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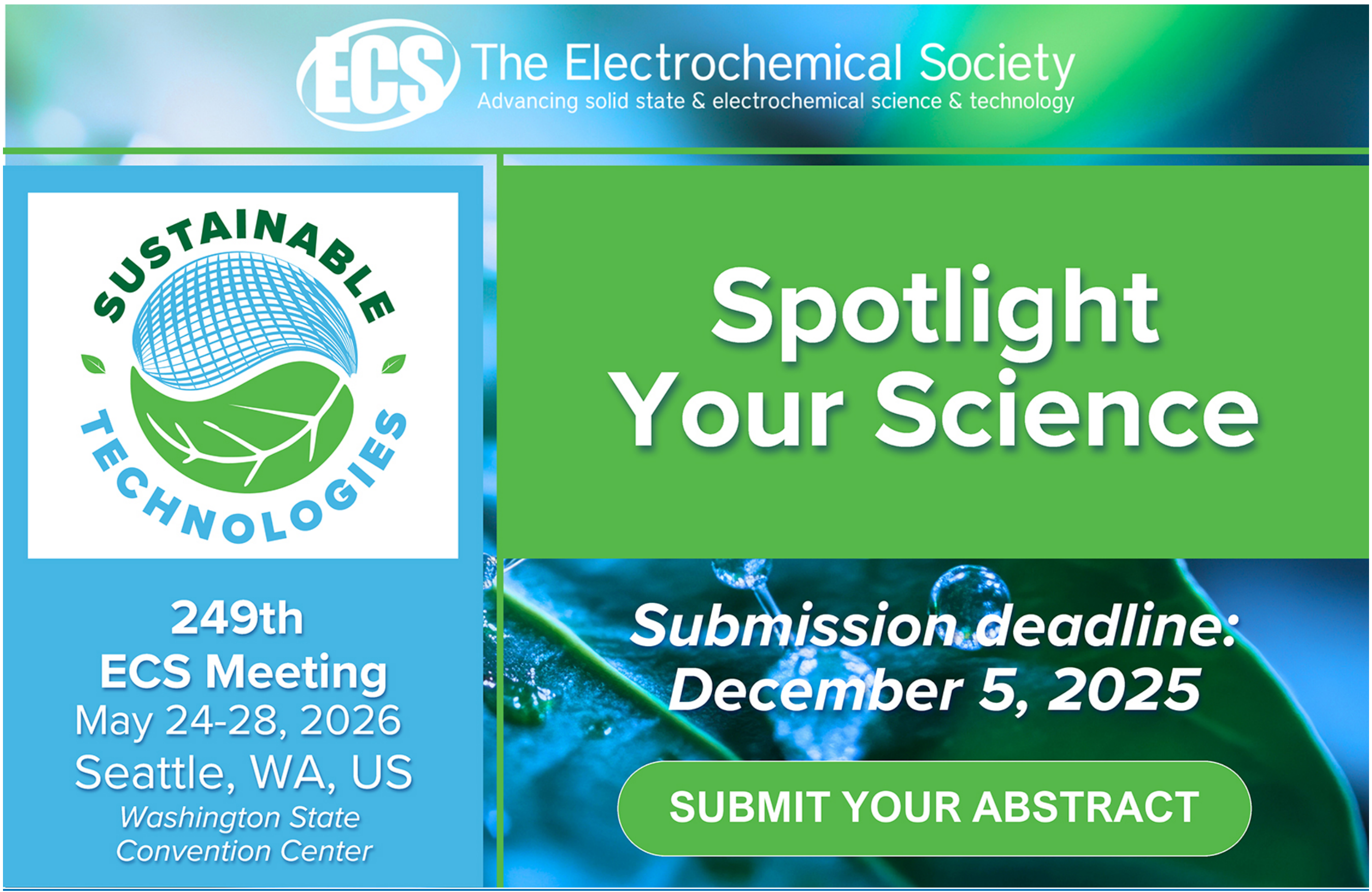

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# Free-running control logic via a 24-hour forecasting platform: self-actuation testing in a Turin demo building

