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Streamlining Sustainable Design in Japan: Case Study on Developing ZEBIA - a Tailored ZEB Simulation Tool

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Abstract

This paper details the three-year development journey of ZEBIA (Zero Energy Building Integrated Analysis), a tool for Zero Energy Building (ZEB) projects. Developed collaboratively between TAKENAKA Corporation-Japan and LOISOS + UBBELOHDE-USA, ZEBIA streamlines the evaluation of environmental qualities, integrating ZEB targets, user comfort, and design preferences. The paper delves into ZEBIA's wireframes, prototyping, user testing, and a comprehensive road-test. It emphasizes lessons learned and the importance of user-centric tools and systematic guidelines in achieving zero-energy building objectives. The discussion underscores ZEBIA's capacity to empower architects and engineers, support ZEB goals, and facilitate effective collaboration.

Introduction

Challenges of the AEC industry practices in Japan.

In recent years, Japan has set ambitious environmental and societal goals that demand innovative solutions from the Architecture, Engineering, and Construction (AEC) industry. In 2020, the Japanese government declared its commitment to achieving a carbon neutral society by 2050, with a significant milestone of reducing 46% of CO2 emissions set for 2030 (Ministry of the Environment 2022). Buildings, taking Tokyo as example, are currently contributing to over 70% of the city's carbon emissions (Government 2021), are expected to undergo a proportional reduction by 2030 and attain carbon neutrality by 2050.

In parallel, the AEC industry in Japan is adapting to meet new labor laws aimed at addressing work-related stress. These policies outline strict limitations on overtime working hours, with a target of reducing annual overtime to 360 hours by 2024. As a prominent player in the construction sector and one of the Big Five contractors in Japan, TAKENAKA Corporation faces the unique challenge of reconciling these dual goals.

Our Corporation has laid out an ambitious roadmap to align with these objectives. Our goals encompass reducing GHG emissions by 40% compared to the fiscal year 2013 baseline. Furthermore, we have pledged to ensure all our projects are Zero Energy Building (ZEB) Ready (Energy saving of 50% or more) by 2030 and reach carbon neutrality by 2050. This intricate balancing act necessitates a strategic solution that allows for the seamless integration of energy and carbon reduction studies into our project workflow, all while adhering to our longstanding legacy of delivering projects on time, with no cost overruns.

What is ZDG & why ZEBIA was needed.

In response, TAKENAKA sent a representative for an extended internship at LOISOS + UBBELOHDE, a consulting firm with decades of experience collaborating to design high performance buildings. The two firms planned ways to share knowledge and accelerate the transformation of TAKENAKA practice given multiple barriers (time constraints of design teams, budget constraints of projects, institutional inertia). Ultimately these efforts produced the Zero Energy Design Guide (ZDG). The ZDG is a map for integrating building performance questions and analysis throughout the design process. It contains studies designed to answer critical performance questions (e.g., see Figure 1). The studies are organized by design phase to ensure that guideline activities are relevant to what the design team is considering at each phase. Performance questions follow a pattern throughout the design process from pre-design throughout construction and post-occupancy (See Figure 2). Early questions involve understanding the potential for performance, and later studies involve verification of performance. Performance studies of design alternatives are presented in parallel with related design team efforts, increasing the potential for performance that is integrated in the design.

In addition, the ZDG anticipates collaboration between architect and engineer, and thus, providing a framework for analysis that supports both. For instance, early

