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DEVELOPMENT AND VALIDATION OF THE GAME ENGINE-BASED DIGITAL TWIN APP "CONNECTIA" FOR PRACTICAL USE IN THE CONSTRUCTION PHASE

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Abstract: CONNECTIA®, a "Digital Twin" application developed under the "Construction DX" initiative to improve productivity. It combines cloud-based data management with native app rendering using Unity, offering advanced visualization and user-friendly UI to simplify 3D workflows. It has shown potential time savings of over 10 hours per person per month.

Keywords: CONNECTIA, Digital Twin, 3D Model, BIM, CDE, Cloud, Game Engine, Unity, DX

1. BACKGROUND

The Japanese construction industry faces various challenges, including a labor shortage caused by a declining and aging workforce, long working hours, and harsh working conditions. Labor productivity in the sector has remained lower than in other industries for several decades. In response, the Ministry of Land, Infrastructure, Transport and Tourism has introduced the i-Construction initiative, aiming to improve productivity by 20% by 2025. However, to sustain productivity while observing the upper limit on overtime working hours introduced in FY 2024 under the revised Labor Standards Act, "work style reform" and further "productivity improvements" are critical challenges that the construction industry must address.

Viewing these challenges as opportunities for transformation, the construction industry has increasingly embraced the idea that digital transformation (DX), which brings innovation to construction production systems and revolutionizes production processes, offers an effective solution. Realizing DX in construction requires accurately assessing current operational processes and on-site conditions through sensing technologies and other tools. To achieve this, the authors have been developing an application named "CONNECTIA", which facilitates the creation of general-purpose digital twin models of construction sites. These models reproduce site conditions in real time by linking physical space with cyberspace. This technology, which applies various metaverse and game development technologies to the construction sector, was awarded the grand prize in the "Co-Creation Category" at CEATEC 2023, held in October 2023, in recognition of its technical excellence.

In order to solve the most important issues of "work style reform" and "productivity improvements," we call the overall efforts, including the development of new digital technologies, "construction DX" and consider them systematically. As shown in Fig. 1, we have defined the levels of construction DX, the basic level of digitalization, from DX level 1 to the final goal level 5, and are planning to achieve each level in stages. CONNECTIA, introduced in this paper, is an app for mainly achieving levels 2 and 3, which integrate and utilize digitized data on-site. Chapters 2 to 5 mainly discuss the challenges and solutions for achieving level 2, and Chapter 6 discusses the data integration platform required for level 3. The focus of this paper is mainly on level 2 in chapters 2 to 5.

In the future, we will return to level 1 and develop automatic generation of 3D data and related technologies, and we will aim to achieve level 4, which is robotics construction (construction sites where robots are the main players), such as automating and autonomous construction machinery.