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**Abstract**. This study investigates a new approach to optimise the integration of bioclimatic natural cooling solutions in smart free-running buildings to exploit the untapped potential of climate and weather conditions, assuring indoor thermal comfort without the need for an active mechanism. This work introduces a methodological pipeline based on white-box dynamic energy models, allowing for the prediction, optimisation, and suggestion of hourly schedules for shading and ventilation to users (or automatic control systems), with the aim of maximising the adaptive thermal comfort behaviour of a building through the prevention, mitigation, and dissipation of heat gain. The developed platform was initially tested in a demo low-tech case in Turin, Italy, involving user self-actuation of shading and ventilation mechanisms. The initial results confirm the module's reliability in enhancing comfort, although limitations were observed in terms of user adherence to the suggested self-actuation scheme. White-box model-based digital twins can be used to optimise free-running building conditions. However, direct integration within building management systems may be preferable, thus avoiding the need for additional user involvement.

## 1. Introduction and background

Bioclimatic smart building management methods support the potential of free-running buildings, leveraging untapped meteorological factors to reduce energy needs via passive and natural means. Unlike other green building solutions, bioclimatic solutions aim to correlate building technologies and behaviours with the local climate (during building design) and weather conditions (for building operational management), potentially leading to end-user adaptations, the support of free-running solutions, and minimising the activation of mechanical systems while ensuring that comfort requirements are met [1,2]. This study focuses on the summer season, helping to optimise the local passive cooling potential using intelligent control logic. Passive cooling is typically achieved based on three main techniques: heat gain prevention, heat gain mitigation, and heat gain dissipation [3]. Nevertheless, controlling passive systems is essential to align their activation with favourable conditions, thus avoiding overheating or overcooling and maximising the exploitation of natural energy (when available); such means of control must take not only seasonal logic into consideration, but also hourly or sub-hourly patterns based on building dynamics and 24-hour (or longer) cycles [4]. Operational control logic generally refers to threshold control approaches that take advantage of instantaneous indoor and outdoor conditions but do not consider their transitional effects over time, including those induced via thermal mass activation [5,6,7]. Therefore, new solutions are needed, especially those supporting hybrid control measures. Relevant solutions include forecasting the dynamic effect of the natural heat sink dissipation potential within a building, which aligns with the maximisation of free-cooling solutions (e.g., night-time cooling) for thermal mass activation over a 24-hour period [8].

### *1.1. Objectives and topics*

This study introduces an innovative approach based on a newly developed building dynamic simulation platform—the Python Realtime Energy DYnamics and Climate Evaluation (PREDYCE) [9]—with the aim of optimising building thermal management over a future 24-hour interval using the following methods: i. movable shading systems to prevent heat gains; ii. ventilative cooling systems to dissipate excessive heat in each thermal zone; and iii. thermal mass activation to mitigate heat gains, forecasting the effects of the first two methods at a daily interval. This new approach is based on the definition of a 24-hour forecasting module (24-hf) that can be integrated with building management systems. The module is developed to enhance indoor thermal comfort in buildings by integrating weather forecasts with digital-twin building simulations via EnergyPlus. This new tool is integrated with the PREDYCE platform, which can automatically couple building energy simulations with measured data to support the computation of personalised key performance indicators. The 24-hf module suggests optimised shading and ventilation schedules to improve comfort via passive means while reducing energy consumption. The system supports different control approaches via a newly developed middleware, including automated actuators for building management systems (BMSs) and/or manual user guidance through a Telegram bot for self-actuation (as demonstrated in the case presented in this study) that requires a low level of intelligence.

This study is focused on describing the methodological pipeline. Preliminary testing results in a multi-apartment residential demo building in Turin, Italy, are reported, supporting the self-actuation scenario via Telegram bot suggestions. The module uses locally installed cloud-monitoring solutions to measure indoor environmental conditions at the room level and provides weather data. Data from a commercial weather forecasting facility are also adopted as input to the PREDYCE simulations.