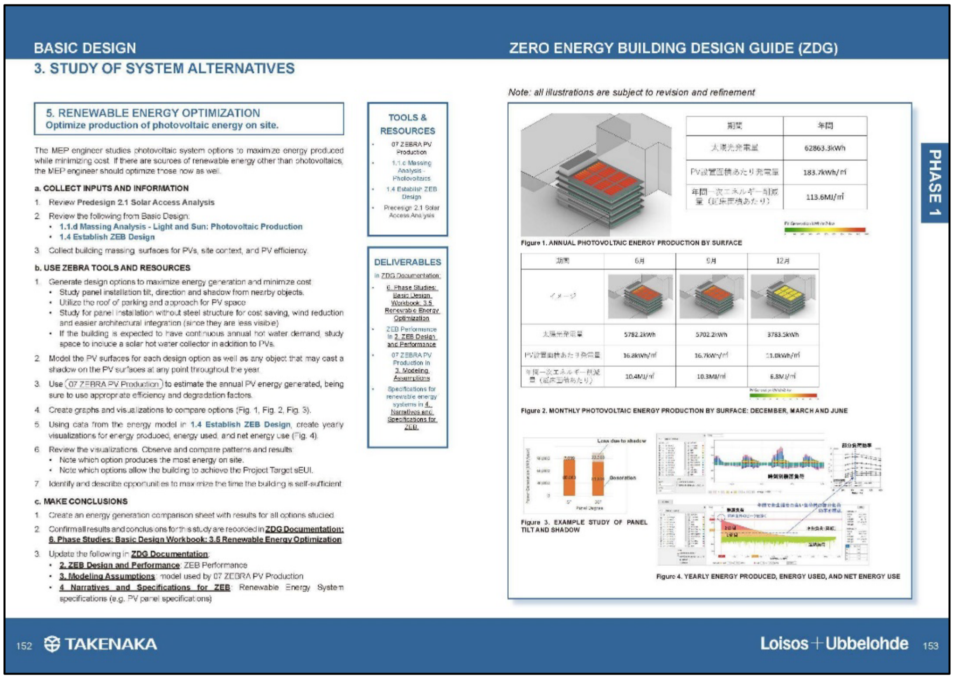


Figure 1 Example study from the ZDG

analyses are broad enough to help architects explore potential, with underlying assumptions that are meaningful for engineers. Similarly, late design analyses are detailed to satisfy engineering requirements while comprehensive for architects to understand ongoing progress to whole-building performance.

While the ZDG maps out these performance questions, it requires tools to support the analyses so that the questions being asked can be answered in a timely manner. This paper presents the process used by the team to specify, source and design the tools needed to perform the analysis described in the ZDG.

Tool Requirements

While the need for suitable tools to perform the ZDG performance evaluations became evident, it was equally clear that these tools needed to address specific requirements to successfully implement this transformative approach. The insights gained from Attia et al. (2009) helped confirm the importance of these requirements. Guided by the lessons learned from various building performance simulation tools, it was crucial for the use of the tools to be simple, fast and versatile given the inherent time and cost constraints in the industry, and the fact that both architects and engineers, particularly MEP engineers, will shoulder the responsibility of conducting ZDG performance evaluations and reviewing the results, as depicted in Figure 3.

Phase	Content Progression
Predesign & Early Design	describe performance potential
Design	study performance of alternatives
Late Design	quantify performance as designed
Construction & Post Occupancy	verify performance

Figure 2 Content progression

- First, simplicity was a paramount attribute. The tools had to be designed with a user-friendly interface to ensure that non-specialists could seamlessly navigate back and forth between the tools and the questions posed in the ZDG.
- Secondly, speed was of the essence. Meeting tight project timelines, a hallmark of TAKENAKA's legacy processes where design phases could be as short as one month, was indispensable. Fast simulations were not only critical for project timelines and budgets but also encouraged users to explore a broader spectrum of design permutations.

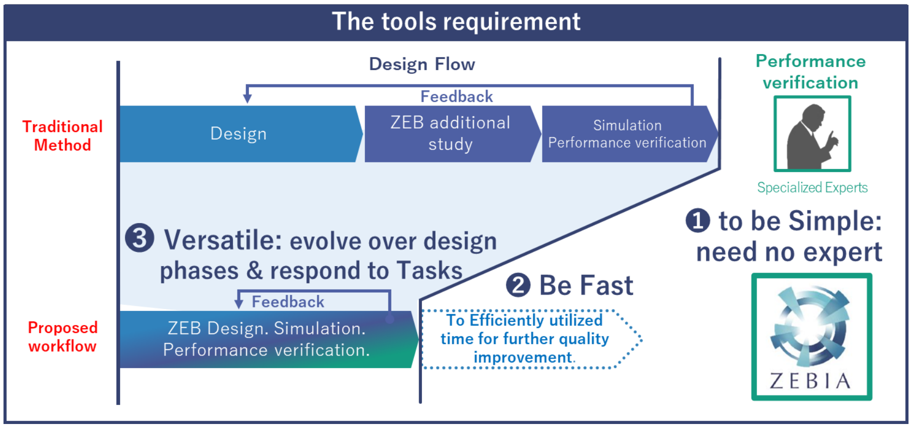


Figure 3 The Tool's workflow aimed to be Simple, Fast and Versatile

- A swift turnaround would allow for more comprehensive design studies, helping gain valuable insights into the implications of design variations and changes.
- The final attribute of these tools was versatility. TAKENAKA undertakes over 200 projects annually, each varying in size, type, and complexity. The tools needed to be adaptable enough to address the unique challenges of each project, capable of providing answers to a diverse array of ZDG performance questions concerning thermal comfort, daylight, natural ventilation, and more.

Furthermore, the tools had to be adaptable to different design phases. For instance, during the early design stages, users should be able to input the building's grade, ranging from average to premium, in accordance with TAKENAKA's rankings. At subsequent stages, the tools would need to allow analysis of specific construction sets, and as the project advanced, they would need to enable more in-depth exploration of the specific material layers comprising a construction. Figure 4 gives a conceptual sketch of the required tool flexibility; the tools needed to cover the full spectrum of design phases (progressing vertically), as well as being able to exchange the information related to the various question content areas (Horizontal data exchanges).

