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Real-time energy efficiency analysis of buildings using ir imaging and computer vision

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Abstract. Reducing consumption of energy and emissions of greenhouse gas emissions is a critical worldwide problem, with the buildings' sector accounting for up to 44% of fossil fuel consumption. Residential buildings, in particular, have great technical potential for energy savings. Our study addresses this by creating a model for real-time energy efficiency analysis of building insulation using infrared imagery and computer vision. The model monitors and offers important insights of energy transfer by continually evaluating a building's thermal envelope. Additionally, an experimental stand comprising of a miniature model house made from different materials and insulation types, an IR camera and a Raspberry Pi were considered. It will provide data for an AI based model, which employs a robust and already proven architecture, YOLOv8 namely, used to determine the thermal characteristics of the analysed materials and the energy performances respectively.

1 Introduction

A contemporary global issue is the attempt to reduce energy consumption and greenhouse gases emissions, which are mostly caused by industrial, transportation, and buildings sectors. The construction industry accounts for about forty percent of all energy related consumption and emissions of greenhouse gases. Most of these emissions come from residential structures, which have the most potential for energy savings [1]. There is a growing interest in formulating rules governing the operation and efficiency of buildings. Estimating Heat Energy Loss (HEL) is another critical problem in understanding energy efficiency in buildings, where a broad variety of construction components are used for thermal envelopes, thus, determining their properties becomes an important issue [2]. At the European Union level, the main objective of related specific Directives is to create the blueprints required to be met by members to meet the imposed criteria. For example, the Directive 2024/1275/EU governs the energy efficiency of buildings.

The primary goal of this regulation is to improve energy efficiency in buildings across the European Union while taking into consideration members' specific climate conditions, culture, while also considering cost-effectiveness [3]. Furthermore, the European Committee for Standardization (Comité Européen de Normalisation, CEN) releases a series of standardized laws known as European Standards (ENs), which serve to establish the calculating basics and verify numerous aspects and methods. Each EU country establishes its own national legislation in accordance with the Directives and ENs. These national rules later provide a set of numerical values for the energy components to accomplish the Directive's energy efficiency goals.

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The thermal envelope transmittance, buildings geometry and interior temperature are three important design elements that influence envelope energy losses and, as a result, energy consumption due to thermal loads in air-conditioned buildings [3]. Currently, all of the evaluated legislation provides maximum energy consumption restrictions for a whole building, including its amenities. Even if the loss of energy due to the insulation shortcomings can be covered by efficient equipments or renewable energy sources, this strategy is not feasible and proper insulation is preferred.

Recent improvements in technology have provided novel methods for improving building energy efficiency. One strategy is to employ infrared (IR) imaging alongside with computer vision algorithms to analyse energy efficiency in real time. The process provides a fluid and dynamic approach to assessing the thermal performance of buildings by detecting regions of heat loss and possible inefficiencies. In the broad context of buildings, thermography has been employed primarily to analyse features of the building envelope. In such cases, an IR sensor may be utilized to accurately analyse heat dispersion over interior or external closing surfaces, such as roofs and walls [4]. Changes in climatic variables, such as ambient air temperature (AAT) and relative humidity (RH), affect not only the thermal conductivity but also specific heat and density of materials, which has a substantial impact on heat transmission through building envelopes [5].

In this given context this paper proposes the development of a complex AI based model to analyse the thermal insulation of buildings through IR imaging and computer vision.

2 AI Model

Deep learning and computer vision gained increased attention over the years because of the large abundance of data and the increase of computational resources. Recently, enterprises operating within this sector have highly favourable stock market valuation, one example is *Nvidia* (dominant supplier of artificial intelligence hardware and software) which got to hold the title of largest company by market cap in 2024, according to *Yahoo Finance*. The applications of this technology are already a success story in many domains: weather forecasting, stock market prediction and many more. [6]

These advancements in computer vision have enhanced the capabilities of infrared camera by improving image recognition, object detection and thermal pattern analysis. Research has been done in this area, for example, Wang et al. [7] developed "the first deep-learning-based methane detection method (*GasNet*)" a convolutional neural network designed to mitigate the shortcomings of the inability of IR camera to give feedback of leaks, without human intervention. The ability of machines to detect objects in images is valuable for the process of insulation audit because it can enhance the information extracted from the visual and IR cameras with precise recognition of the elements that compose the facade of the buildings.