## 2. The Proposed Methodology

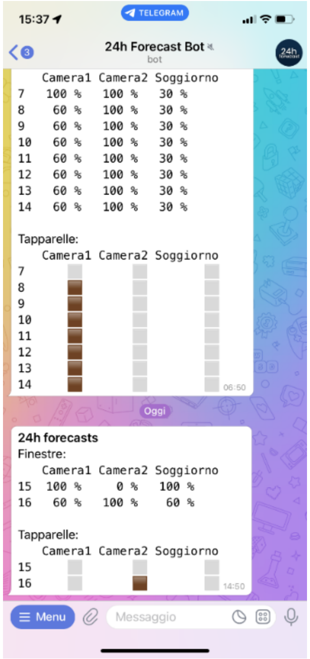
This section details the 24-hf methodology (§2.1) and introduces the sample demo integration (§2.2).

### *2.1. The 24-h forecasting methodological pipeline*

The proposed 24-hf pipeline is based on a 5-step process, starting with the selection of a specific building-validated EnergyPlus model, integrating measured conditions from historical data, and finally communicating the optimised schedules to actuators or end-users.

*2.1.1. First step—Model preparation.* A preliminary procedure is required to adapt the general 24-hf code to a specific demo case. Firstly, it is necessary to develop an EnergyPlus model of the building (in IDF file format), including the thermal zones to be optimised; then to validate this model via measured data, considering free-running behaviours and hourly intervals. For this purpose, the ASHRAE model validation guidelines [10] are adopted, supporting hourly validations. Secondly, the IDF is adapted, enabling the simulation platform to force the internally measured temperature of each room, thus aligning the digital twin with reality until forecasting over the next 24 hrs is performed. To achieve this, the following steps are performed: i. Indoor cloud-monitored data are downloaded from the project middleware (FusiX platform [11]) via a Python script and saved as a CSV file; then ii. another script, part of the 24hf PREDYCE module, modifies the IDF by setting the HVAC setpoints to temperatures and humidity equal to the monitored data provided in the obtained CSV file. As such, the initial errors are minimised. Finally, before simulating the future period, the IDF is switched to free-running behaviour and the HVAC facilities are deactivated. The simulation weather file (EPW file format) is automatically produced via PREDYCE by combining measured data from the cloud-connected weather station with weather prediction data for the next 24 hours obtained from the Meteoblue Weather API+ service [12].

*2.1.2. Second step—Control strategy variations.* After establishing the forecasting starting point, the 24-hf module defines all the potential variation strategies, computing a set of combinations of the different shading and ventilation control conditions available. Firstly, the independent control points and logic are determined. In particular, the number of shading systems that can be moved independently is multiplied by their potential control domains (e.g., ON/OFF), while the number of available independent ventilative cooling solutions (e.g., adaptable windows or inlet vents that can be controlled independently; these are set with certain ranges, e.g., {0,30,100%}) is multiplied by their control domains. Then, the whole list of strategies is combined into a matrix. Each specific scenario may have different forms of ventilation, shading control logic, and ranges that can be applied independently to all windows or various groupings of which. For this reason, before running the 24-hf module via PREDYCE, the code is initially adapted to the specific building, supporting subsequent automatic IDF variations.



```
   Camera1 Camera2 Soggiorno
7   100 %   100 %   30 %
8    60 %   100 %   30 %
9    60 %   100 %   30 %
10   60 %   100 %   30 %
11   60 %   100 %   30 %
12   60 %   100 %   30 %
13   60 %   100 %   30 %
14   60 %   100 %   30 %
```

Tapparelle:

```
   Camera1 Camera2 Soggiorno
7     □       □        □
8     ■       □        □
9     ■       □        □
10    ■       □        □
11    ■       □        □
12    ■       □        □
13    ■       □        □
14    ■       □        □
```

**24h forecasts**

Finestre:

```
   Camera1 Camera2 Soggiorno
15  100 %     0 %   100 %
16   60 %   100 %    60 %
```

Tapparelle:

```
   Camera1 Camera2 Soggiorno
15    □       □        □
16    □       ■        □
```

**Figure 1.** Sample screenshot of the Turin Telegram bot. *Camera* means room, *Soggiorno* Living room, *Finestra* window, and *Tapparelle* shading.