State of the Art

Existing tools, as showcased by the IBPSA Tools Directory (IBPSA-USA n.d.), offer a diverse range of performance evaluation options. Although tools like Ladybug & Honeybee, FlowDesigner, Climate Studio, Climate Consultants, and Meteonorm were initially considered to meet the ZDG's analysis requirements, it became evident that a more tailored solution was essential. The literature review on Building Information Modeling (BIM) for building energy modeling (BEM)

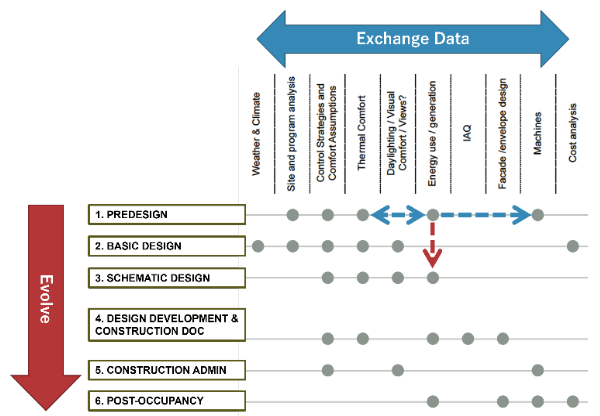


Figure 4 Tools are to Seamlessly exchange data to cover the Phase-Design Matrix Canvas

conducted by Farzaneh, Monfet and Forgues (2019) highlights the challenges and gaps in the current design processes and technological approaches. These insights underscore the necessity for tools that holistically align with the architectural workflow and decision-making processes.

Moreover, the paper by Hemsath (2013) on conceptual energy modeling emphasizes the impact of leveraging powerful building performance simulation tools during early design phases, indicating the potential long-term impact on energy conservation in architecture. This aligns with the need for tools that not only meet immediate analysis requirements but also contribute to the overall efficiency of the architectural design process.

Despite their capabilities, the previously mentioned tools lacked meticulous alignment with the Zero Energy Design Guide (ZDG). Additionally, their outputs needed refinement to seamlessly integrate with our Corporate design workflow, in-house developed tools, and the skill sets of our architects and engineers.

To emphasize, the ZDG was crafted to capture pivotal moments in the architectural design process, considering our Corporate's unique design phase timeline characterized by non-uniform intervals. This unique timing allows architects the flexibility to revisit and modify their designs, aligning them with the ZDG as the project evolves. To highlight this necessity, a group of specialists compared the ZDG workflow with various widely used performance evaluation tools. The distinct requirements of ZDG and our Corporate's unique workflow underscored the limitations of existing tools, leading to the development of a user-centric solution.

To exemplify the inadequacies of existing tools, they frequently overlook the prioritization of relevant information. These tools, for instance, commonly request the PV installation area and report PV energy production (NREL n.d.). However, they often lack a more intuitive representation, such as the total PV area required to meet the project EUI targets—essential in the context of the ZDG. Moreover, the required installation area is directly linked to architectural discourse and influences design decisions. This critical information is integral to the ZDG's objectives and underscores the necessity for tools that holistically align with the architectural workflow and decision-making processes.

Development Process

In this section, we provide a detailed account of the development process for the ZEBIA tools. From the ZEBIA's 20 Tools (Functionalities) The paper focuses and draw examples from two essential tools: the PV production tool and the Site Analysis tool. These tools were chosen for illustration because they play a critical role throughout various design stages and are inherently linked to the ZDG objectives. The development process entails a sequence of well-defined steps that can be summarized in four milestones:

1. Functionality Specification: Translate ZDG requirements into tool tasks and functions.
2. Wireframes: Create visual blueprints for the dataflow and the user interface.
3. Prototyping/Development: Realize the wireframes and code specific functionality.
4. Road Test: Refine ZEBIA before implementation.

The Rhino-Grasshopper (GH) platform was selected as the environment for developing and deploying most of the ZEBIA tools. Compared to other approaches, such as creating an interface from scratch, GH was the most promising, feasible, and reliable option. Essentially, we had to build the tools within a daily-used BIM platform to easily and seamlessly integrate sustainable design analysis with the ongoing design process routines. Users shouldn't need extra time to import, export, and exchange their design masses and models through various platforms.

