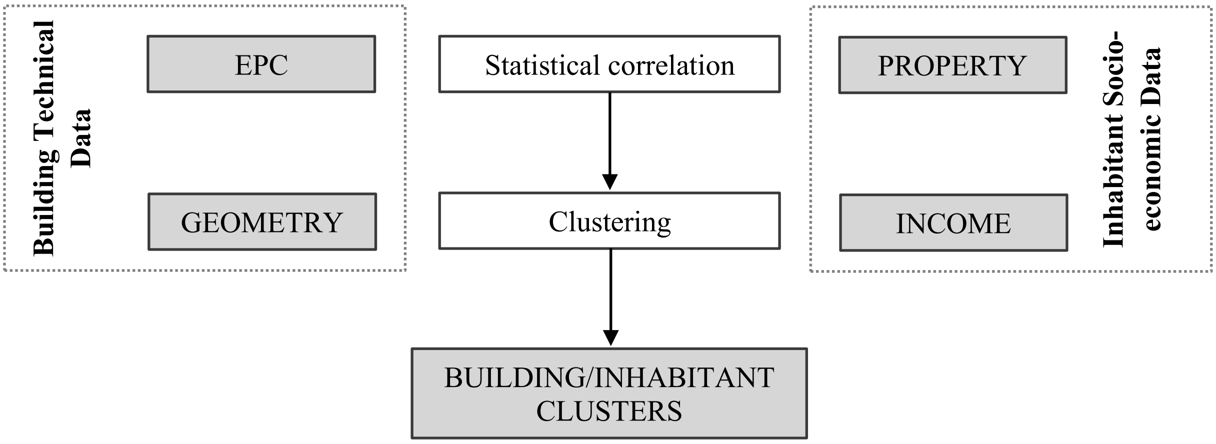

Figure 2. Conceptual framework on the correlations between the technical characteristics of the building and the socio-economic characteristics of the inhabitants.

This model of the built stock is based on many assumptions, each of which brings its uncertainties and approximations. At this stage, it remains largely theoretical. It is therefore necessary to compare it with a field study, the aim of which would be not only to validate or correct the model's initial conclusions. The field study could also make it possible to establish the link between the clusters identified and the renovation strategies to be implemented for each one. One of the techniques identified for this purpose is InfraRed Thermography (IRT).

Building Infrared Thermography: Process

Before going any further with a review of the literature, here is a reminder of the use of IRT in the energy analysis of a building. Without going into the details of the physical calculations, materials send out radiation in the infrared range in two components: the radiation emitted by the material as a function of its temperature and the radiation reflected by the surface of the object. Figure 3 illustrates the results obtained, as well as some of the difficulties associated with this measurement. The perimeter of window frames can be seen as a hot spot in the wall, compared with brick and stone, indicating the existence of a thermal bridge. On the other hand, glazing appears much cooler than brick, despite its lower thermal performance, because glazing reflects more radiation from the colder environment. As we shall see later, the results of an IRT can be used in many ways. However, this method also has its limitations and requires precautions to be taken when using it.

Figure 3. Comparison of infrared thermography and a visible image

Standards regulate these analyses ISO 6781 (*ISO 6781-1*, 2023) and EN 13187 (*UNE EN 13187*, 2000-11-01), which set out guidelines for detecting thermal defects in the envelope using the infrared method, and ISO 9869 (*ISO 9869-2*, 2018) for in-situ measurement of resistance and thermal transmittance using IRT, to limit the risk of errors in interpreting the results.

One of the rules to follow to ensure good quality IRT is that the temperature difference between inside and outside must be at least 10°C. And that this temperature difference is present long enough before the test to limit the impact of inertia. Similarly, it is preferable to have precise knowledge of emissivity and reflection temperature factors, which are common sources of error in IRT. In addition to IRT, it is necessary to take regular readings of the ambient temperature and relative humidity to ensure that they are relatively constant or to take account of any changes. The wind should be light (<5 m/s). Finally, it is not advisable to study a facade that is sunny or has recently been sunny. For all these reasons, the best time to survey in Europe is on a winter's morning, before sunrise and with plenty of cloud cover. However, it is also possible to survey the rest of the day, if you pay particular attention to the other criteria.

