再現可能な検証試験を利用したZEHシミュレーション環境の標準化に関する研究

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Toward a Standardized Framework for Developing Zero-Energy House Simulation Environments Using Reproducible Validation Tests

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Abstract– This paper proposes a framework for developing zero-energy house (ZEH) simulation environments. The proposed framework ensures workflow maintenance, reproducibility, and model soundness by performing targeted validation tests. Simulating the energy consumption of a building is a demanding task and requires intricate knowledge about the thermodynamics, the building geometries, and the materials used. The building energy dynamics are nonlinear and influenced by a plethora of stochastic factors, including the ground-temperature and weather fluctuations. In the proposed framework, we simulate the building dynamics with Simulink and EnergyPlus using real climate and ground-temperature datasets. In particular, we first define the building geometries using Sketchup. Next, the wall-, roof-, ground-, and window materials are specified using OpenStudio. For fine-grained tuning, the EPLaunch editor is used to specify the ground-temperature schedules, add insulating materials onto the existing ones, and equip the house with heating, ventilation, and air conditioning (HVAC) systems. For model validation, we make the model interact with Simulink through the MLE+ toolbox, and test it by simulating the building's free response. To assess the ZEH performance improvement, we simulate the building closed-loop dynamics using a PI controller to assess the non-ZEH and ZEH power consumption.

Key Words: Zero-energy house, Simulator development, Modeling and control, Workflow standardization

1 Introduction

In the realm of building HVAC systems, extensive research has been conducted[2, 1, 13, 12, 6, 16], encompassing areas like system modeling[10, 8, 14], control design[9, 7], and real implementation or co-simulation[15, 2, 11]. In the control design, numerous effective control strategies for HVAC systems have been proposed, including proportional-integral-derivative (PID) control [9, 7], model predictive control (MPC), and data-driven control [5, 3] methods. A more comprehensive overview of control applications in HVAC systems can be seen in several survey papers[1, 12, 6, 16].

The building sector accounts for a significant portion of the global energy consumption and greenhouse gas emissions. To alleviate the ongoing global warming, transitioning to sustainable construction practices is indispensable. In this context, the zero-energy house (ZEH), which aims to achieve net-zero energy consumption by producing as much energy as it consumes, provides a possible solution to reducing the environmental impact of the building sector. To attain the status of a ZEH, it is crucial to first lower the energy consumption without compromising daily activities and human comfort.

Achieving this balance is made feasible through advancements in building technologies, the use of innovative building materials, and the implementation of sophisticated control techniques. However, taking full advantage of these techniques demands a robust simulation tool to accurately model and predict the building's thermal performance. Despite the growing interest in ZEHs, there is a lack of standardized simulation environments to facilitate consistent and comparable results across different projects through reproducible tests.

In this work, we aim to bridge this gap by developing an advanced simulation environment for ZEH, utilizing tools like Simulink, EnergyPlus[4], OpenStudio, and the EPLaunch editor. These tools are instrumental in accurately modeling building dynamics, defining geometrical structures, specifying building materials, and conducting thorough simulations for model validation. We will concentrate on co-simulation, particularly through the development of ZEH simulation environments, to perform targeted validation tests that ensure workflow maintenance, reproducibility, and model soundness. By bridging the gap between the theoretical framework and practical implementation, this work also contributes to the field of sustainable building practices. It offers a comprehensive guide for developing robust, maintainable, and reproducible ZEH simulation environments, paving the way for more efficient and environmentally friendly building designs, as well as more advanced