The GH platform also provides access to robust simulation engines: ZEBIA tools are built to utilize the key components of Ladybug (LB) & Honeybee (HB) (Roudsari, and Pak 2013), which provide a linkage to EnergyPlus and Radiance. However, a user would need to customize and link LB and HB tools to complete the advanced investigations specified by the ZDG. This algorithmic wiring, as simplified and described in the

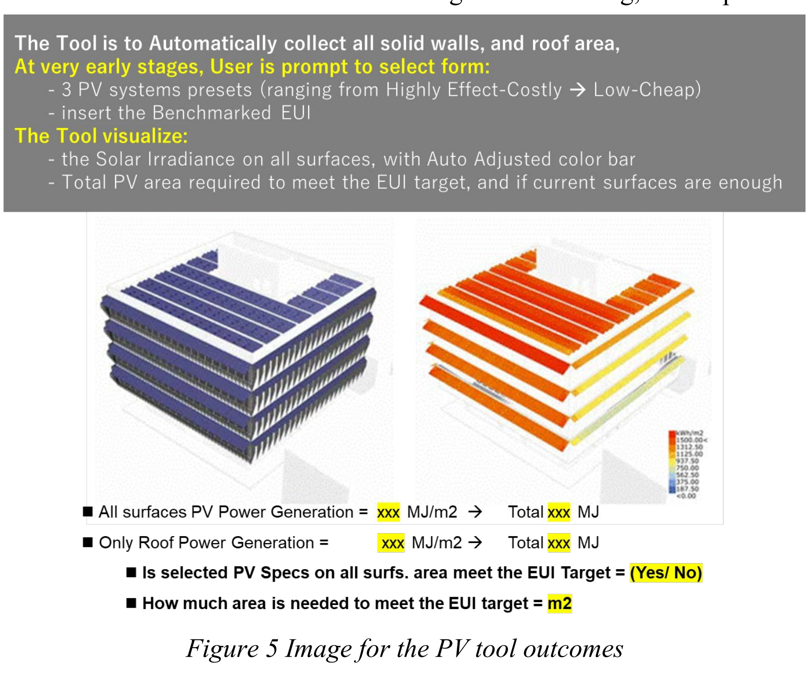


Figure 5 Image for the PV tool outcomes

"Wireframing Stage," would require advanced knowledge of GH, LB, and HB. ZEBIA's innovation lies in the customized algorithms that harness the power of advanced simulation tools and allow a non-specialized user to complete studies specified by the ZDG. In addition, ZEBIA development in GH also allowed complex input preprocessing, complex output post-processing, and the development of new components to realize our ideal user experience.

Functionality Specification

At the outset of the development process, we embarked on the crucial task of translating the comprehensive requirements outlined in the ZDG into specific simulation tasks. These tasks articulate what each tool should accomplish, detailing the input requirements, processes, and expected outputs., For example, During the earliest design phases, architects required a tool that could provide insights into energy generation potential and help in comparing different geometric and configuration options. The PV production tool needed to offer quick, informative outputs for benchmarking purposes and setting early expectations.

As design stages progressed, the tool had to adapt to more specific requirements, like providing detailed information about the energy performance of photovoltaic systems in later design phases. The functionality specification phase also involved creating ideal visual representations of the outputs, including graphical formats, file structures, and pop-up