The reading distance should be as constant and as small as possible to minimize atmospheric noise and increase the resolution of the image obtained: between 5 and 20 meters is recommended for the thermography of a façade. While it is recommended to be perpendicular to the building, it should be noted that some sources (Kylili et al., 2014) recommend shifting slightly to avoid impacting the thermography with the reflection of the thermographer and equipment's infrared emissions.

Building Infrared thermography : A review of reviews

Now that the technique is known, it's worth asking how it can be used. What are the limitations, advantages and potential areas for improvement of IRT? To do this, we will conduct a literature review. To reduce the amount of text, we will concentrate on analyzing literature reviews that have already been carried out using the following keywords: "*building infrared thermography review*". Excluded are reviews that deal exclusively with fault detection, envelope damage, structural analysis and reviews that deal specifically with heritage buildings.
The ten studies selected are listed in Table 1, in order of publication and annotated with their number of citations according to google.scholar. The recent nature of this field of research can already be seen. Indeed, without any date criteria in our searches, the first literature review article on this subject only appeared in 2014. On the other hand, there has been a clear acceleration in this research since 2018 due to the clear material and treatment advances raised by these various articles (Lucchi, 2018).

Table 1. Literature reviews in the field of infrared thermography of buildings

Sources	Name	G.Scholar citation
(Kylili et al., 2014)	Infrared thermography (IRT) applications for building diagnostics: A review	576
(Lucchi, 2018)	Applications of the infrared thermography in the energy audit of buildings: A review	266
(Kirimtat & Krejcar, 2018)	A review of infrared thermography for the investigation of building envelopes: Advances and prospects	124
(Nardi et al., 2018)	Quantification of heat losses through the building envelope: A state-of-the-art analysis with critical and comprehensive review of infrared thermography	149
(Shariq & Hughes, 2020)	Revolutionising building inspection techniques to meet large-scale energy demandes: A review of the state-of-the-art	70
(El Masri & Rakha, 2020)	A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections	98
(Martin et al., 2022)	Infrared thermography in the built environment: A multi-scale review	51
(Ramón et al., 2022)	Thermal point clouds of buildings: A review	21
(Tardy, 2023)	A review of the use of infrared thermography in building envelope thermal property characterisation studies	6
(Kim et al., 2023)	Innovations in building diagnostics and condition monitoring: A comprehensive review of infrared thermography applications	10

In 2014, Kylili et al. published an article on the applications of IRT for building diagnostics. (Kylili et al., 2014). This article discusses the physical foundations and history of IRT. It also gives a broad overview of the many uses of IRT. There are two approaches to building and civil engineering thermography: passive thermography measures the temperature difference of a structure under normal conditions. In contrast, active thermography measures the temperature difference of a structure subjected to an external heat source. The passive approach is mainly qualitative, enabling anomalies such as thermal bridges or the presence of moisture to be located. However, passive quantitative approaches have been developed by controlling the climatic parameters on both sides of the wall. In this way, it is possible to quantify the value of a thermal bridge, calculate the U-value of a wall with a deviation of the order of 10 to 20%, or even cross-reference thermal and photogrammetric data to estimate the energy performance of an entire façade. The infrared active pulsed and active lock-in thermography are mainly used to detect construction defects in materials and very little for an overall analysis of the envelope due to the greater complexity of the installation. A paragraph is also devoted to infrared image analysis, highlighting the importance of considering the reflection of different materials.
Lucchi offers a comprehensive review based on 148 publications on the use of IRTs in building energy audits. Passive and active approaches are again distinguished. The passive approach remains the typical approach for energy audits. This approach is itself subdivided according to the method used to obtain it: "aerial, automated fly-past, street pass-by (or drive-in), perimeter walk around, walkthrough, repeat, time-lapse, and mock target" (Lucchi, 2018). These approaches progress from the fastest and

most inaccurate (aerial shots) to the most precise and time-consuming (time-lapse, mock target). The drive-in approach already appears to be an interesting compromise for studying the built stock on a large scale. Finally, the article concludes that qualitative approaches are already widely covered in the literature. By contrast, quantitative applications, such as insulation level detection and U-value measurements, require more research.