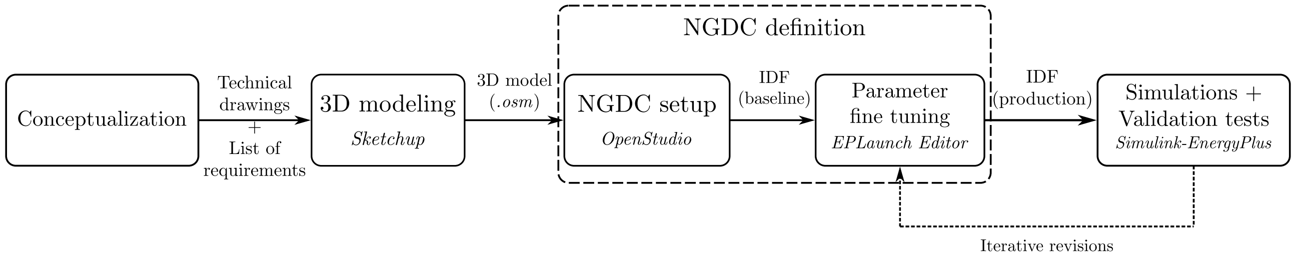


Fig. 1: Proposed workflow to build the ZEH simulation environment. The workflow is composed of abstract blocks, which have well-defined functionalities and entry points. The process begins with the conceptualization phase, which outlines the list of requirements, documents the process, and outputs the technical drawings. Next, based on the drawings, a 3D model is generated. The non-geometrically defined component (NGDC) setup phase follows, which is broken down into a high-level and low-level parameter tuning. Finally, the simulations and validation tests are performed, where the IDF is iteratively revised to achieve the desired outcome.

control strategies.

The rest of this work is organized as follows. In Section 2, we introduce the standardized framework for ZEH simulation environments. In Section 3, a comparative study between the non-ZEH and ZEH power consumption of a single house unit is presented. Finally, the work is concluded in Section 4.

2 Simulation-Environment Development Framework

This section proposes a framework for building ZEH simulation environments. This framework needs to be standardized, maintainable, and have well-defined entry points. To do so, we break down the workflow into five parts:

1. Conceptualization of the simulation environment;
2. 3D building modeling using CAD software;
3. Setup of the materials and other non-geometrically definable components (NGDC);
4. Fine-grained tuning of the simulation parameters;
5. Simulations and validation tests.

Note that this workflow provides the necessary abstraction to methodically and accurately build the simulation environment. Furthermore, note that it helps deconstruct a complex procedure to implement the environment components in a consistent, reproducible, maintainable, and testable way. The proposed workflow is depicted in Fig. 1.

2.1 Conceptualization

In the conceptualization phase, we define the overall objectives and the scope of the simulation environment. For example, in this paper, we set the goal to be a comparative study in the power consumption between the non-ZEH and ZEH responses using real climate data over a year. This will be detailed in the next section.

Next, we define the following elements: (i) the building geometries, (ii) the room names, (iii) the wall, roof, ground, and window materials, (iv) the HVAC systems, and (v) the monthly ground-temperature schedule. This will result in the generation of technical drawings and a list of requirements. Moreover, at this stage, we need to perform precise preliminary calculations, such as the ones to derive the average heat-transfer coefficient ratio to design the insulating materials of the house.

2.2 3D Modeling

In the 3D modeling phase, we use the computer-aided design (CAD) software "Sketchup" to define the geometries of the building. This phase creates a "*.osm*" file, which will be exported to "OpenStudio" for adding NGDCs.

Note that the building model needs not be overcomplicated since only the main geometries must be outlined. This is due to the fact that EnergyPlus does not use finite-element methods; it synthesizes the calculations and iteratively computes the average room temperatures using basic thermodynamic principles.

2.3 NGDC Setup

At this step, we need to generate a baseline "*.idf*" file, which will be run by EnergyPlus. Input-data files (IDFs) are standard text files, which are human readable and structured in a particular format, which allows EnergyPlus to parse, interpret, and run them.

The 3D model derived from the previous step does not account for NGDCs, such as materials, outputs, and so forth. OpenStudio, a free and open-source software, provides a high-level abstraction layer in the form of a GUI to assist the user in encoding the NGDCs by minimizing source-code generation errors.

2.4 Fine-Grained Parameter Tuning

This step is complementary to the previous phase. In fact, since EnergyPlus is continuously maintained, we frequently face versioning issues where new implemented features are unavailable in OpenStudio. Hence, we propose to use a "separation-of-concerns" approach, where we output a baseline IDF in the previous step and fine tune it here.