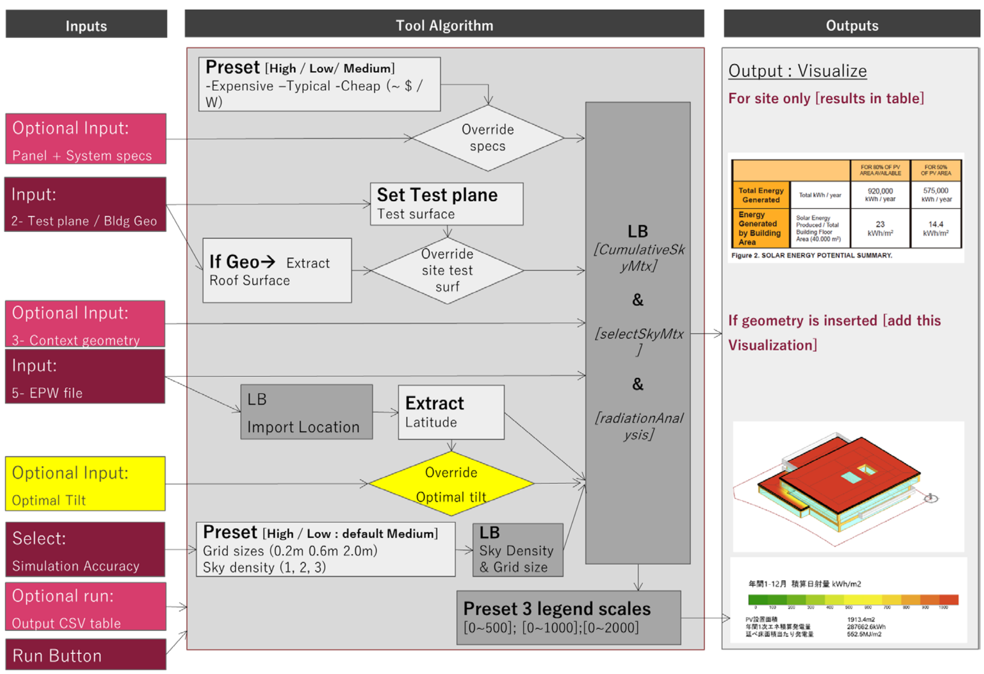


Figure 6 PV tool early wireframe development

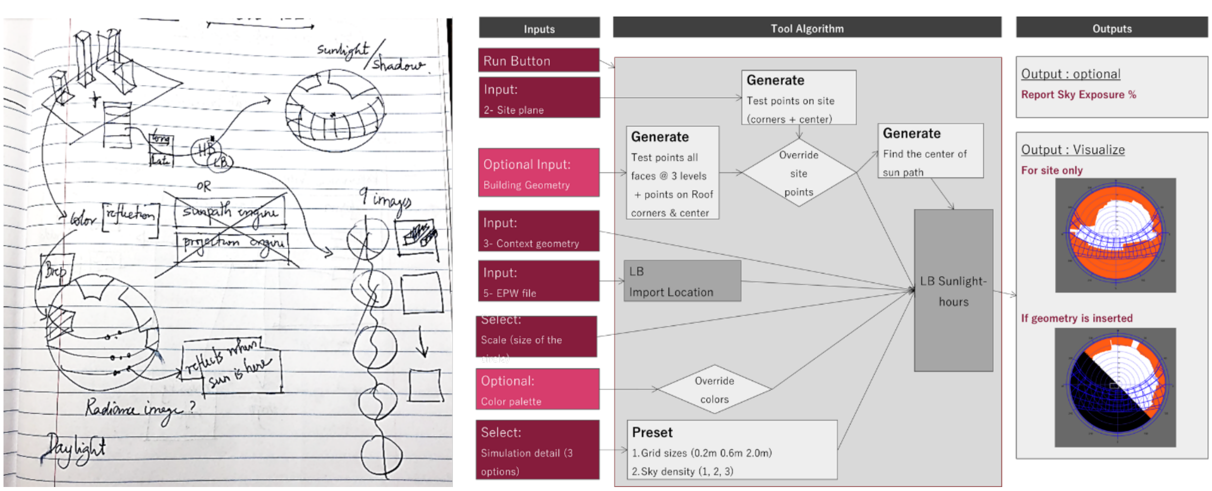


Figure 7 wireframe sketches used in to create more detailed algorithmic wireframes notifications, to enhance the user experience. At this stage, we generated sample images of the tool's outputs, providing a clear representation of the expected results. An example of such an image can be seen in Figure 5.

Wireframes

With functionality specifications in place, we moved on to the stage of creating tool wireframes, which served as the visual blueprints of the tool's user interface. These wireframes transformed the functionality statements into clear data flows, outlining what users would see, control, and configure. For example, the PV production tool wireframes (Figure 6) contained predefined settings to ensure the tool's engine produced meaningful outputs by default. These default settings were derived from TAKENAKA's extensive database, which cataloged product information and case study experiences. In creating these wireframes, we carefully designed every aspect of the user interface, determining what was visible, what remained hidden, and what had default values. We also introduced intuitive elements to help users navigate the tool seamlessly, such as interactive pop-ups and helpful prompts.

It is noteworthy that the wireframe design process began with initial sketches for quick discussions, evolving over time to incorporate more detailed elements. These wireframes served as a bridge between the ZDG team and the tool coding team. Figure 7 presents examples of sketches and wireframes for a specific functionality within the Site-Analysis tool. This functionality aimed to automatically generate multiple fish-eye graphs for predefined points, whether for an empty site or a preliminary massing. These graphs display the fish-eye perspectives for each direction and at predefined heights. The wireframes identify the input requirements, the initial use of Ladybug components for simulation processing, and the expected output formats.

This stage ultimately culminated in the creation of

detailed wireframe representations within the Grasshopper canvas. For instance, Figure 8 demonstrates an example of a simple GH empty component algorithm, related to the weather analysis supporting tool, which aimed to identify missing data in weather files and generate custom weather files by combining data from multiple sources. These tools facilitated quick studies, enabling the testing of hypothetical weather conditions, and enhancing intuitive comprehension of the project site's weather conditions.

Prototyping/Development

As the wireframes (and dummy algorithms) began to take shape, we entered the prototyping and development phase. During this stage, the tools began to function with GH canvases, albeit in an initially unorganized state. This phase marked the commencement of rigorous efforts aimed at aligning the tools with their intended functionality and the wireframes. Also, while the core simulation engines remained unchanged, the focus gradually shifted to extensive coding, ensuring that the tools delivered the intended user experience, which included the desired user interface and graphical formats.