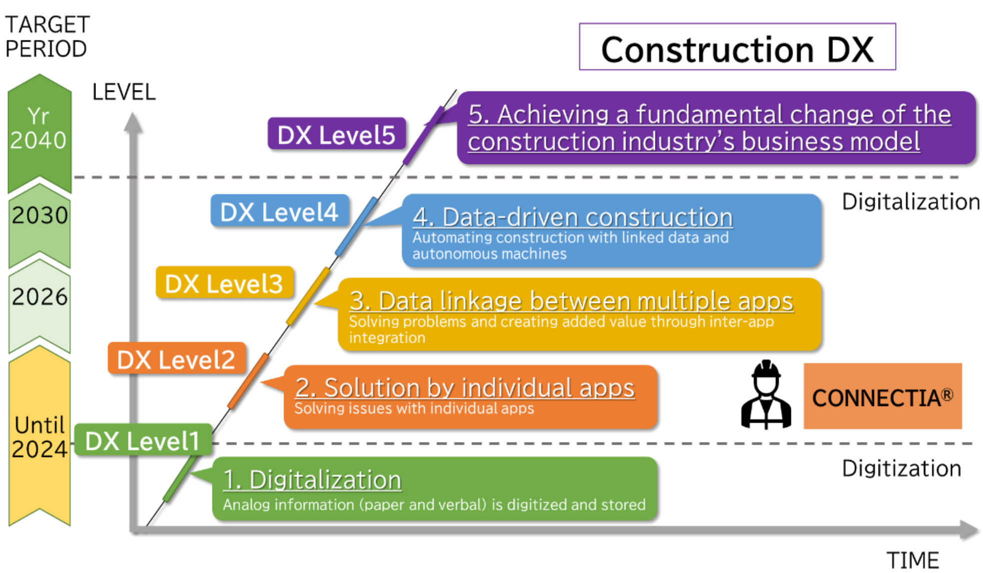

Fig. 1 Roadmap for Construction DX

2. CHALLENGES

In the construction industry, the benefits of 3D models, including BIM, likely require no detailed explanation. However, at least in the construction execution phase in Japan, these technologies have not yet been fully adopted or effectively utilized in daily operations. While there are numerous high-level factors, such as cultural and policy-related issues, two fundamental challenges stand out:

1) Hardware-related challenges (e.g., the need for high-spec PCs).
2) Software-related challenges (e.g., significant costs associated with learning and adopting new applications).

From 2022 to 2023, we conducted a study focusing on construction site offices that were reported to utilize 3D models. The findings revealed that only a few individuals used the relevant software or applications, while the majority of team members did not. Upon investigating the reasons, two key issues emerged.

First, the existing PCs at these sites lacked the specifications necessary to handle the software or applications effectively. Upgrading to PCs capable of processing 3D data would require significant time and financial investment. Second, transitioning from the traditional 2D-centric workflow to one centered on 3D models demands substantial time and resources for training and familiarization with the new software and applications. However, construction sites are generally unable to allocate the necessary time or budget for this transition. These challenges underline the difficulty of integrating 3D models into construction workflows, despite their potential benefits.

To overcome both hardware and software challenges, we developed CONNECTIA (Fig. 2), a digital twin application that allows anyone to easily manage construction work using 3D models. As there are software and applications available for handling 3D models at each stage, the scope of CONNECTIA is shown in Fig. 3. The system is designed to focus on functions specifically for the use of 3D models in construction work, making it easier to use than existing products. Additionally, it aims to create a common data environment (CDE) using various technologies that will be described later.

