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Abstract *According to the French Environment and Energy Management Agency (ADEME), a poorly insulated roof can be the cause of 25 to 30% of heat loss from a building. Given that a municipality's real estate consists mainly of old buildings, a comprehensive approach is essential to improve roof thermal efficiency.*

In this context, the Urban Region of Compiègne (URC), in partnership with ADEME, has implemented an extensive public awareness campaign on building insulation, targeted at local residents and elected officials. Among other initiatives, the campaign conducted an aerial thermographic survey of the entire URC. The urban region of Compiègne organized a Thermography conference to help residents interpret data about their own residence and to inform them about relevant financial aid and other programs. To extend the study beyond an analysis of individual buildings, the URC asked the Department of Urban Systems Engineering of the University of Technology of Compiègne to perform additional studies. This article presents the work we did for building stock. The scope of the study was to propose a tool to conduct a comprehensive diagnostic of the territory of Compiègne and identify areas of particular interest.

One point in particular will be discussed in this article: the creation of a set of indicators to refine the analysis relativizing heat loss through the roof and to identify priority intervention areas.

1. INTRODUCTION

Under the Kyoto Protocol, France has pledged to cut its greenhouse gas emissions fourfold. To fulfil this commitment, the French government has implemented legislation and regulations mobilizing all its local authorities to help reduce greenhouse gas emissions [1]. In the urban region of Compiègne (URC), emissions of greenhouse gases (GHGs) stand at 8.1 tonnes of CO_2 per capita per year, thus exceeding the national average (5.5 tonnes in 2010). But the target set by the Grenelle Environment Plan for 2050 is to not exceed 2 tonnes CO_2e per capita per year. The URC has therefore required its territory to reduce GHG emissions by 30% – especially for residential private properties. Indeed, according to ADEME, a poorly insulated roof can be the cause of 25 to 30% of a building's heat loss [2]. Given that existing real estate stock consists mainly of old buildings, it is essential to implement a comprehensive approach to improve the thermal efficiency of roofing.
This contribution is based on an energy audit using aerial thermography and the GIS tool to carry out a comprehensive analysis of an urban territory – specifically on the residential building stock in this case. The aim is to provide a diagnostic tool for an overview of the territory and locating priority intervention areas. One point that will be particularly discussed in this article is the creation of a set of indicators to refine the analysis relativizing heat loss through the roof and identify priority intervention areas.

2. AERIAL THERMOGRAPHY MEASURING ENERGY PERFORMANCE

The energy consumption of buildings has been the subject of several studies. In urban physics, authors generally use the calculation of energy consumption based on the age of the building and the urban form as their main input [3]. With regard to this modelling, Arantes et al. [4] have largely weighted evidence of relationships between urban compactness, density and energy efficiency, to promote the concept of "morpho-energy optimization". This work highlights the difficulty of working on energy efficiency and urban forms across the city. Furthermore, the analysis of actual energy loss from buildings at the urban scale is, to our knowledge, less studied. Ham and Golparvar-Fard [5] highlight the limitations of the use of energy simulation software for such projects. They offer a 3D model based not on the theoretical energy consumption of urban forms, but on facade thermography. This tool offers a real representation of the current state of the energy performance of buildings. However, it is long and expensive to implement at the agglomeration level. Beyond facade thermography, aerial thermography offers an alternative through large-scale evaluation of the actual energy performance of a city. Yet few scientific papers use aerial thermography and most focus on the upstream stages of infrared image processing [6] or evaluate the urban micro-climate [7].
This contribution is based on energy audit using aerial thermography and the GIS tool to provide a comprehensive analysis of the residential stock. The task of the URC was to understand the relationship between heat loss captured by the infrared camera and other elements to characterize the urban space in terms of urban form (block forms, density of buildings, etc.), type of building (building height, collective, individual, etc.) or year of

construction, especially after the introduction of thermal regulations in 1974. The second objective of our study was to identify priority intervention areas for which, after gathering more information, pooling of interventions would be beneficial. It also requested the development of a knowledge aggregation tool of the housing stock and the creation of a database incorporating the results of the aerial thermography. Both tools should facilitate decision-making.

3 METHODOLOGY AND RESULT

3.1 Introduction

Our method is divided into 4 stages: **a**. Interpretation of georeferencing and statistical analysis of the thermographic image; **b**. Creation of a set of multi-source data to link data from the thermographic survey campaign to the residential building stock and its various characteristics; **c**. Creation of a set of indicators. The aim is to relativize the thermographic data with a roof heat-loss index. This index estimates the percentage of heat that might escape through a roof. These indicators help quickly assess heat loss through roofs at the agglomeration scale; **d**. Use of these indicators to define priority intervention areas.