In particular, we use the official EPLaunch IDF editor, which is a low-level GUI that allows for better control over the parameter tuning. For example, we can add ZEH materials onto the existing ones so that we do not inadvertently modify the pre-existing baseline parameters. As a result, we minimize errors, have better control over the workflow, and ensure maintainability and reproducibility.

Furthermore, note that HVACs are considered as control inputs in Simulink. At present, in OpenStudio, we cannot directly add the HVACs due to a missing feature accounting for sockets and client/server communication between Simulink and EnergyPlus. Therefore, this step is crucial to generate codes that are up to date with the latest EnergyPlus, and avoid incompatibility and deprecation issues.

2.5 Simulations and Validation Tests

The last step is the actual simulation part, which is used to validate the model and perform tests to study the open- and closed-loop dynamics of the building energy consumption. To obtain the desired outcome, this last step is iteratively revised with the "fine-grained parameter tuning" step.

It is worth noting that EnergyPlus is not inherently suited for the integration of control design and synthesis. Consequently, middleware software and interface protocols have been developed to facilitate an interface platform bridging these simulation systems with control-oriented tools like MATLAB[15, 2, 11]. In particular, we adopt the co-simulation tool MLE+ that interconnects EnergyPlus with Simulink, allowing for the implementation of advanced control strategies with real-time input and output. The simulations are thus performed in Simulink, which directly interfaces with the user.

3 Comparative Study Between the Non-ZEH and ZEH Power Consumption of a Single House Unit

This section demonstrates the utility of the workflow proposed in the previous section by applying it to a comparative study between the non-ZEH and ZEH power consumption of a single house unit.

3.1 Conceptualization

Objectives – The main objective of this case study is to assess the performance improvement in the power consumption of a single house using standard materials and ZEH-enhanced materials.

In particular, we analyze the room-temperature evolution of the open- and closed-loop systems using a proportional-integral (PI) control action. The simulations are run over a year using real climate data from Jono, Fukuoka. Moreover, in the simulations, we account for the ground-temperature fluctuations, where the data are provided by JAXA's "Public-health Monitor and Analysis Platform[1]."

Furthermore, note that, as we do not have access to the real measurements of the room temperature over a year, we address the model-accuracy issue by conducting relative comparisons between each case. To further support our discussion, we complement our study with a third case, which does not account for the ground insulating materials; it serves as a middle ground to discuss the performance improvement between non-ZEH and ZEH power consumption. This case will be termed "mid-case" for future reference.

Technical drawings – The house is an actual unit from Jono, and is modeled according to real data. However, note that, due to confidential reasons, we only provide the high-level blueprints of the house in Fig. 2.

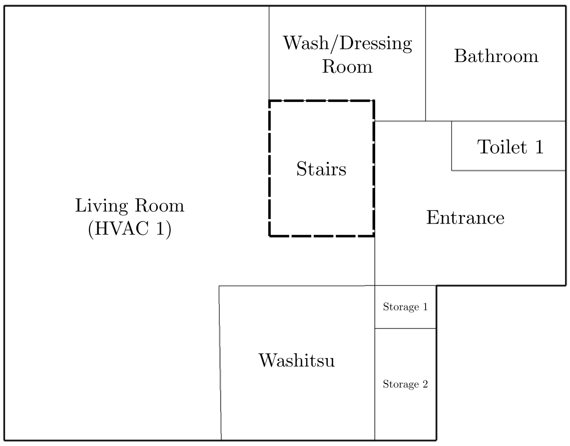
Material Design – The design guideline for the wall, roof, ground, and window insulating materials is based on the HEAT20 ZEH standards[2]. In particular, the average heat-transfer coefficient ratio U_{a} [W/m^{2}K] of the house is computed by