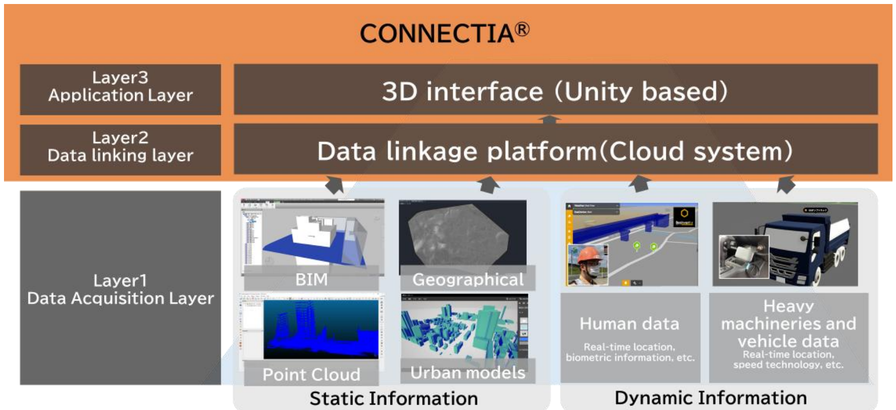

Fig. 2 Structure of CONNECTIA

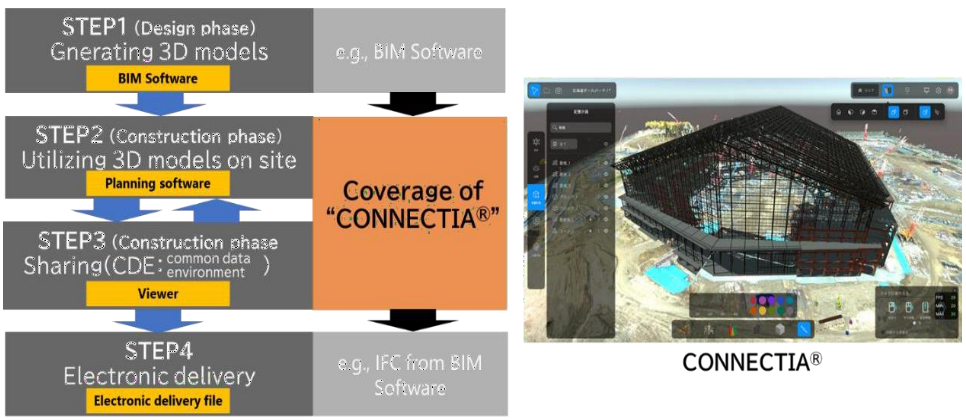

Fig. 3 Scope of CONNECTIA

3. CORE TECHNOLOGIES ADOPTED TO ADDRESS HARDWARE CHALLENGES

Recently, cloud applications that can be used directly in a web browser without installation have become mainstream, and several products that can handle 3D models have been introduced. However, for large-scale and high-volume 3D data typically used in construction, technical challenges remain, particularly in achieving high-speed rendering. This is evident in the fact that BIM software still predominantly relies on native applications. CONNECTIA combines the advantages of both approaches by adopting a hybrid system architecture: it uses cloud (AWS: Amazon Web Services) for data management and a native application for rendering (Fig. 4 - left). Since all data is stored in the cloud, a digital twin environment can be deployed anywhere as long as connection is established. The system is also designed using a microservices architecture that includes functions such as data utilization via API, authentication and authorization, and storage, ensuring the cloud's inherent availability and scalability.

For 3D models, BIM data is processed for lightweight optimization in the dedicated cloud, while the native application uses a dedicated viewer, developed with the Unity game engine, for rendering. This allows the system to run smoothly even on standard PCs without a GPU (Fig. 4 - right). Details of the cloud system will be discussed in Chapter 6.

As a result, these efforts have largely addressed hardware challenges, with performance tests showing that project load times have been reduced by approximately 87%, delivering high performance compared to conventional BIM software (Fig. 5).

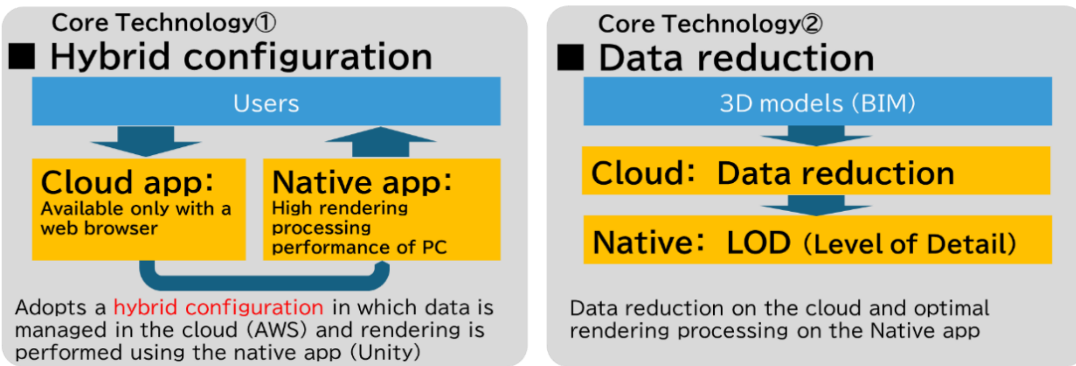

Fig. 4 Hybrid System (left) and Model Optimization Technologies (right)

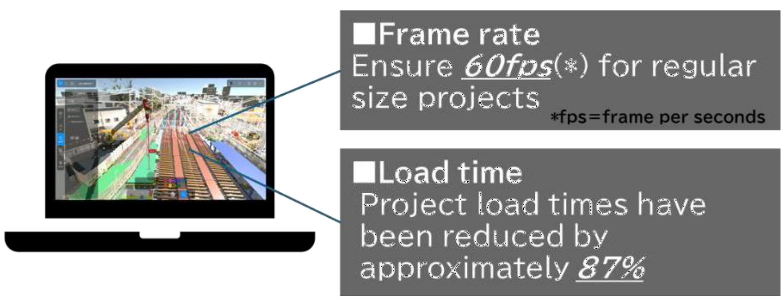

Fig. 5 Results of Validation with BIM Software

4. UI/UX DEVELOPMENT TO ADDRESS SOFTWARE CHALLENGES

Even if the hardware barriers are reduced, the implementation of on-site construction management using 3D models remains challenging if the time and cost required for application training and education are substantial. To address this, we collaborated with a UI/UX development team to repeatedly refine and improve the software's user interface and experience, focusing primarily on resolving software-related challenges.