Multiple techniques were employed for this task by researchers, one of them being an ANN approach by Baumann et al. [8] to detect windows, balcony etc.; a 3D reconstruction of the building helped to increase the accuracy of the detection. In the process of selecting the right architecture for our project we made the following considerations: the model needs to be small because the computation will be done on edge device (Raspberry pi). The model needs to be fast with low computational resources requirements. To fulfil all these requirements, YOLOv8 was used, and its internal processing architecture is depicted in the figure below.

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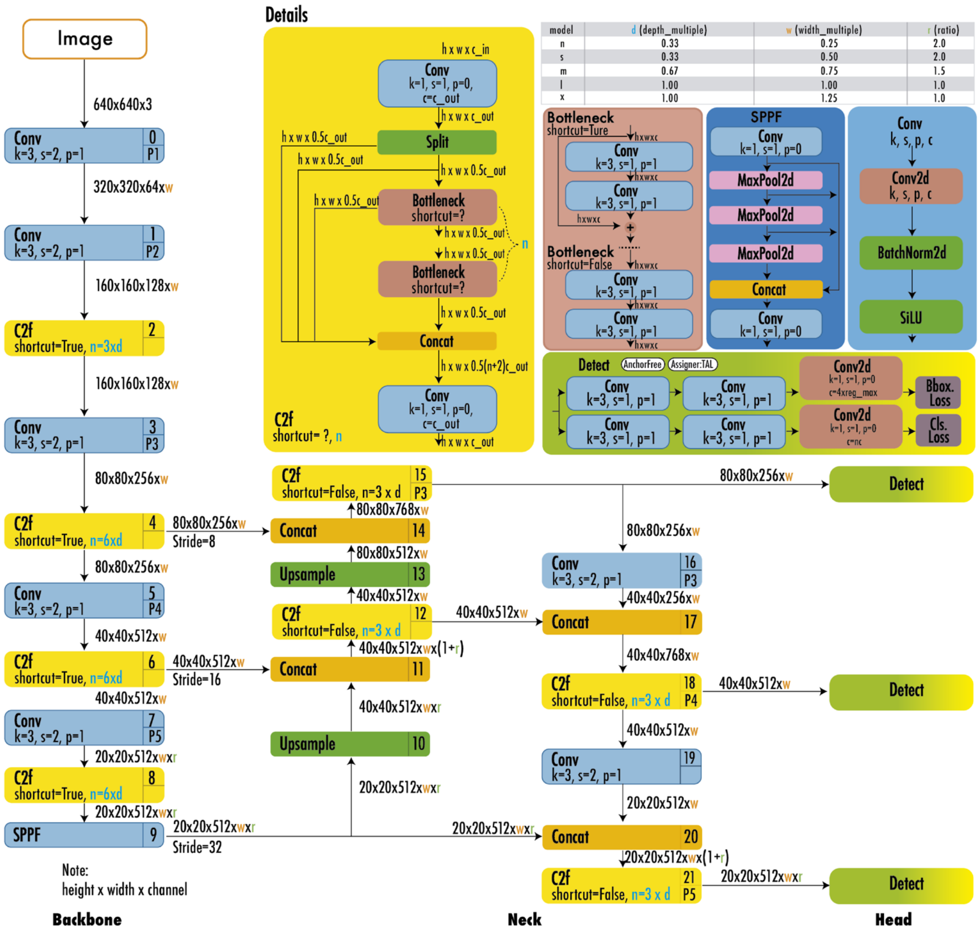

Fig. 1. YOLOv8 Architecture [9]

Ultralytics, the developers of this architecture, provides pre-trained models on large-scale datasets like COCO or ImageNet with various sizes. For the purpose of this application, a medium sized model was used as the starting point, but the deployment to a low resource device will require further engineering and testing. In this first version, the focus was on energy efficiency analysis of windows, but using the same methodology the model can be extended to multiple elements of the house's facade. An open-source dataset windows-detect from *Roboflow*, containing almost 4000 labelled images of windows was used, 80% of images for training and 20% for testing. The initial training to prove the concept was done using a RTX 4050 graphics card for 20 epochs at an image size of 640 achieving an accuracy of around 80% but the test data can be biased, and the real accuracy should be assessed in real house audit scenarios. In a future iteration the number of epochs will be increased to 50 – 100 which is more suitable for this dataset size. The algorithm and the data flow are shown in Figure 2. The process' steps will be explained in detail in the following paragraphs.