Based on the previous article, Nardi et al. (Nardi et al., 2018) published an article the same year focusing more specifically on the problem of determining U-value. An easy, quick and inexpensive method of determining the U-value is an important issue in building energy improvement strategies. Five methods can be used to determine the U-value of a wall: analogies with coeval buildings, calculation method, heat-flow meter measurements, laboratory testing and IRT measurements. IRT measurements to determine the U-value are the subject of 34 articles, classified according to whether they concern the façade, roof, glazing or thermal bridges. The study of façades is the most studied subject, while the study of glazing and roofs presents specific difficulties, such as reflection. The study concludes once again that this technique is effective and profitable on a large scale. However, it is necessary to use good quality instruments, and to ensure that the climatic conditions for the survey are maintained.

In parallel Kirimtat and Krejcar (Kirimtat & Krejcar, 2018) publish their own literature review on the field of infrared thermography in building envelope research. Sixty-two studies published between 1998 and 2017 are classified according to criteria similar to those already mentioned: the measurement method (quantitative or qualitative), the analysis scheme (active or passive), the type of analysis (thermal bridge, U-value, moisture, air leakage, heat loss, other problems), the component analyzed (exterior wall,, interior wall, floor, roof, ceiling, window, sample, junctions), the surface material, testing locations (in-situ and/or laboratory) and the type of study (experimental and/or numerical). The article's conclusions include the growing number of studies in the field. The IRT is a robust tool that can be used in many ways. They are particularly well suited to the study of buildings prior to renovation, provided that the data obtained is properly processed. Passive in-situ studies provide rapid and cost-effective results.

Shariq and Hughes (Shariq & Hughes, 2020) are interested in the detailed examination of large-scale building inspections and, in particular, study the feasibility of combining the latest hardware advances in terms of IRT, photogrammetry and drones. They highlight the potential for combining these different techniques, accentuated by rapid advances in Artificial Intelligence (AI) for combining and analyzing the results obtained. A simultaneous survey using monocular photogrammetry and IRT using a drone would enable 3D mapping to be produced quickly and efficiently. Lidar, on the other hand, is highly suitable for in-depth analysis of a façade but requires too much time to carry out this work on a large scale.

El Masri and Rakha (El Masri & Rakha, 2020) propose a literature review of six Non-destructive Techniques (NDT) for building performance inspections: Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDaR), IRT, Ultrasound, Close range photogrammetry and Through Wall Imaging Radar (TWIR). No single NDT technique fulfills all the categories defined for a building energy audit as defined by the ASHRAE 211P standard. Among the various possible combinations of NDT, IRT and GPR offer interesting prospects. The article highlights the importance of rationalizing the combination of these tools, using hybrid hardware or software to process the results. In any case, these mixed, large-scale databases would be extremely valuable for assessing the validity of building energy policies. Finally, it is emphasized that most of these techniques, except for GPR, can be implemented on a drone to streamline the process further. The ability to automate the process and the possibility of connecting different tools to the drone are thus becoming priority areas for research into large-scale energy renovation of buildings.