Initially, we analyzed the features and operations included in existing BIM softwares and applications, then significantly narrowed down the functionality to those essential for the construction phase. This was necessary because many features in existing software were either irrelevant or overly sophisticated for use during this phase. For the selected features, we developed UI mockups from scratch using the UI design tool *Figma*. Subsequently, we conducted a "blind test" involving 14 participants—seven with construction experience and seven without (having IT backgrounds). In these tests, participants were instructed on the task they needed to accomplish (e.g., placing a object of heavy machinery at a specific location) but were given no guidance on how to operate the application. Their interactions were recorded using video cameras for analysis.

By examining the results, we identified areas where users encountered difficulties and investigated the reasons for these challenges through follow-up interviews. Based on these findings, we iteratively revised and enhanced the UI to create a more intuitive and effective user experiences (Fig. 6).

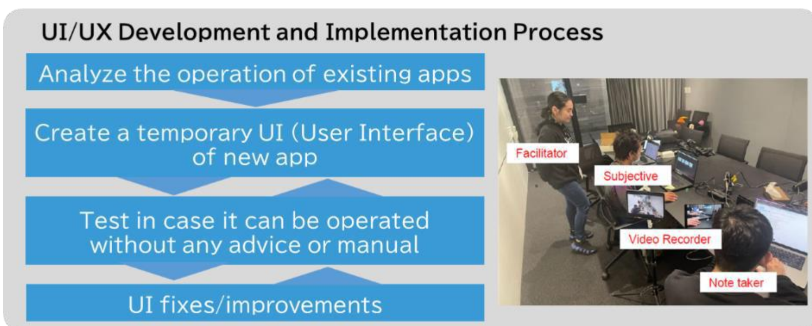

Fig. 6 UI/UX Development and Implementation Process

4.1. VALIDATION METHOD

We compared the usability of our UI with that of a conventional 3D viewer application. For the comparison, we created two scenarios: Work Case ① and Work Case ②, based on a series of tasks frequently performed in the construction field. After preparing integrated data that included BIM models, point cloud data, and terrain models, we configured Work Case ① with the task of placing four heavy machinery models (a hydraulic excavator, a crane, and a crane in two different orientations). Work Case ② involved the task of placing four boxes of different sizes. The operation time and the number of steps required to complete the tasks using the conventional application and ours were then measured and compared under identical conditions using standard engineering notebook PCs (Fig. 7)

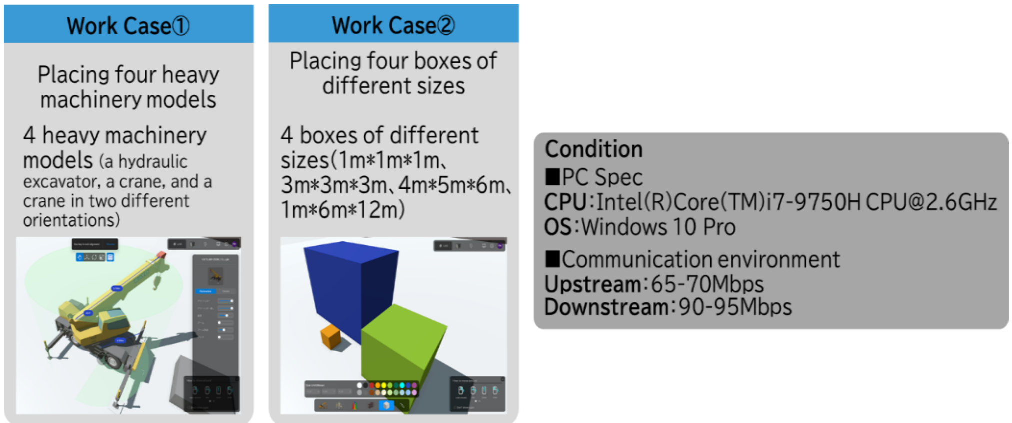

Fig. 7 UI Validation Method

4.2. VALIDATION RESULTS

The validation results are shown in Fig. 8. In Work Case ①, the conventional procedure, where the coordinates of the machine models created during data integration did not match the field coordinates, required rough repositioning of the machinery, followed by fine-tuning of the horizontal position and height. In contrast, our UI required only selecting the model from the heavy machinery list and clicking the location to complete the task. When placing the crane model in different orientations, the conventional procedure involved editing the model in 3D CAD software and importing it into the viewer application. However, with our UI, this entire operation could be completed within the application. As a result, our UI took only 132 seconds (18 steps) to complete the task, compared to 1,523 seconds (40 steps) using the conventional approach, reducing the time to less than one-tenth.