To gain insight about the user experience, before we even had users, we utilized storyboarding, a technique popular in the fields of User Experience (UX) and film production. This approach allowed us to create a visual narrative of what a ZEBIA-ZDG user might experience, emphasizing the need to track variables, record outputs, and build a simulation tree. These insights informed our development process. Subsequently, rigorous testing became imperative as we advanced in tool development,

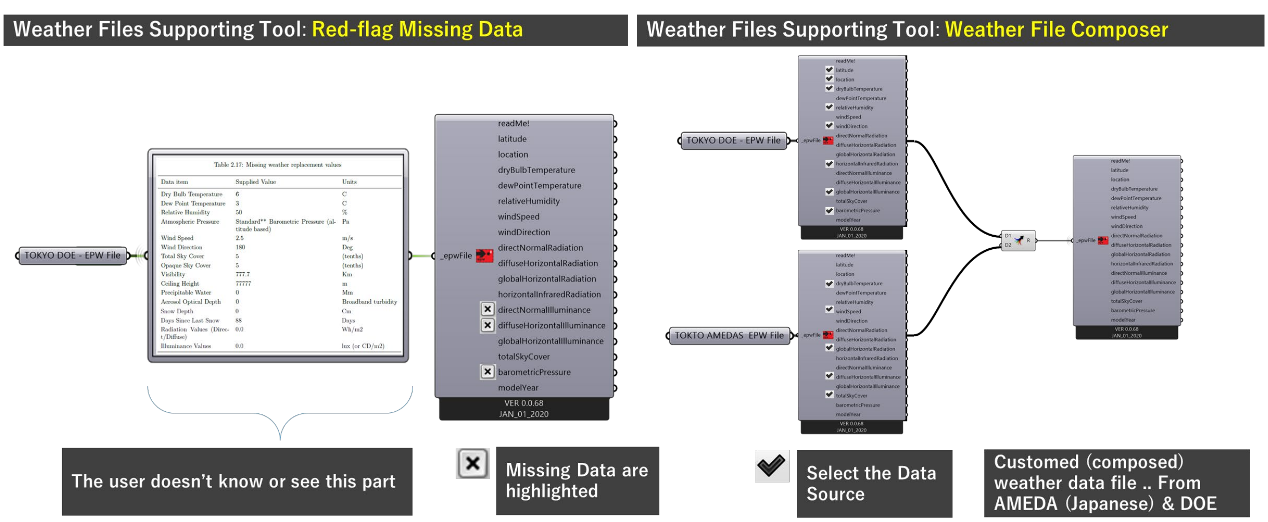


Figure 8 algorithmic connections with empty components describes the UI of Alpha V. of the tools

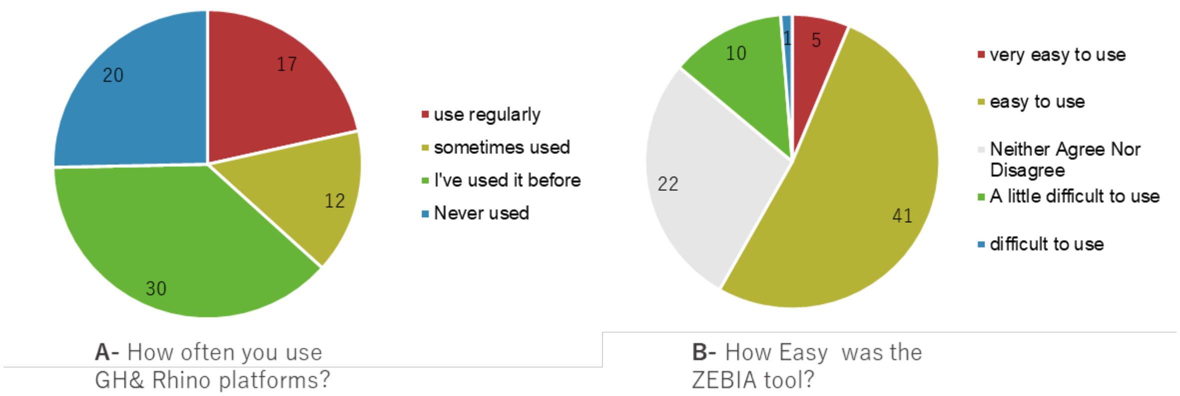


Figure 9 User Feedback from Tool's First Hands-On

including a comprehensive road test that evaluated the ZDG and ZEBIA's practical application.

Road Test

In preparation for the finalization of the ZDG and ZEBIA tool set, we conducted a critical phase known as the "Road Test." The primary objective of this phase was to pinpoint areas within ZDG and ZEBIA that required further refinement before its initial implementation at TAKENAKA. To conduct the Road Test, we selected LOISOS + UBBELOHDE office, a renovation project, due to its advantageous attributes, including the availability of documentation, project simplicity, and the potential to explore multiple facets of the ZEB concept.