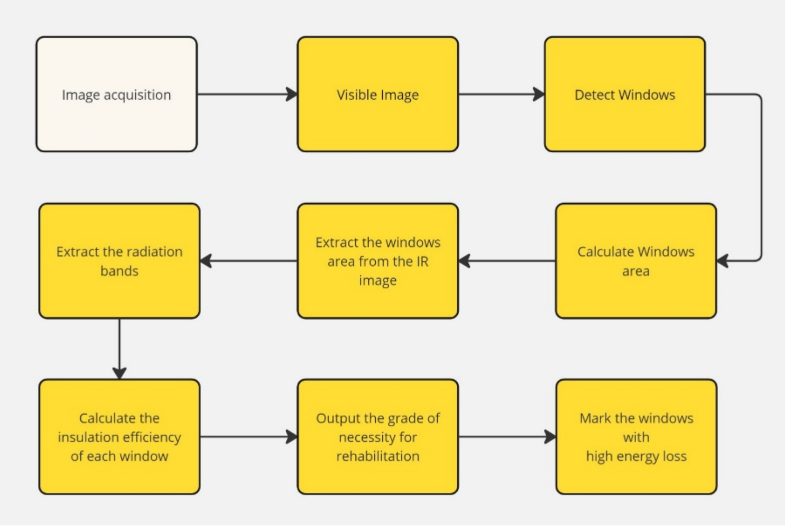

Fig. 2. AI based model's data flow diagram

Image acquisition is provided by a dual-spectrum camera (also known as fusion cameras). These devices are necessary to gather image from both spectrum: light spectrum (visible) and IR radiation. Also, an important factor in the calculation of radiation for each detection is to have images taken from the same spot/angle. In terms of hardware, another device that will enhance further the process is a lidar system, which will determine the distance between the camera and the building, providing the ability to compute the areas of detected elements. The lidar system's integration is subject to further research and will be included in the future iterations of this complex AI application.

Using this model, the next step is to detect the windows from the visible image of the camera. In absence of datasets with both IR and Light spectrum window images, we will leverage the availability of datasets that provide windows in the visible images. In future iterations, as we gather more data from the camera, we can train neural networks with feature fusion from both spectrums to enhance the detection process.

Fig. 3 Windows detection (image retrieved from https://www.thermascan.co.uk/)

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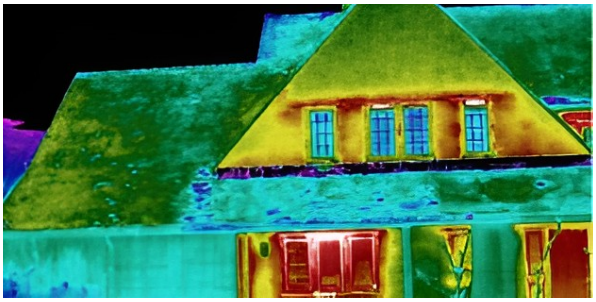

Fig. 4. IR image (image retrieved from https://www.thermascan.co.uk/)

The results of the detection are the coordinates used in the image above to draw the red bounding boxes. With these coordinates, we can calculate the total area of windows in terms of pixels regions that will be further extracted from the IR image (matrix). For illustrative purposes a merged image of all the windows regions is shown in the figure below.

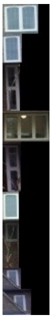

Fig 5. Merged image of windows detection

We take the first window as an example of how the algorithm handles the extraction of IR regions from the IR image. The algorithm computes the regions for all the windows and group them accordingly.