$$U_{\mathrm{a}} = K_{\mathrm{s}}/A_{\mathrm{s}}, \qquad (1)$$

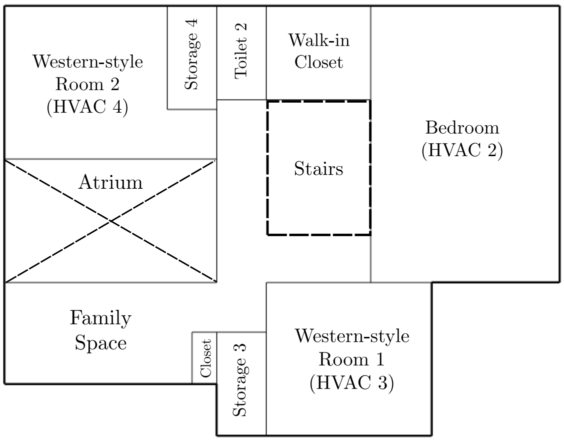
where $A_{\mathrm{s}} \triangleq \sum_{j=1}^{4} S_j$ [m^2] is the total area of the house, which is defined by the summation of each area covered by the walls (S_1), roof (S_2), base-level ground (S_3), and windows (S_4), respectively. $K_{\mathrm{s}} \triangleq \sum_{j=1}^{4} K_j S_j$ [W/K] is the average heat-transfer coefficient, and K_j [W/m^{2}K] is the heat-transfer coefficient ratio of the walls ($j = 1$), roof ($j = 2$), base-level ground ($j = 3$), and windows ($j = 4$), respectively. According to the technical drawings, $S_1 = 176.56$ m^2, $S_2 = 154.72$ m^2, $S_3 = 68.39$ m^2, $S_4 = 31.44$ m^2, and $A_{\mathrm{s}} = 431$ m^2. The objective is to achieve a G2-grade standard for a category-7 district according to the HEAT20 ZEH standards, that is, $U_{\mathrm{a}} \leq 0.46$.

For the computation of K_j, note that all the materials follow a layered structure, which is composed of two parts: the "non-insulating" and the "insulating" part. For $j \in \{1, 2, 3\}$, which corresponds to the walls, roof, and base-level ground, respectively, K_j is

[1]`https://www.jpmap-jaxa.jp/jpmap/en/`
[2]`http://www.heat20.jp/grade/`



(a) First floor (1F).



(b) Second floor (2F).

Fig. 2: High-level technical drawings. The building geometries and the room names are defined. For non-disclosure reasons, the dimensions and original resources are not provided.

computed by

$$K_j = \frac{1}{\alpha_{\mathrm{out}}^{-1} + \sum_{i=1}^{n_{\ell,j}} \ell_{i,j}\lambda_{i,j}^{-1} + \alpha_{\mathrm{in}}^{-1}}, \qquad (2)$$

where α_{in} [W/m^{2}K] and α_{out} [W/m^{2}K] are the interior and exterior total heat-transfer coefficient ratios, respectively, $\ell_{i,j}$ [m] and $\lambda_{i,j}$ [W/mK] are the thickness and the conductivity ratio of the i-th layer pertaining to the j-th house part, respectively, and $n_{\ell,j}$ is the total number of layers of the j-th house part.

Assuming an average windspeed of approximately 3 m/s, $\alpha_{\mathrm{in}} = 9$ W/m^{2}K and $\alpha_{\mathrm{out}} = 23$ W/m^{2}K. For all $j \in \{1, 2, 3\}$, for the conductivity of the non-insulating parts, we use the OpenStudio default values, and for the insulating parts, we use the default values of "AirBlast_txx," which has a conductivity of $\lambda_{i,j} = 0.026$ W/mK. For the thickness of the non-insulating parts, we use the OpenStudio default values, and for the insulating parts, we use $\ell_{i,1} = \ell_{i,3} = 40$ mm for the walls and the base-level ground, and $\ell_{i,2} = 80$ mm for the roof.

Regarding the window compositions ($j = 4$), for the non-ZEH case, we use a single-layered structure, and for the ZEH case, we use a multi-layered structure. In particular, a single-layer window is composed of a single glass of 3 mm, and a multilayer window uses a glass-air-glass structure, where the airgap is 12 mm. To compute K_4, we refer to the public documentation of the heat-transfer coefficient ratios provided by Alumi[3], where $K_4 = 6.51$ W/m^{2}K for the single-layer case, and $K_4 = 2.33$ W/m^{2}K for the multilayer case.