In Work Case ②, the conventional procedure took 557 seconds (48 steps), as it required model creation and coordinate adjustments using 3D CAD software, whereas our UI completed the task in 115 seconds (10 steps), reducing the time and steps to about one-fifth. These results indicate a significant improvement in operation time and steps compared to conventional BIM software, addressing the challenges primarily on the software side.

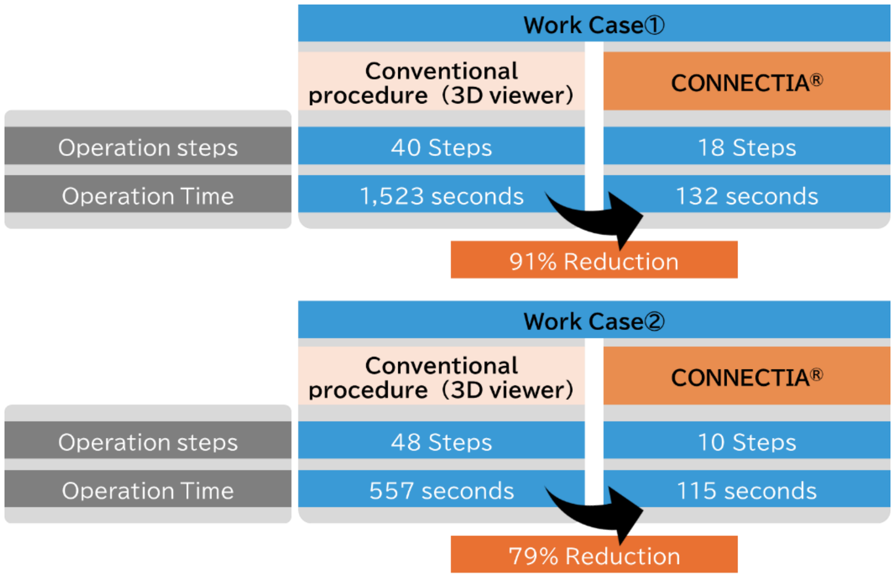

Fig. 8 UI Validation Results

5. VALIDATION OF CONNECTIA IN REDUCING CONSTRUCTION MANAGEMENT WORK

Through a series of development processes from FY 2022 to FY 2023, CONNECTIA has addressed certain hardware and software challenges, significantly lowering the barriers for users. However, since the use of 3D models in construction and on actual work sites was still in the experimental phase, it was necessary to further test CONNECTIA in real construction management settings to evaluate how effective it is in streamlining management tasks. The methods used in this assessment and the results are detailed below.

5.1. MAIN FUNCTIONS INSTALLED IN CONNECTIA

Prior to the validation, we will introduce some of the functions that have already been implemented and that are necessary during the construction stage based on interviews with users. These functions are categorized into three groups: machinery model placement, construction review, and real-time functionality. The main functions from each group are listed in Fig. 9

Fig. 9 Main Functions of CONNECTIA (by Function Group)

5.2. ON-SITE VALIDATION METHOD

To evaluate whether CONNECTIA, developed between FY2022 and FY2023, could be effectively utilized on construction sites, a field validation study was conducted during the first half of FY2024. The primary focus of this evaluation was not only to assess the functionality and completeness of CONNECTIA but also to identify the challenges faced by the sites and measure how effectively these challenges could be addressed. The evaluation also considered processes outside the scope of CONNECTIA, such as model creation, model uploads, and the preparation of materials for client presentations. For instances where CONNECTIA's current capabilities were insufficient, we also conducted interviews to explore what additional features or support systems would be necessary to complete these processes. The field trials followed a structured process: 1) Identifying on-site challenges, 2) Setting up a 3D utilization environment, 3) Trial implementation, and 4) Evaluation (via surveys)

Particular emphasis was placed on the challenge-identification phase, which required significant time. To minimize the burden on site offices, the setup of the 3D utilization environment was handled almost entirely by the headquarters team. This approach ensured consistent conditions for comparison and evaluation with traditional 2D workflows.