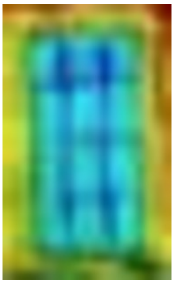

Fig. 6. IR image of the first window detection

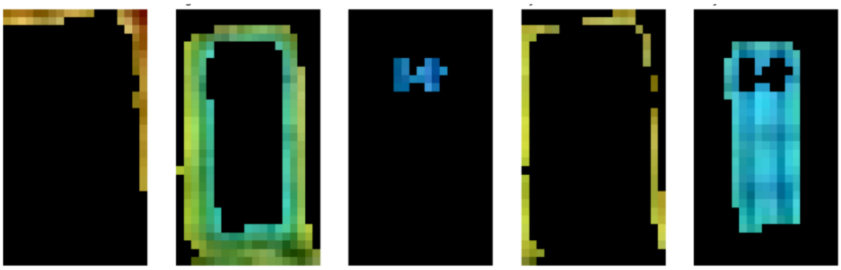

Fig. 7. Illustrative example of temperature gradient extraction

The colour scheme of the thermal camera is used to represent temperatures that correlate to the infrared radiation being emitted as the Stefan-Boltzmann law states:

$$M = \varepsilon M^{\circ} = \varepsilon \sigma T^4 \left[\frac{W}{m^2}\right] \tag{1}$$

where M is the radiant emittance, M° is the radiant emittance of an ideal black body, σ is Stefan–Boltzmann constant, ε is emissivity of the matter doing the emitting and T is temperature.

The image extraction is necessary to determine spots of interest with high radiant emittance, which are important to consider in the decision of possible refurbishment of the elements of the house facade. With these results, we can score the overall efficiency as a weighted sum of each type of temperature interval or by using certain thresholds.

$$S = \sum\nolimits^{n}_{i=1}(W_i \times I_i) \tag{2}$$

where I_i is the temperature interval percentage in the image and W_i is the weight assigned to each interval (for example the red colour interval would have a high weight because of particular interest to fix regions with high energy loss). However, these weights should be adjusted using real world scenarios.

With this scoring mechanism, elements that pass a certain threshold for colours that represent high infrared radiation being emitted are marked. The figure bellow depicts windows that have more than 40% red colour which would be marked as a major rehabilitation class.

Fig. 8. Window Detection that could require rehabilitation

3 Applying the model on a future application

The objective of this proposed stand is to evaluate and conduct building material and insulation properties analysis, also providing data for the AI based model. For this purpose, a model house will be built from various materials, visible and hidden insulation which will be monitored by a custom acquisition system comprised of an IR Camera that will send constant data to a Raspberry Pi which hosts the AI model to make inferences about the thermal properties of the elements that comprise the building, and then show them on a display for the users to observe. Multiple thermocouples will be spread around the model house to gather additional information. Furthermore, an automatic system will be used to close and open the heating and cooling system. The figure below encompasses the components presented above.

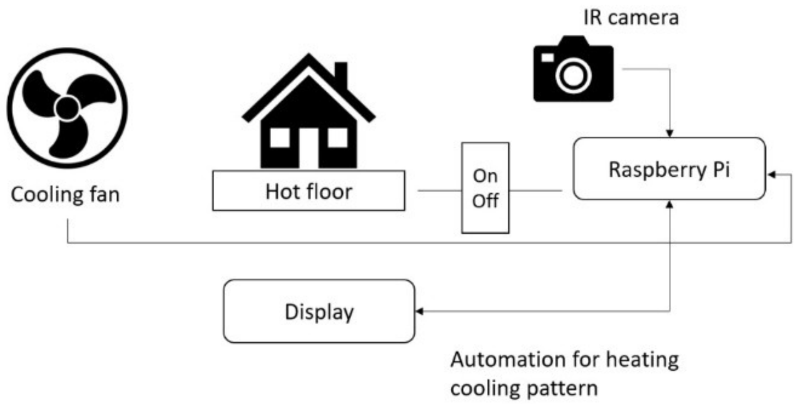

Fig. 9. System diagram

The application flow is simple, a cycle of heat and cooling is started, during this the IR camera sends a constant video feed of both visible and IR data. This data is fed into the AI model and the detection is interpreted by algorithms that were explained in detail in the AI model section of this paper. The display constantly shows the results of the model and various temperatures extracted by the thermocouples. The cooling fan can be powered on from the display.