In 2022, Martin et al. (Martin et al., 2022) carried out the same literature review of IRT on buildings, looking at the different scales of study through 197 articles. Meta-analysis tools were used to analyze this large body of text. Among the scales of study, they distinguish between the city-scale observed by satellite, the neighborhood scale observed from the air and the building-scale observed by drone or from the ground. Some specific studies have even chosen to combine different scales. Martin et al. in turn, raise the interest of cross-referencing infrared data with other data sources, not only other image sensors but also data from the Internet of Things (IoT), which could be used to produce a digital twin. Another area of exploration is the development of street thermography alongside new thermal image processing mechanisms. The analysis of urban heat flows to understand the Urban Heat Island (UHI) would also benefit from more detailed studies on small scales, as well as comparing estimates of urban heat flows on different scales. Finally, the authors also highlight the potential of infrared imagery used on a large scale to feed Urban Built Energy Models (UBEM) and reduce their uncertainties. These lines of research are all avenues for better analysis of how a city functions and strategies for energy improvements.

The literature review published by Ramón et al. (Ramón et al., 2022) focuses more specifically on Thermal 3D Points Clouds (TPC), with a review of 21 articles. This field of research is still in its infancy. Among the research gaps in this field, Ramon et al. show that most of the work is done outdoors. Surveys are generally carried out in a single pass without considering the temporal dimension that could be used to refine the results and limit uncertainties. The transition from a thermal point cloud to a semantic model and the format of these computer models are other major problems. Finally, the IRTs still need to improve the automatic calibration of temperatures according to exogenous criteria.

Tardy (Tardy, 2023) provides a literature review comparing U-value assessment techniques. ISO 9869-1 (*ISO 9869-1*, 2014) defines thermal resistance using Heat Flux Meters (HFM). ISO 9869-2 (*ISO 9869-2*, 2018) defines the definition of thermal resistance based on IRT but restricts it to steady-state lightweight structures. In the field of IRT, standards still need to be improved and clarified. Most of the research is based on the need to carry out several measurements over time. In theory, in-situ research should be based on resistance-capacitance models rather than resistance-only models, which is not the case for most of the research using IRT. In conclusion, there is still considerable improvement to be made in IRT surveys to offer more accurate results at the same time. With sufficient improvement, it would be possible to achieve results equivalent to those of an HFM in a simpler and less invasive way.

Kim et al. (Kim et al., 2023) reiterate many of the observations already made, such as the existence of passive and active methods or the effectiveness in detecting envelope defects. The emissivity and reflectivity of surface materials are crucial parameters for the accuracy of measurements. In the field of urban auditing and analysis, the use of AI and machine learning could lead to significant progress in terms of accuracy and speed of data processing.

At the end of this qualitative analysis of literature reviews on the IRT as an energy audit tool, several common lessons can be found summarized in Figure 4:

- The first point is the importance attached to the precision of the IRT. As mentioned above, the IRT must follow a rigorous protocol if it is to be usable. In addition, the quality of the equipment and the training of the technicians are just as important in ensuring the quality of the results.
- IRT can already provide a significant amount of information, both on building defects and on the general energy audit of the building.
- IRT must take advantage of its simple and inexpensive nature to increase the number of readings and thus reduce the intrinsic uncertainties.
- IRT must be accompanied by other surveys: weather conditions, photography, photogrammetry, Lidar, etc., which will be analyzed together, not only to limit errors of interpretation but also to identify new information.
- IRT can benefit greatly from advances in image processing, particularly in the field of automatic learning. One of the major challenges is to succeed in automating image processing to be able to take many readings in a short space of time.