The calculation results are shown in Table ??. Note that, for the ZEH case, since $U_{\mathrm{a}} < 0.46$, we successfully achieved the HEAT20 ZEH G2-level standard using the insulating materials that were suitably designed in this phase.

Parts	non-ZEH	Mid-Case	ZEH
Walls	$K_1 = 0.856$	$K_1 = 0.369$	$K_1 = 0.369$
Roofs	$K_2 = 0.273$	$K_2 = 0.148$	$K_2 = 0.148$
Ground	$K_3 = 1.493$	$K_3 = 1.493$	$K_3 = 0.453$
Windows	$K_4 = 6.51$	$K_4 = 2.33$	$K_4 = 2.33$
House	$U_{\mathrm{a}} = 1.160$	$U_{\mathrm{a}} = 0.611$	$U_{\mathrm{a}} = 0.446$

HVAC – On the first floor, we install an HVAC unit in the living room and, on the second floor, one in the bedroom and one in each western-style room (see Fig. 2). As a result, we have four HVACs in total, where the control input of each HVAC is the power in watts.

Ground-temperature schedule – The monthly ground-temperature (GT) schedule is given in Table 1. The GT measurements have been acquired in 2021 above Kitakyushu using NASA satellites, and are reported by the JAXA's "Public-health Monitor and Analysis Platform."

3.2 3D modeling

After having laid down the general guidelines of the project, we can now start to model the house based on the technical drawings generated by the conceptualization phase. Fig. 3 shows the completed 3D model of the house using Sketchup from the blueprints provided in Fig. 2.

Although this model is highly detailed, EnergyPlus cannot interpret it. Thus, we must convert the 3D model into a simplified one using the OpenStudio plugin to outline the general geometries. This step is illustrated in Fig. 4. Note that the balcony and the doors are objects that are not recognizable by OpenStudio and must be deleted in the simplified version.

[3] `http://alumi.st-grp.co.jp/sumai/shouene/pdf/mokuzo.pdf`

Month	Daytime GT	Nighttime GT	Avg GT
Jan	9.67	-0.01	4.83
Feb	12.45	4.90	8.675
Mar	16.81	5.81	11.31
Apr	20.04	8.81	14.425
May	25.13	12.63	18.88
Jun	29.66	18.95	24.305
Jul	29.40	22.05	25.725
Aug	29.07	22.98	26.025
Sep	27.23	17.60	22.415
Oct	24.81	15.68	20.245
Nov	16.97	7.17	12.07
Dec	10.56	3.13	6.845

Table 1: Monthly GT schedule in Celsius degrees. "Avg GT" is the daytime/nighttime average ground temperature in Celsius degrees.

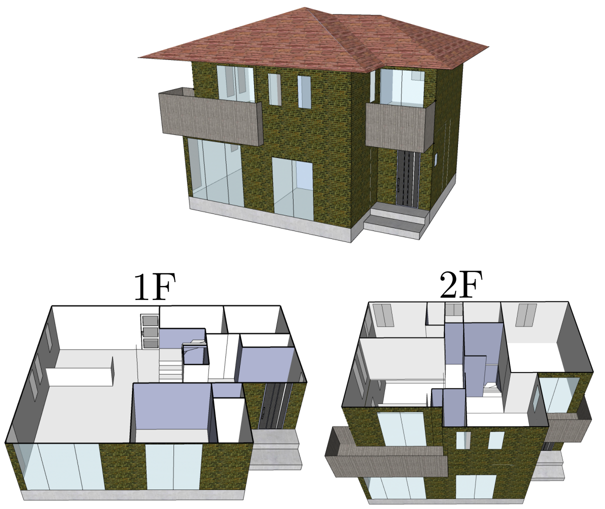


Fig. 3: High-fidelity 3D modeling of the house from the technical drawings of Fig. 2 using Sketchup. The lower left and right figures show the cross section of the first and second floors, respectively.