The Road Test Team was composed of employees at LOISOS + UBBELOHDE, with a preference for those who were not experts in the field of study. This approach was deliberately chosen to ensure that the testing process closely adhered to the specific tasks and requirements outlined in the ZDG, rather than relying on specialized knowledge. The road test team was instructed to use ZEBIA tools where possible, and use workarounds as needed when ZEBIA tool functionality was not yet developed. The road test involved internal design reviews and mock meetings with the client, mirroring real project scenarios.

The feedback gathered during the Road Test played a crucial role in refining and enhancing ZEBIA's features and user interface. One of the key findings from the Road Test was the importance of visualizations and outputs. Occasionally the workaround tools did not provide results that were easily understood by a non-expert. This underscored the need for critical data to be presented clearly to facilitate intended comparisons. Visualizations need to be both clear and aesthetically pleasing, while outputs should be consistent in format and design, making them familiar and easily understandable. In addition, results should be suitable for direct use in presentations to the client, eliminating the need for additional time to enhance their appearance.

The road test team suggested improvements on several technical parts, starting from the tool's installation, the interoperability between the various tools, as well as suggestions on the means of installing, and retrieving the simulation files themselves. The user prompts and input descriptions were revised to reinforce the relation between ZDG questions and tools. It was also recommended that the tools couldn't be limited to providing raw numerical data; they had to offer inputs and outputs that could be readily translated into actionable design decisions. For instance, when a ZDG requires testing a "high thermal mass" option, how much thermal mass is that? The tools could always include a physical or architectural specification with variable options e.g., 25 cm Concrete Slab. This phase served as a vital bridge between the theoretical development of ZEBIA and its practical application within the context of The TAKENAKA's design practices.

Results

The culmination of the ZEBIA development process and its integration into the design workflow yielded valuable insights and outcomes. With the tools in their final form, the results illustrate how well the ZEBIA development process met the tool requirements, identified development challenges, and responded to user feedback. The development hurdles encountered along the way were addressed, ultimately enhancing the tools' usability and effectiveness.

User Testing

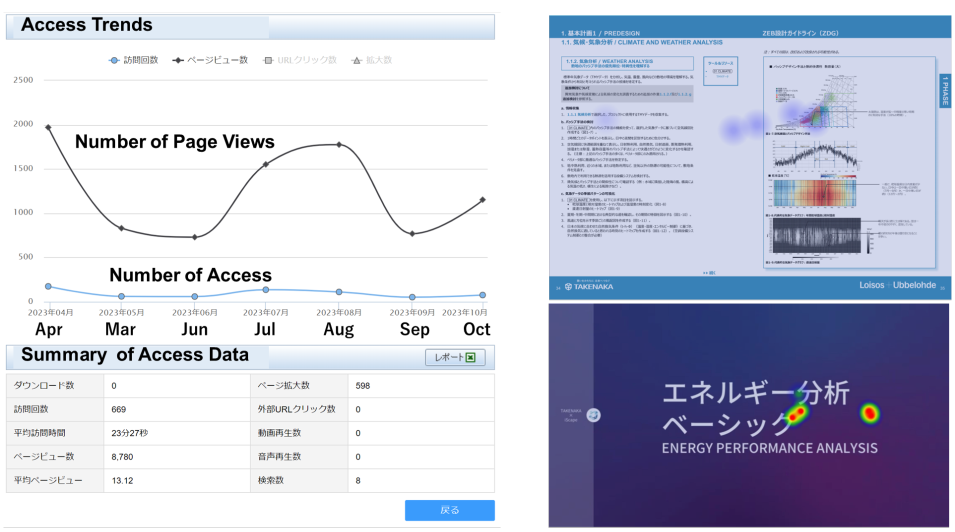
In the final phase, we distributed the tools to potential users, particularly those engaged in sustainable design simulations. This step involved conducting eight-hour hands-on sessions and creating video tutorials for each tool, which were made accessible via TAKENAKA's internal portal. During the hands-on sessions, participants provided valuable feedback, detailing their backgrounds and their proficiency in utilizing Rhino, Grasshopper, and their levels of experience. Additionally, the video tutorials were equipped with tracking capabilities, enabling us to monitor the mouse's position and screen focus of viewers. This information was instrumental in assessing which parts of the tutorials were engaging or required more attention, further refining the tools' usability.

The hands-on questionnaires distributed to potential users played a pivotal role in gauging the tools' effectiveness and user-friendliness. Given that the tool targets all design teams, encompassing almost 2,400 architects, the hands-on feedback received so far up to 2023-3Q was received from 79 participants, largely from architectural backgrounds. Regular hands-on sessions are ongoing to ensure proficiency across these design teams, and the votes and surveys provided reflect the collective insights from participants engaged in these sessions.