The study involved 14 operational civil engineering construction sites. Evaluations and interviews were conducted to gather insights and feedback from these sites. The evaluation was based on a questionnaire (shown in Table 1), with results organized into four rating categories: ◎ (very good), ○ (good), △ (fair), and × (poor). The main respondents of the survey were "Site Managers" (about 27% of all field staff) and "Chief Engineers" (about 12%), primarily representing the younger demographic, accounting for approximately 39% of the on-site supervisors.

5.3. RESULTS OF ON-SITE VALIDATION

As an overall assessment, 71% of the 14 surveyed sites responded that they expect a reduction of 10 or more hours per person per month in the near future by using CONNECTIA. Regarding specific reasons, 36% of the sites answered that the "work required for construction review and preparation of construction plans (TYPE A)," would be reduced by 30-50%, while 43% expect a 10-30% reduction, compared with the conventional approach using 2D drawings. Similarly, for the "prevention of omissions in the review process and reworking (TYPE B)," 43% of the sites expect a 30-50% reduction, while 50% expect a 10- 30% reduction. As for "expediting the consensus-building process among stakeholders by promoting mutual understanding (TYPE C)," 43% expected a 30-50% reduction, and another 43% expected a 10-30% reduction. Regarding " reducing the workload of preparing explanatory materials during construction reviews (TYPE D)," 54% answered that there was a reduction of 10% or more. In addition, 38% answered "no change," however we believe that if they can create 3D explanatory materials, which handle an increasing amount of information, in the same amount of time as traditional 2D work, users will be able to improve the quality of explanatory materials without increasing the burden. Furthermore, in the future, we plan to continue development with a view to speeding up work compared to traditional 2D work by incorporating assistance, such as automatically arranging models of safety equipment and guards that need to be installed in the vicinity in conjunction with the placement of cranes. (Fig. 10).

The challenges faced at each site varied widely, and due to space limitations, detailed descriptions cannot be provided here. However, it became evident that compiling the types of challenges encountered and the solutions implemented as use cases would be valuable for scaling the application to other sites. Additionally, the study revealed that the significant workload associated with preparatory tasks such as model creation and uploading highlighted the critical importance of establishing support systems to drive broader adoption.

TYPE (A)	**work required for construction review and preparation of construction plans**	**Compared to traditional construction planning using 2D drawings, to what extent do you think the workload of construction planning (construction planning) work will increase or decrease when using CONNECTIA?** **Please rate on a 4-point scale: ◎, ○, △, ×.** **Based on the amount of time previously spent on construction planning, by what percentage will it be reduced?** **◎:30-50 % reduction (imagine completing 10 hours of study and discussion in 5 hours)** **○:30 % or less reduction (imagine completing 10 hours of study and discussion in 7 hours)** **△:No change** **×:Takes longer**
(B)	**prevention of omissions in the review process and reworking**	**Compared to traditional construction planning using 2D drawings, to what extent do you think CONNECTIA can prevent oversights and rework?** **Please rate on a 4-point scale using ◎, ○, △, or ×.** **◎:Greatly prevented (Imagine overlooking something being reduced by 30 % or more) ○:Slightly prevented (Imagine overlooking something being reduced by 10 % or more)** **△:No change** **×:Increased rework**
(C)	**expediting the consensus-building process among stakeholders by promoting mutual understanding**	**When creating explanatory materials for customers and partner companies, how much do you think your workload will increase or decrease by using CONNECTIA compared to traditional 2D models? Please rate on a 4-point scale: ◎, ○, △, ×.** **Based on the amount of time you've spent on reviewing the work up until now, by what percentage will it be reduced?** **◎:30-50 % reduction (imagine completing 10 hours of study and discussion in 5 hours)** **○:30 % or less reduction (imagine completing 10 hours of study and discussion in 7 hours)** **△:No change** **×:Explanation takes longer**
(D)	**reducing the workload of preparing explanatory materials during construction reviews**	**When explaining construction plans (creating construction step diagrams, etc.) to customers and partner companies using conventional 2D drawings, how much do you think it would be possible to improve the other party's understanding of the situation and, as a result, to what extent would it be possible to speed up or simplify discussion times? Please rate on a 4-point scale using ◎, ○, △, ×.** **◎:30-50 % reduction (imagine completing 10 hours of study and discussion in 5 hours)** **○:30 % or less reduction (imagine completing 10 hours of study and discussion in 7 hours)** **△:No change** **×:Explanation takes longer**