3.3 NGDC setup

Next, we define the non-geometrically definable components. This step is carried out using Open-

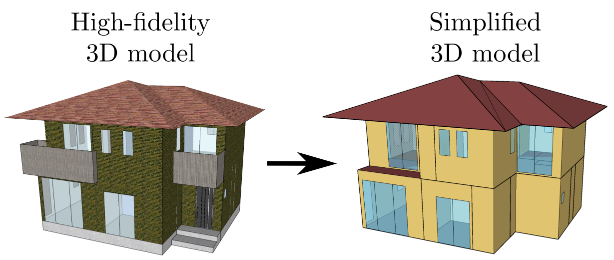


Fig. 4: Conversion from the high-fidelity model (left) to a simplified one (right), which must be eventually recognizable by EnergyPlus. Note that, since the balcony and the doors on the left are not recognized by EnergyPlus, they must be deleted in the simplified version on the right.

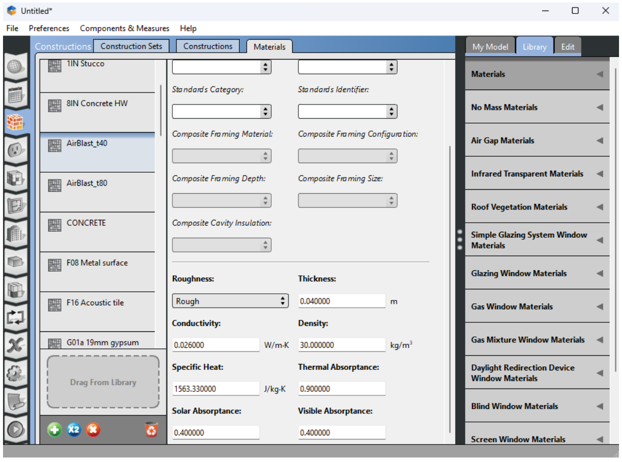


Fig. 5: Openstudio GUI. On the screenshot, we setup the "Airblast_t40" material by modifying the material thickness, conductivity, etc.

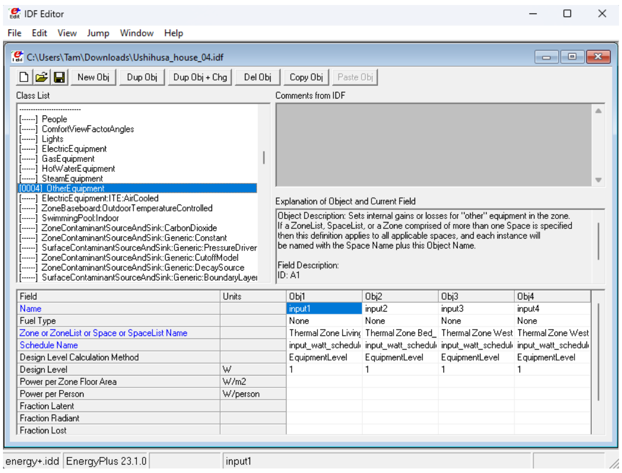


Fig. 6: EPLaunch IDF Editor. On the screenshot, we define and position the four HVACs, which are located in the living room (1F), the bedroom (2F), and the two western-style rooms (2F).

Studio. In particular, we define the materials of each house part, the simulation outputs, and the simulation setup parameters. Fig. 5 illustrates the setup of the insulating material "Airblast_t40."

3.4 Fine-grained tuning

After having generated the baseline IDF, we fine tune it using the EPLaunch IDF Editor. In particular, we define the HVACs, specify the GT monthly schedule, add the insulating materials to generate different cases, and fine tune the simulation parameters (e.g., the timestep), which cannot be modified in OpenStudio. Fig. 6 illustrates how we defined and positioned the four HVACs using EPLaunch IDF Editor.