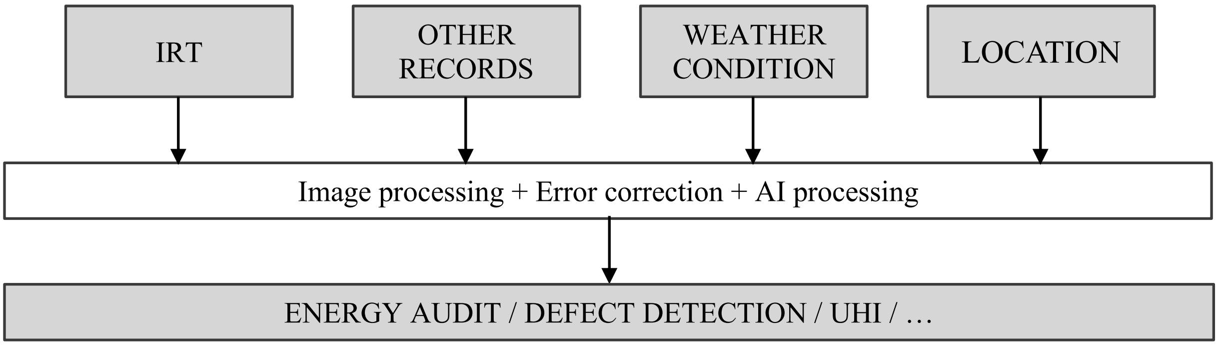

Figure 4. Conceptual summary of the main findings of the literature review on IRT of buildings.

Discussion

In the first part, we looked at how statistical analysis of databases on the built stock and the inhabitants enabled us to estimate the correlations that exist between certain technical data on the building and certain socio-economic data on the occupant. Clustering has enabled us to go even further by proposing building/inhabitant pairs that are representative of the composition of Wallonia's built stock. However, this approach has yet to be validated by field studies and currently remains a macro approach that does not tell us much about the occupancy of a specific building.
In parallel, the second part of this article has identified the strengths of the IRT to understand the specific characteristics of a building better. Not only is it a relatively quick and cheap technique to implement on a large scale. Would it then be possible to imagine that this IRT survey of a building, coupled with a statistical analysis of the building stock in which it is located, could give us relatively reliable hypotheses, not only on the technical composition of the building but also on the socio-economic characteristics of its occupant?
By cross-referencing the thermography results with knowledge of building occupancy, for example, based on energy consumption data, we could further refine the results. In parallel, as we have already shown, the location of the property itself provides us with estimated information on a whole range of parameters that play a key role in the decision to renovate. The IRT could, therefore, become the ultimate tool for refining these estimates and reaching out to a certain number of households that would benefit from support and personalized assistance to improve the energy performance of their homes (Figure 5).

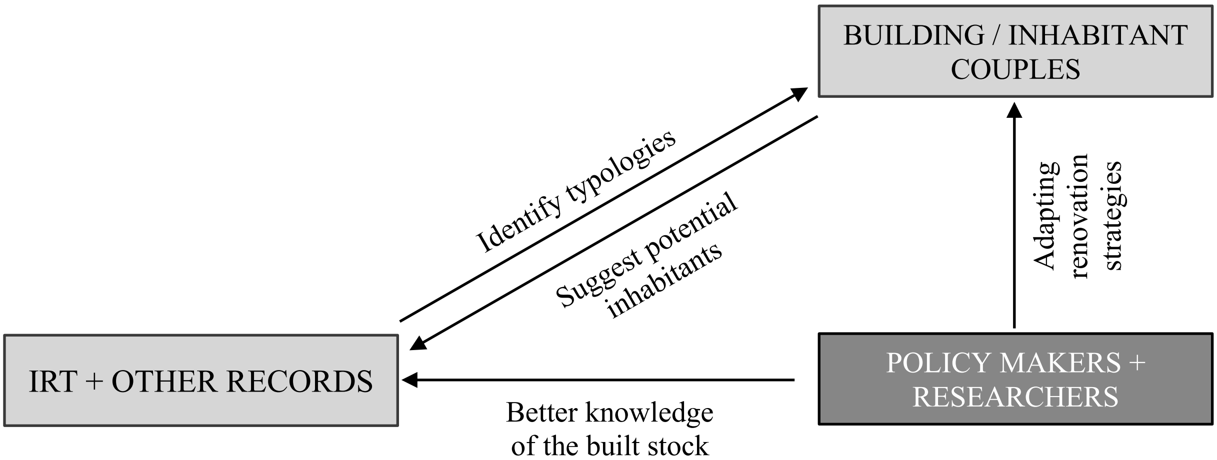

Figure 5. Crossing of IRT and statistical studies to target policies in favor of energy renovation

This cross-referencing of results between a scan of buildings based on an IRT and a statistical analysis of macro databases should make it possible to propose the most appropriate strategies for each building. However, given the many assumptions underlying the relationship between the IRT scan and the statistical analysis, it is advisable to validate it before extending it. We therefore propose to begin by validating these hypotheses through a survey carried out in the buildings subjected to the scan (Figure 6).