A notable observation was that approximately one-fourth of the users frequently utilized software like Rhino and Grasshopper, while another quarter used them occasionally (Figure 9-a). The questionnaires illuminated specific user expectations, such as the desire for simplified 3D modeling and simulation, support for building energy indices (BEI and BPI), and an expanded focus beyond photovoltaics (PV). Users also sought optimized solutions for design elements like eaves and openings, alongside a comprehensive visual aid for presenting conditions to third parties. Furthermore, the questionnaires revealed that while a significant portion of users had limited experience with GH and Rhino, over half found the tools easy to use and operate, with less than a quarter reporting difficulty (Figure 9-b), proving that the tools were simple enough to use even for non-specialized users.

To delve deeper into understanding user behavior and preferences, mouse heatmaps were employed. These heatmaps enabled us to identify which tool tutorials garnered the most attention, thus helping prioritize our refinements. For instance, (Figure 10-a) visually illustrates how many users engaged with specific tutorials, enabling us to discern the areas of greatest interest. Subsequently, (Figure 10-b) showcases heatmaps' usefulness in pinpointing precise sections within the ZDG that garnered user attention.

By correlating this data with tool operation, user questions, and needs, we gained insights into whether these focused areas corresponded to common architectural tasks or highlighted aspects that required further attention and improvement. For example, and as seen in the same figure below, we observed that the Psychromtric chart and the Passive Design overlays during the Pre-design phase garnered significant user attention in the ZDG pages as well as when the users were following the tool tutorial. This was mainly due to the detailed and intricate steps that held their focus while on the page. The integration of mouse heatmaps into our development process was instrumental in refining ZEBIA and ensuring it met the specific requirements of users and the ZDG.



a - Access log to the ZDG

b - Heatmaps on the ZDG above, and in the tutorial video - bottom

Figure 10 ZDG & ZEBIA users' accessibility and concentration heatmaps

Discussion

The development of ZEBIA, a comprehensive set of tools designed to support TAKENAKA's Zero Energy Building Design, was a multifaceted endeavor that involved rigorous planning, prototyping, testing, and user feedback. This section delves into the key lessons learned from the ZEBIA development effort and highlights the significance of ZEBIA in the context of sustainable architectural design.

Lessons Learned from ZEBIA Development

The journey to create ZEBIA offered several critical lessons that can guide future endeavors in developing tools for sustainable design:

1. Iterative Wireframing: The evolution of wireframes from initial sketches to detailed representations greatly facilitated communication between the ZDG team and tool development team. These wireframes acted as a visual bridge, conveying essential information about tool functionality.
2. Storyboarding for User Experience: The utilization of storyboarding techniques allowed for a comprehensive understanding of what a ZEBIA-ZDG user might experience. Storyboarding clarified the user journey and the tools' role in it, influencing the subsequent development stages.
3. User-Centric Design: The user testing phase emphasized the importance of user-friendliness. The process revealed that even with limited Grasshopper and Rhino proficiency, over half of the users found the tools easy to operate. This user-centric approach ensured that ZEBIA could be effectively integrated into TAKENAKA's design process, aligning with the ZDG's objectives of simplicity, speed, and versatility.
4. Post-Occupancy Feedback: Over time, insights gathered from completed projects in post-occupancy evaluations not only inform default inputs in the tools but also contribute to an iterative improvement process. This ensures that knowledge is rapidly disseminated across all ZDG users, enhancing the analysis, and progressively refining the simulations for greater accuracy.

Significance of ZEBIA

ZEBIA stands out as an inclusive platform that allows users to learn and practice various simulation methods across a wide spectrum of performance metrics crucial for Zero Energy Building (ZEB) design. This eliminates the need to navigate different software tools for distinct aspects of sustainable design, streamlining the simulation process. Serving as a powerful tool for architects and engineers, ZEBIA provides real-time feedback and analysis to equip professionals with the necessary information for informed decision-making. This not only contributes to the reduction of environmental impact but also aids in minimizing operational costs. The tools integrated into ZEBIA offer practical and comprehensive solutions for sustainable design, empowering designers to confidently create environmentally friendly structures.

ZEBIA is not only a stand-alone tool but also a fundamental component of the Zero Energy Design Guide (ZDG). Its role within the ZDG provides a structured framework for designers to achieve Zero Energy Building (ZEB) goals. This integration ensures that the objectives outlined in the guide are not just theoretical but practically attainable. ZEBIA's commitment to ZEB objectives reflects our Corporate's dedication to sustainability in complex design workflows. The project showcases that, with the right tools and a user-centric approach, ZEBs are achievable, setting a precedent for sustainable design in the industry.

In conclusion, ZEBIA's development process offered invaluable lessons for custom tool development while making significant contributions to the field of sustainable design. Its user-centric approach and integration with systematic guidelines demonstrate the transformative potential of achieving zero-energy building objectives. Despite the tools being limited to internal use within TAKENAKA Corporation, their impact resonates in the broader context of sustainable design.

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