3.5 EnergyPlus Weather File

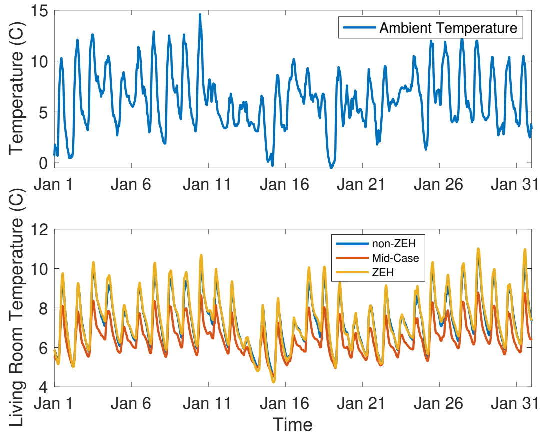
The ".epw" (EnergyPlus Weather) file is a crucial component for EnergyPlus simulations, encapsulating comprehensive hourly weather data. For accurate building energy modeling in EnergyPlus, it is essential to prepare an EPW file that accurately represents the local climatic conditions. We developed an EPW file by adapting the standard Fukuoka weather file, sourced from the EnergyPlus database[4], to incorporate specific weather data from Jono for the year 2022. This customization included key parameters such as dry bulb temperature, relative humidity, and solar radiation, ensuring a more accurate representation of local climatic conditions for our simulations.

3.6 Simulations and validation

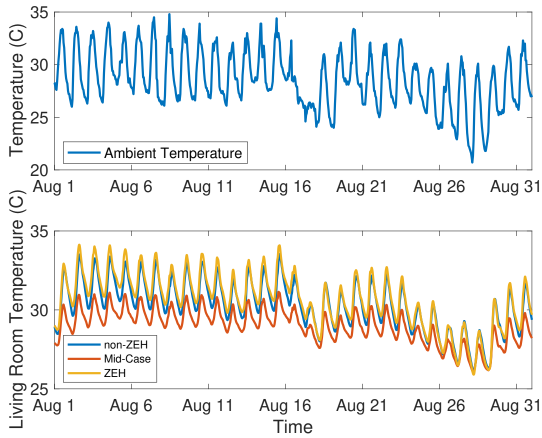
Based on the cases discussed in Section 3.1, we construct three house models employing different building materials. The first one, which is coined "non-ZEH," is constructed in the absence of insulating materials ($U_\mathrm{a} = 1.16$ [W/m^{2}K]). The second one, termed "Mid-Case," is constructed with wall and roof insulating materials and multilayered windows ($U_\mathrm{a} = 0.61$ [W/m^{2}K]). The third one, labeled "ZEH," shares the same setup as the second model but with an additional 40 [mm] insulating material for the base-level ground ($U_\mathrm{a} = 0.45$ [W/m^{2}K]). We run the EnergyPlus simulation on Simulink via the MLE+ co-simulation toolbox[5], enabling real-time control implementation[2)]. We simulate temperature trajectories for an entire year and present data from January and August for illustrative purposes. The temperature simulation for the living room is depicted in Fig. 7. It can be observed that the temperature trajectories of the non-ZEH and ZEH houses show no significant differences, whereas the Mid-Case typically exhibits lower temperatures with less variation.

Next, we employ proportional-integral (PI) control to maintain the temperature at 25 °C across all rooms. The control inputs and the living room temperature for January and August, under three different building material settings, are depicted in Fig. 8. It can be observed from Fig. 8b that the Mid-Case house consumes less energy for heating compared to the non-ZEH house, while the ZEH house shows a significantly lower energy requirement than both the Mid-Case and non-ZEH houses, despite similar uncontrolled temperature profiles in Fig. 7. This difference in energy consumption is less pronounced in August, as illustrated by Fig. 8a. This is due to the ground naturally cooling down the houses, and the insulation in the ZEH house further minimizes heat exchange with the ground. The energy consumption and efficiency under PI control for different reference temperatures across the three building material settings are summarized in Table 2.

Note that, due to the slow thermal dynamics and varying ambient conditions, the room temperature



(a) Ambient temperature and living room temperature in January 2022.



(b) Ambient temperature and living room temperature in August 2022.

Fig. 7: Simulated living room temperature under the three building material settings non-ZEH, Mid-Case, and ZEH, respectively.

fluctuates even under PI control. More advanced control strategies, such as the model predictive control, could be implemented to regulate the room temperature. This study is left for future works.