Fig. 10. An example of a model house window detection (Model House - Barbaras Mouldings)

4 Conclusions and future work

To summarize, employing artificial intelligence applications to analyse construction materials and insulating qualities provides an effective tool. User of the stand may examine how various materials and insulation work in real time by creating a model home and monitoring it with an IR camera linked to a Raspberry Pi. The Raspberry Pi's AI model evaluates thermal qualities and presents the findings, providing users with a clear, hands-on explanation of how insulation works.

Moreover, there is an increasing need for applications that provide real-time energy efficiency assessments of building insulation. These modern instruments can continually evaluate a building's thermal performance, detect locations where insulation is inadequate, and recommend modifications. By delivering precise and timely data, such applications may greatly improve energy efficiency, resulting in considerable cost savings and a smaller environmental imprint. Furthermore, stakeholders and governmental institution could use this model to conduct analyses and develop strategies to increase the district energy efficiency. The application Google Street View gives users the ability to explore streets in a virtual environment, to achieve this Google has a car fleet that drive around cities equipped with cameras that record in 360 degrees [10]. During this process images of facades of buildings are also recorded. If the camera capability is extended to capture IR, automatic thermal analysis can be done on the images captured by the cars that are scanning the city. However, this approach poses limitations, for example: trees that cover parts of facades, car or human activities. Nevertheless, this will provide valuable insights that can be leveraged to implement cost efficient solutions.

As for future work, the model would be extended to detect multiple elements of the facade, increase accuracy of detection and leverage the collected data from the stand and residential buildings to create better datasets of visible and IR images.

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References

1. B. Rodríguez-Soria, J. Domínguez-Hernández, J. M. Pérez-Bella, and J. J. Del Coz-Díaz, “Review of international regulations governing the thermal insulation requirements of residential buildings and the harmonization of envelope energy loss,” Renewable & Sustainable Energy Reviews, vol. 34, pp. 78–90, Jun. 2014, doi: 10.1016/j.rser.2014.03.009.
2. C. Giraldo-Soto, A. Erkoreka, L. Mora, I. Uriarte, and L. Del Portillo, “Monitoring System Analysis for Evaluating a Building’s Envelope Energy Performance through Estimation of Its Heat Loss Coefficient,” Sensors, vol. 18, no. 7, p. 2360, Jul. 2018, doi: 10.3390/s18072360.
3. European Commission. Directive 2024/1275/EU of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings. Official Journal, Document 32024L1275, 24/4/2024. Strasbourg; 2024
4. J. Ortiz-Sanz, M. Gil-Docampo, M. Arza-García, and I. Cañas-Guerrero, “IR Thermography from UAVs to Monitor Thermal Anomalies in the Envelopes of Traditional Wine Cellars: Field Test,” Remote Sensing, vol. 11, no. 12, p. 1424, Jun. 2019, doi: 10.3390/rs11121424.
5. J. J. M. Campos, D. A. García, F. R. Delgado, and D. M. García, “Threshold values for energy loss in building façades using infrared thermography,” in Springer eBooks, 2017, pp. 427–437. doi: 10.1007/978-3-319-51442-0_35.

6. T. Diwan, G. Anirudh, and J. V. Tembhurne, “Object detection using YOLO: challenges, architectural successors, datasets and applications,” Multimedia Tools and Applications, vol. 82, pp. 9243–9275, Aug. 2022, doi: 10.1007/s11042-022-13644-y
7. J. Wang et al., “Machine vision for natural gas methane emissions detection using an infrared camera,” Applied Energy, vol. 257, p. 113998, Jan. 2020, doi: 10.1016/j.apenergy.2019.113998
8. R. Baumann, Jan-Friso Evers-Senne, and M. Strand, “Classification of 3D structures based on an object detection for facade elements in multiple views during the reconstruction process,” May 2019, doi: 10.1109/icphys.2019.8780181
9. J. Terven, D.-M. Córdova-Esparza, and J.-A. Romero-González, “A Comprehensive Review of YOLO Architectures in Computer Vision: From YOLOv1 to YOLOv8 and YOLO-NAS,” Machine Learning and Knowledge Extraction, vol. 5, no. 4, pp. 1680–1716, Dec. 2023, doi: 10.3390/make5040083
10. D. Anguelov et al., "Google Street View: Capturing the World at Street Level," in Computer, vol. 43, no. 6, pp. 32-38, June 2010, doi: 10.1109/MC.2010.170.