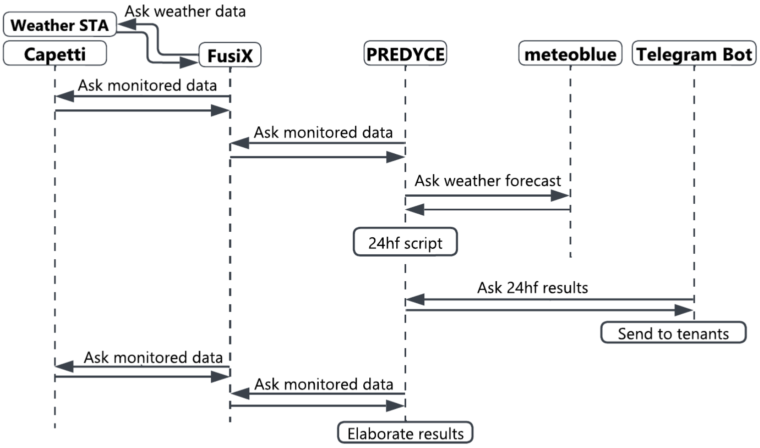


**Figure 2.** The 24-hf module workflow for the Turin demo case. Once the actuation mode is set to a specific scenario, the workflow will automatically repeat each day. Nevertheless, in the considered scenario, tenants can manually control the actuation based on provided suggestions.

*2.1.3. Third step—Control schedules.* After defining the matrix comprising all control combinations, a set of schedules to control shading, window opening, and mechanical ventilation flow actuators is automatically produced via PREDYCE, generating a pool of alternatives to modify the original IDF. These alternative schedules are organised to progressively support the module in simulating the next 24 hours, dividing this period into a series of homogeneous steps. Each step comprises a variable set of consecutive hours in which a single combination of controls—one per technical element—is selected and applied. This set is one hour for BMS or aggregated hours for the self-actuation mode, as the suggestions can be expected to change during periods in which users are at home and able to provide manual actuation commands (e.g., passing only one command for the whole time they are asleep and not one per hour). After defining these homogeneous periods, the 24-hf automatically generates a pool of alternative IDFs and selects the best configuration for each step by progressively simulating the whole pool of alternative IDFs for all steps. In the evaluated simulation period for each run, the impact of each defined strategy in a specific step on the entire daily forecasting period is assessed. When the batch of simulations is completed, the strategy yielding the best results for the analysed step is selected and embedded into the model for the specific step and, thus, the associated period of time. The next step involves updating the IDF and repeating the process until the end of the given day is reached. To progressively select the best strategy, different scoring parameters are considered: the forecasted thermal comfort conditions, the potential impact of daylight, solutions with less shading among options with the same comfort results, a reduction in fan energy needs, selecting solutions with less ventilation with the same level of comfort, and potential customised logic (e.g., fixing shading at night in line with user preferences).

*2.1.4. Fourth step—Output definition.* After identifying the best control schedule for each of the homogeneous time steps, the 24-hf module produces a daily output for each building. The output consists of a CSV file stored in the PREDYCE simulation server facility. This file is automatically converted into JSON format to be shared with the project middleware (FusiX platform) via REST in a fully automated workflow.

*2.1.5. Fifth step—Communication logic and actuation modes.* Two different actuation modes are available: i. Automatic connection to a BMS to support smart building actuator controls, and ii. a self-actuation mode, which allows tenants to control the logic of their technical elements (i.e., shading and windows). The entire process is automated via the project middleware for the first mode (or high-tech cases). In contrast, in the latter mode (or low-tech cases), user notifications are communicated via a Telegram bot, which is managed using the PREDYCE server facility (see Figures 1 and 2). The bot receives the outputs and sends several daily notifications to the end-users, combining sets of optimised hourly scheduling conditions. Each building/system has a devoted bot implemented as an individual chatbot, allowing users to subscribe or unsubscribe to the notifications.

### 2.2. *Specific Demo Integration*

The 24-hf module must be customised for each building, in order to align with its local measurement infrastructure, validated building model, weather conditions, and available actuation logic. In this study, the application of the proposed methodology in a demo building in Turin, Italy, without automatic actuators (i.e., a low-tech case) is reported, supporting end-user suggestions considering shading system (on/off) activations and window openings (%) for natural ventilation.