Table 1 Questionnaire Sheet

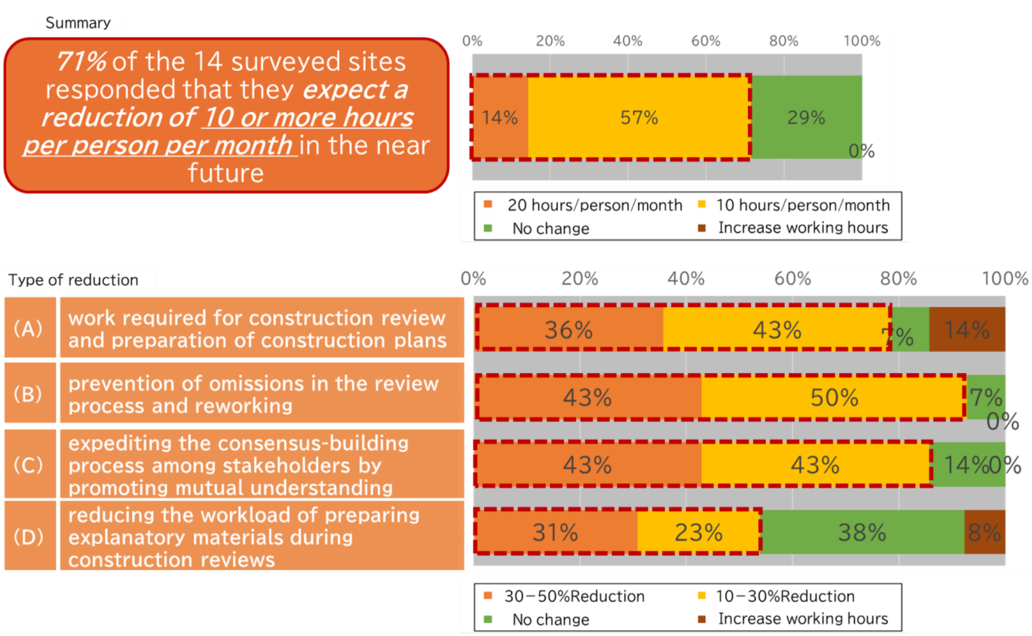

Fig. 10 Results of Effect Validation

6. DATA LINKAGE PLATFORM

In the previous chapter, we discussed how to use CONNECTIA to solve site issues, mainly in relation to level 2 of construction DX. In this chapter, we will explain the backend of CONNECTIA, with the realization of level 3 in mind. Constructing a digital twin requires to handle both "static information" with little time variation, such as 3D models and point cloud data used in BIM received at the start of design and construction, and "dynamic information" with large time variation, including the position data of moving objects like field workers, heavy machinery, and vehicles, as well as sensing information from the surrounding environment. Since we are also building an environment for data linkage platform that integrates these types of information to aggregate, convert, link, store, and render data in various formats, we provide below a brief description of the platform.

6.1. OUTLINE OF THE PLATFORM

The data linkage platform currently under development is a system that collects data from various sources, including internal systems, external services, and cloud platforms, and stores it in an integrated data repository. Additionally, it has a function to convert data with different formats and protocols into an interoperable format so that it can be uniformly processed by the platform. This ensures data consistency while minimizing the load on resources even when processing large volumes of data, enabling effective data utilization.

To minimize vendor dependency, the system uses FIWARE, a globally renowned open-source software (OSS) product commonly used as an “Urban OS”, as its core component. Furthermore, it is structured by combining microservices that provide various functions, such as linking applications used in the construction sector, utilizing data via APIs, authentication and authorization, and storage. The data linkage platform leverages AWS, offering high availability and scalability (Fig. 11).

