Abstract

To meet the European targets of carbon neutrality and reduced environmental impact from buildings, improving energy efficiency, lowering CO_2 emissions, and increasing energy demand flexibility are essential. Adaptive Façade Systems (AFS), through their ability to dynamically respond to transient boundary conditions, can enhance both energy performance and indoor environmental quality (IEQ). Their operation simultaneously affects multiple comfort domains, and their impact is highly dependent on the adopted control strategies and on occupant interaction. It is therefore crucial to design their control effectively by adopting an occupant-centric perspective, comprehensively assessing their multi-domain impact and understanding occupant-technology interactions. However, state of the art reveals several gaps: primarily the absence of simulation tools capable of fully assessing the multi-domain impact of AFS and of occupant-centric controls strategies, plus a lack of experimental facilities and procedures to evaluate AFS performance under real-life conditions, involving occupant in daily tasks to avoid physical and psychological bias. Living Labs emerged recently as a promising arena for testing technologies in this conditions: however there are no standardized methodologies for testing AFS in Living Labs. In this context, this PHD work aims to contribute in filling the gaps by developing methodologies for assessing multi-domain AFS performance and informing occupant-centric control strategies both in simulation and real-life environments with occupants, and to investigate the effectiveness of a Living Lab approach in testing AFS.

To do so, firstly, a simulation-based methodology is developed to evaluate the impact of AFS on occupant comfort and energy performance. A co-simulation workflow integrating EnergyPlus, Radiance, and Python enables the analysis of thermal, visual, and air quality performance under different control strategies. The workflow is applied to a case study involving an openable double-glazing unit with an in-cavity blind in an office in Rome. Results show that optimal occupant-centric control strategies can reduce energy use by up to 38% for ventilation and 8% for shading, while influencing comfort conditions across all domains by 1–10% and improving IAQ by up to 65%.

Secondly, the digital and physical monitoring infrastructure requirements for implementing AFS Living Lab research are defined, and a flexible, modular, and non-intrusive data acquisition (DAQ) infrastructure is developed and deployed at PoliTO Living Lab. It integrates accurate and low-cost IEQ measurements with a digital platform capable of data storage, visualization, data post-processing and actuator control. The influence of sensor accuracy and model-based compensation (e.g., for estimating direct occupants solar exposure) on comfort KPIs is analysed, demonstrating that DAQ characteristics significantly affect calculated comfort levels, component operation, and, potentially, energy outcomes.

Lastly, the Living Lab approach is used to investigate AFS and occupant interaction in real-world settings. A longitudinal study with 73 participants is conducted across multiple seasons, involving the objective and subjective assessment of thermal, visual, and air quality comfort. A rule-based control strategy is applied to the AFS, and correlations between measured performance and occupant feedback are examined. The findings highlight the value of the Living Lab framework for understanding AFS acceptability, preference, and interaction under naturalistic conditions.

In conclusion, the proposed multi-domain framework— including occupant-centric simulation, monitoring infrastructure, and occupant integration in Living Lab experimentation—demonstrates the importance of adopting an occupant-centric perspective in AFS design and control. Moreover, it contributes to lay the foundation for the development of standardized procedures for AFS testing in Living Lab environments.