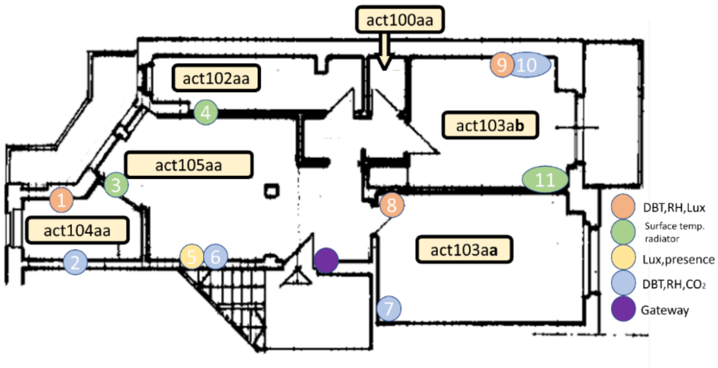


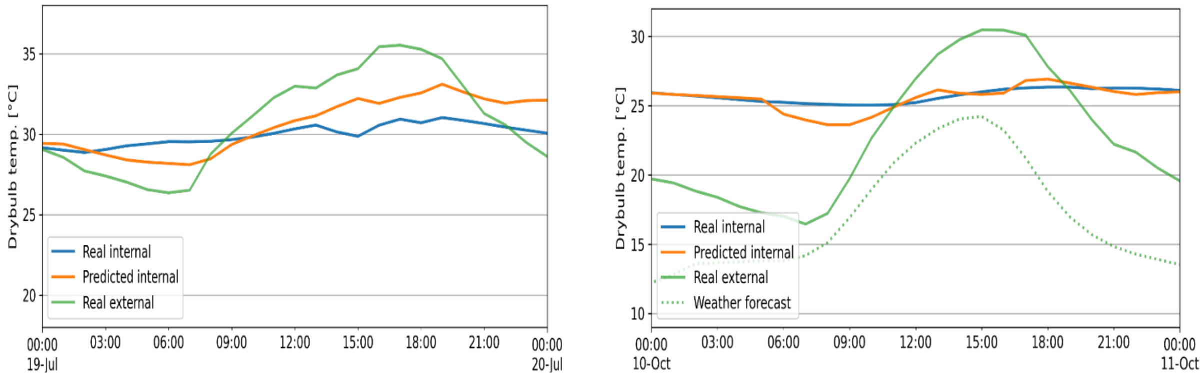
**Figure 3.** The installed sensors in the demo building.

**Figure 4.** The weather station.

The testing scenario is an apartment on the ninth floor of a 10-floor multi-apartment residential building built in the 1960s (Figure 3). This building represents Turin's industrial expansion period, and was initially modelled by adopting envelope conditions aligning with energy certification standards as a reference. The model has been upgraded after performing in situ inspections and measurements, and has been validated over measured data using the PREDYCE calibration module, aligning with the work presented in [9,10,13]. For this study, three rooms were controlled (a living room with kitchenette, double bedroom, and single bedroom), each with an independent window ventilation logic and shading system; see the sample suggestions presented in Figure 1. The control logic developed for this demo case is reported in Figure 2, which depicts the automatic workflow realised through the 24-hf PREDYCE module. The implementation was carried out in collaboration with EMTECH (using FusiX), integrating the building's smart monitoring system with the project middleware and the PREDYCE server. Sensors were based on the Capetti WINECAP$^{TM}$ monitoring system and installed in each room to measure air temperature, humidity, $CO_2$, and pressure levels (Figure 3). A weather station was also installed on a nearby roof, including a Thiess Clima Sensor US and a RAZON+ pyranometer (Figure 4). The homogeneous steps were determined in alignment with the tenants' typical living habits. Similarly, Telegram bot notifications were sent based on the tenants' availability; namely, one notification in the morning before they went to work, one at 7:00 a.m. and one between 8 and 14:00, then every two hours from 2:00 p.m. until late evening (10:00 p.m.), and one notification at night-time (between 22:00 and 6:0 a.m.).