Four indicators have been developed: **Index1**: Based on the thermographic image, calculation of an average energy loss for each building; **Index2**: Calculating, using land registry data, the index of potential heat loss roofs; **Index3**: Cross-referencing the first two indexes to identify priority intervention areas; **Index4:** Correlating priority areas with statistical data on low incomes to derive the ultra-priority intervention areas.

3.2 Average heat loss of buildings index (Index1)

This index was obtained in two steps. Firstly, transformation of the 4096 grayscale infrared image into a map of 256 color levels. Secondly, reclassification of the 256 colors into 6 levels. Each of the six classes covers the same proportion of surface.
This index is easily exploited. It corresponds to average heat loss of buildings. By comparing the loss of all the buildings, it highlights the less insulated buildings. Although these results are subject to the limitations of the thermographic data, they do provide an overall view of the city. The map produced highlights several areas of issue. These sectors correspond to geographical sets of more or less large areas where the majority of buildings are identified as poorly insulated.

Limitation of this index:

The first index already gives us a first idea of the state of the housing stock. However, this index only focuses on the thermographic data. It does not take into account the specificity of different urban forms. However, the characteristics of urban morphology can halve the energy consumption of a town [8].

3.3 Calculating the potential share of roofs in the actual loss of a building (Index2)

To overcome this limitation, a second index has been developed. It evaluates the “potential share of roofs in the actual heat loss of a building”. Three additional datasets are needed: roof area, the total area of facades and the area of terraced facades. This index is independent of the thermographic results. It allows us to identify buildings for which, if necessary, roof insulation will significantly lower the total heat loss of the building. It will be cross-referenced with the thermographic data.
Several steps are necessary: **a.** Calculation of roof area; **b.** Calculation of the area of terraced façades; **c.** Calculation of the potential share of roofs in the actual heat loss of a building.
This index helps identify a more realistic share of losses through the roof of a building. The higher this ratio, the greater the potential leakage rate through the roof. It confirms that the share of potential loss through the roof frame may vary depending on the shape of the building (area, height) and the presence or absence of terraced façades.

Limitation of this index:

This index does not take into account the potential insulation of the roof. If a roof is well insulated, loss through the roof will be minimal, even if the share of potential loss is large.

3.4 Perimeters of priority intervention areas

Indexes 1 and 3 are cross-referenced to identify buildings whose share of potential loss through the roof is above the average of the agglomeration and whose heat losses are high or very high. This new index highlights buildings with potential high roof loss and where the thermographic campaign revealed heavy losses. The incorporation of thermographic data into the model overcomes this limitation. Over 18% of the URC’s housing stock is concerned by this indicator.

Limitation of this index:

This index does not take into account the socio-economic profile of the people living in the buildings. The thermal quality of the building and the low income of its occupants are two of the three nested factors that lead to household energy poverty [9]. Excessive energy consumption, caused by poor insulation of housing, will be all the more harmful if the persons concerned have modest incomes. In some cases, poorly insulated housing thus increases the risk of fuel poverty.

3.5 Perimeters of ultra-priority intervention areas

To incorporate this parameter, we undertook to identify potential energy poverty areas. We used statistical data from INSEE to locate geographical areas with low average income. We considered low-income areas, where more than 25% of households were under the low-income threshold (10% of the total population of the URC). The selected areas were then cross-referenced with the buildings identified as priorities.

This last indicator greatly restricts the number of priority buildings and we focused on what could be called ultra-priority buildings. These represent less than 2% of the agglomeration's residential stock, but stress territorial inequalities.
This initial work of locating intervention areas is the first step of city-wide investigation. It should be clarified through more detailed studies on the buildings identified: facade thermography, and surveys of the occupants of individual houses to improve interpretation of the thermographic image.
This definition of these priority and ultra-priority areas will enable the agglomeration to organize its actions towards residents, owners, social landlords, etc.

4. CONCLUSION

Overall, the study of the URC housing park confirms aerial thermography as an advocacy tool and as an operational tool for energy performance diagnostic at building level in the scale of the city. Taking good account of all the limitations involved in interpreting thermal maps, it should be possible to use energy loss data for the housing stock effectively by comparing the results obtained with the average building heat loss index and by calculating roof losses, in order to inform public and private owners or landlords in charge of the stock. The study therefore identified priority intervention areas related to high energy loss and correlated to population average incomes.
In parallel to this awareness campaign and individual information, the two tools created as part of the workshop project (analysis of the building stock and database on the energy performance of Public housing stock will allow the URC to target interventions and implement public policy that will enable it to reduce its greenhouse gas emissions. To go further, it would be interesting to consider how to improve the quality of data characterizing the building stock. A comparison of our results with those obtained by a typological model would also be relevant.

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