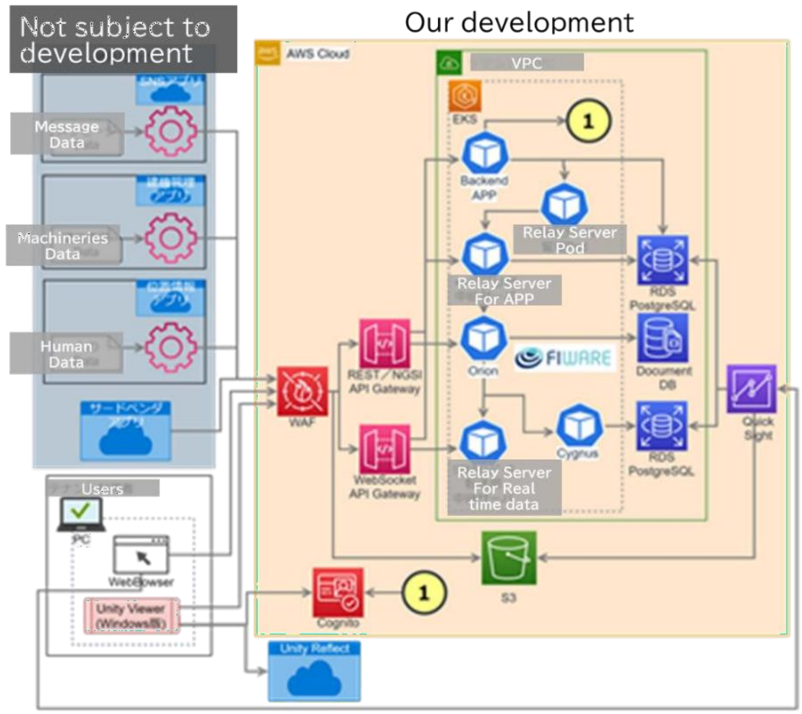

Fig. 11 Data Platform Configuration of the System

6.2. DATA STRUCTURE USED IN CORE PART

This system utilizes FIWARE and NGSI as the data structure for linking applications in the core part of the data linkage platform. NGSI is an open international standard for network APIs, originally developed in Japan. It was standardized by the Open Mobile Alliance in 2010 and has been continuously updated since then. NGSI serves as an interface for linking data between different applications. The data model mainly consists of "entities" and "contexts," which are standardized data (attributes and metadata) representing the essential attributes of objects. This format ensures data interoperability and generality between different applications. Fig. 12 shows an example of a data model in NGSI format. This system uses the stable version NGSI-v24.

Additionally, this system provides APIs for master data managed in an Relational data base (RDB), which is not intended for application linkage, as well as for historical data used in Business Intelligence (BI) analysis and their combined view definitions. Almost all data operations—registration, retrieval, updating, and deletion—can be performed via the APIs. Moreover, both the NGSI API and the above-mentioned API are designed with flexible authentication and authorization settings. All necessary APIs for data linkage are planned to be made available to application vendors, so it is expected that application vendors will develop their own data linkage and utilization solutions in the future.

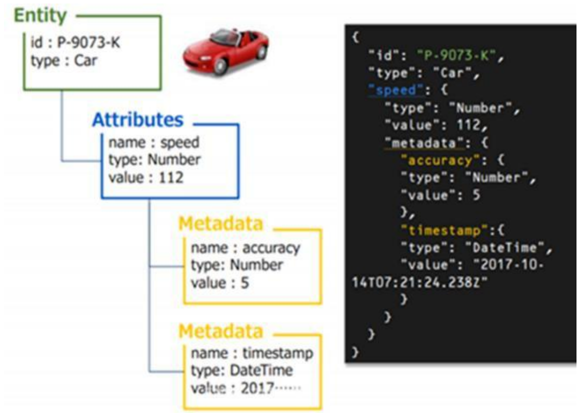

Fig. 12 Example of Data Model in NGSI Format

7. SUMMARY AND FUTURE DEVELOPMENTS

CONNECTIA adopts a hybrid system configuration, using the cloud for data management and a native application for rendering. Through the use of game engine-specific rendering processes, it effectively resolves hardware challenges. Additionally, by focusing on UI/UX development, it addresses software challenges, lowering the barriers to adoption. As a result, 71% of trial sites indicated that they expect a reduction of 10 hours/person/month or more in the near future, thanks to the implementation and improvement of functions specialized for various construction management tasks. We see CONNECTIA as one of the solutions to various issues such as labor shortages due to a declining and aging workforce, long working hours, and difficult working conditions. Moving forward, we will continue to explore on-site needs, identify and implement highly useful functions, strengthen the data linkage function with the goal of creating a CDE, systematize the operation of the app, and build an organizational structure to further promote its use.

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