## 3. Results

Different tests were performed in the Turin demo case, including two specific tests for self-actuation performance and two long-term tests to analyse the technical ability of the module to remain automatically active for two consecutive summer and neutral periods. The latter long-term tests demonstrated that the manual 24-hf approach via the Telegram bot continued to work throughout all the months in which testing was carried out. Minor adjustments were made due to a temporary server blackout. In addition to this functionality test, end-user self-actuation testing periods were defined, which were performed on certain days in July and October of 2023, as well as over a week in the neutral season of 2024, identifying the most suitable periods for users' active participation in manually following the notifications. Figure 5 reports the results for two testing days: a summer day and a fall day. On the first day, tenants followed the Telegram bot's suggestions during morning hours, while, in the afternoon, free-running conditions did not allow for comfort due to the extreme outdoor conditions. The Telegram bot was notified of this issue, as the 24-hf conditions surpassed the adaptive thermal comfort upper category II (EN 16798-1 standard), and the tenants turned on a personal air conditioning facility. On the second day, the occupants followed the suggestions for the whole day. In this case, high correlations between the forecasted optimal conditions and the actual conditions measured during the testing day were observed. This result demonstrates the significant ability of the 24-hf module to predict conditions that align with the measured ones when users follow the provided suggestions. Minor variations may be caused by imprecise weather forecasting or user behaviours.



(a) (b)

**Figure 5.** Post-analyses of internal and environmental air temperatures in the Turin demo building for: (a) A summer testing day (after 13.00, the users turned on their personal air-conditioning system); and (b) a fall testing day, during which tenants continuously followed the given notifications. *Predicted* represents the 24-hf results, and *Real* represents the measured data.

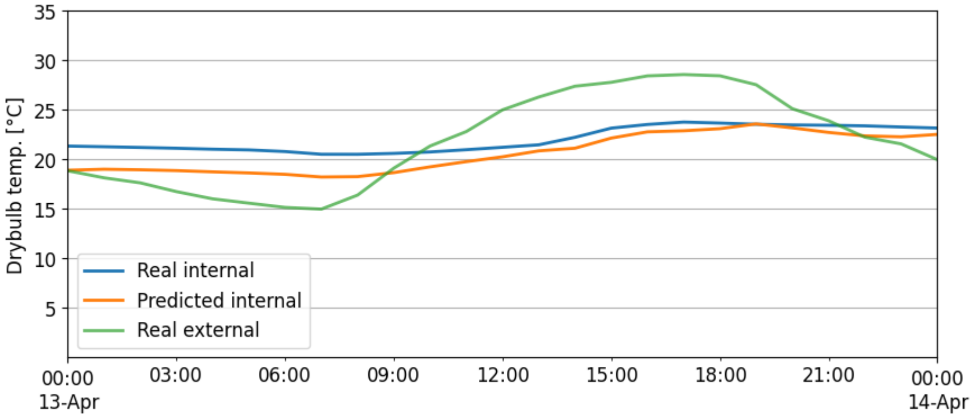


**Figure 6.** Post-analysis results comparing internal vs. external temperatures.

## 4. Discussion and Conclusions

The results obtained in this study are highly encouraging, considering both the technical long-term tests that were used to study the 24-hf module's functionalities and the self-actuation testing results in the demo case. Hence, white-box model simulations may be confidently included in prescient building optimisation loops to valorise the free-running climatic potential of a site. The results of functionality tests that analysed the workflow's technical capacity in a continuously active manner for multi-seasonal periods demonstrated that this approach is feasible. However, ongoing investigations are required to identify any deficiencies and to adapt to variations in the requirements of end-users. Examining the results of the self-actuation tests, the results from days during which users followed the notifications aligned closely with the forecasted optimised conditions. Nevertheless, when using the manual actuation mode, the lack of an automatic method to control movable elements prevented tenants from strictly following the suggestions provided by the scripts, despite the agreement observed on specific testing days. This is mainly due to personal commitments, which may vary from day to day, or the presence of other people in the house who are not willing to follow the provided suggestions. Moreover, as thermal comfort can be subjective and vary from person to person, tenants are expected to close windows or activate shading when they feel uncomfortable due to drafts or sunlight glare, and may overuse mechanical cooling when conditions remain considerably below standard comfort thresholds. Hence, the 24-hf approach, due to the complexity of the overall data flow, is more suitable for buildings with an integrated BMS utilizing actuators than traditional cases in which self-actuation is required, as the results obtained in the latter case may be inconsistent. Alternative approaches to increase end-user participation may be evaluated to address this outstanding issue.

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