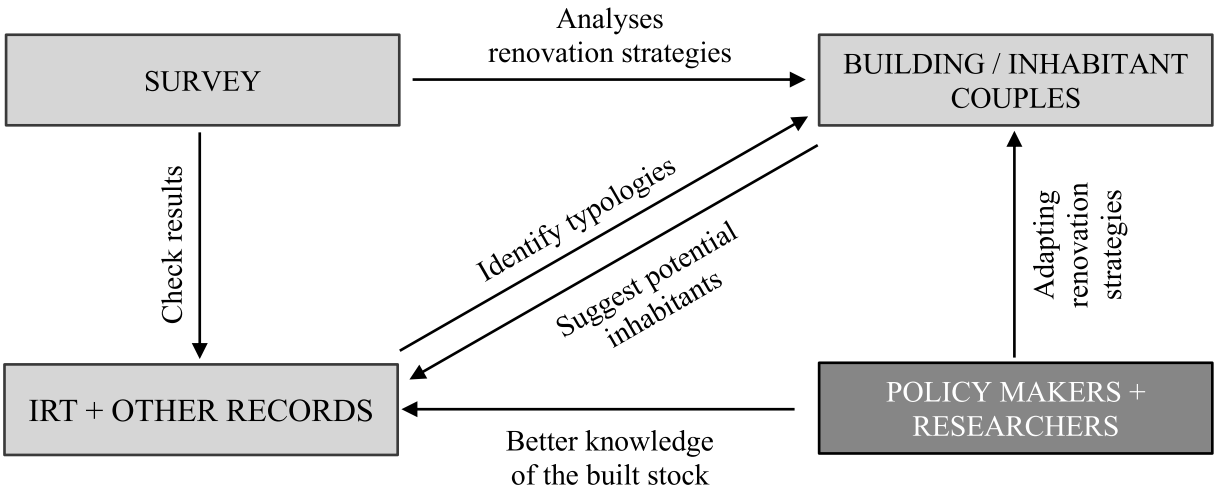

Figure 6. Conceptual framework for a future study linking the couples resulting from clustering to an IRT.

In order to verify all of these results, it is planned to carry out (i) a thermography and photographic survey of a group of buildings from the public space, (ii) an identification of the technical characteristics of the building and the socio-economic characteristics of the occupants based on the elements known and visible from the public space, (iii) and a door-to-door survey in order to compare the data obtained with the reality of the use of the building and to associate them with a set of questions on the possibility of carrying out energy improvement work on the building.

Conclusion

In this article, we first recall the importance of considering both the technical aspects of the building and the socio-economic aspects of the occupant and owner. We then demonstrated the existence of correlations between these different aspects. These correlations make it possible to pool the numerous databases that exist on these aspects. Following this logic, it has previously been possible to establish a mixed model of the built stock for the Walloon region of Belgium. However, this model remains largely theoretical to date. At the same time, a literature review on infrared thermography as a non-destructive energy audit technique gave us an idea of the potential of this technology for improving the energy efficiency of the built stock. While the accuracy of the measurements still needs to be improved, the possibility of combining IRT with other techniques and advances in automated processing are promising.

Ultimately, among the potential areas for future research identified, we believe that the possibility of combining the two techniques mentioned above offers unexplored potential for better-guiding renovation strategies towards effective, efficient approaches. To confirm this intuition, we propose to complement the macro study of the built stock and the IRT survey with a survey that will not only validate the assumed link between these two parts but will also be able to provide more information on the strategies to be adopted.

For researchers in the field of energy efficiency in buildings and for policymakers, this article not only proposes a new way of integrating technical and socio-economic issues. It also proposes a new methodology that still needs to be tested in situ.

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