4 Conclusions

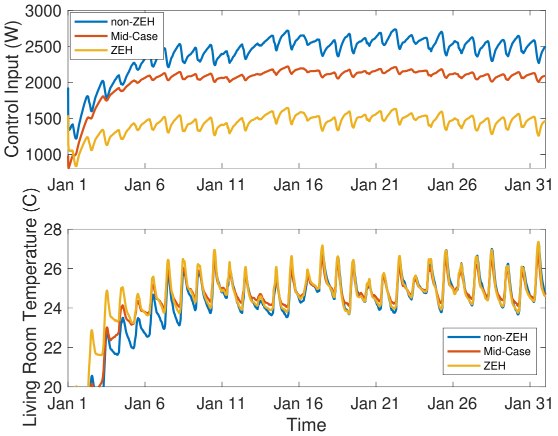
This paper has presented a standardized framework for developing ZEH simulation environments in a modulable, reproducible, maintainable, and testable fashion. In particular, the proposed framework was divided into five parts: (i) the conceptualization, (ii) the 3D modeling, (iii) the setup of NGDC, (iv) the fine-grained tuning of the simulation parameters, and (v) the simulations and validation tests. We demonstrated the effectivess of the framework by applying it to one case study, which was the comparison of the power consumption between a single house unit using non-ZEH materials and ZEH materials.

In particular, we set up the simulation environment by following the procedures of the proposed method-

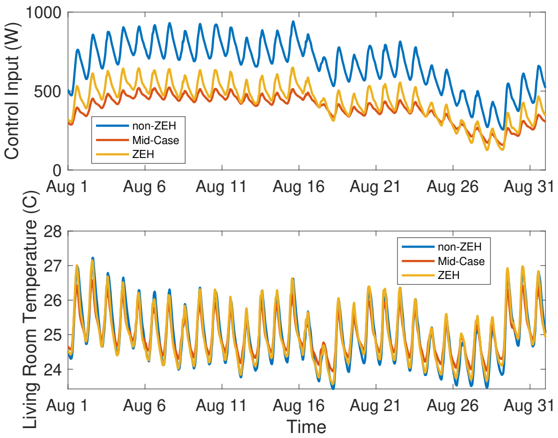
[4] `https://energyplus.net/weather-location/asia_wmo_region_2/JPN/JPN_Shimonoseki.477620_IWEC`
[5] `https://github.com/willybernal/mlep`

Building Materials	non-ZEH	Mid-Case	ZEH
Reference Temperature [°C]	Energy [kWh]	Energy [kWh] (Saving)	Energy [kWh] (Saving)
21	15483.9	11798.5 (23.8%)	9164.8 (40.8%)
25	17727.6	14080.0 (20.6%)	10487.8 (40.8%)
27	19954.9	16087.9 (19.4%)	11740.7 (41.2%)

Table 2: Comparison of the energy consumption and efficiency with PI control under different reference temperatures for the three building material settings.



(a) PI control inputs and living room temperature in January 2022.



(b) PI control inputs and living room temperature in August 2022.

Fig. 8: Simulated living room temperature with PI controls under the three building material settings Non-ZEH, Mid-Case, and ZEH. respectively.

ology, and compared the open- and closed-loop dynamics of three cases: the non-ZEH case, the mid-case, and the ZEH case. The mid-case was created to provide a middle ground for discussions between the non-ZEH and ZEH cases. It was shown that, compared to the non-ZEH case, the mid-case had an improvement in power efficiency of 19.4% up to 23.8%, and the ZEH case exhibited a further improvement of 40.8% to 41.2%.

These promising results showed the importance of using insulating materials to reduce the power consumption. However, due to the presence of unpredictable disturbances, it was shown that a PI control was insufficient to maintain the room temperature constant. A solution to this would be to use more advanced control techniques, such as the model predictive control. This study will be the aim of our future works.

5 Acknowledgments

This work is supported by the Japanese Ministry of the Environment. The authors would like to express their gratitude to Prof. Takeshi Hatanaka (Tokyo Institute of Technology) and Prof. Yoshiaki Ushifusa (The University of Kitakyushu) for their invaluable help in providing the necessary resources (technical drawings, software, and other documentation) to build the ZEH simulation environments.

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