Distribution and Utilization of Three-dimensional Life-cycle Information on Civil Infrastructure in Japan

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***Abstract*—To promote innovation in public works, an environment is needed where three-dimensional (3D) information on civil infrastructure can be used efficiently and smoothly throughout the life cycle of projects. In Japan, 3D information is not often used on civil infrastructure construction projects. In this paper, schemes are investigated for the distribution and utilization of 3D information in accordance with international organization for standardization (ISO) standards and were produced by using 3D computer-aided design (CAD) software based on the concept of product data models. First, the existing literature is classified by work stage to provide context for utilizing 3D information. Next, the paper discusses the necessary steps and areas of future research to promote the utilization of 3D information, including the establishment of standards for exchanging 3D information, modifying relevant systems, constructing road data models, creating work process models, developing 3D CAD engines, and providing 3D information utilization environments. Finally, the potential for utilizing 3D information in road construction projects by local government and small- and medium-sized businesses is examined, and the steps to be implemented for this purpose are summarized.**

***Index Terms*—Civil infrastructure, information management, three-dimensional information, product data model.**

I. Introduction

To promote innovation in public works through the use of information and communication technology, an environment should be provided in which three-dimensional (3D) information on structures can be used efficiently and smoothly throughout the life cycle of projects. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism has established the continuous acquisition and life-cycle support/electronic commerce (CALS/EC) Action Program 2008 [1], which advocates the development of a utilization environment for 3D information. Presently, two-dimensional drawing data are used in the design and construction stages, whereas the use of 3D information has only just started. In addition, the use of electronic data in civil infrastructure construction projects has not been optimized and efforts have not yet been undertaken from the viewpoint of total optimization in the life cycle of projects. Therefore, it is necessary to identify and define specific work procedures where distributing and utilizing 3D information is beneficial and uses with clear downstream process improvements such as data input into quantity calculation software. Furthermore, work processes should be designed based on these uses, and if necessary, systems should also be created and exchange standards developed.

The objectives of this research are to identify the schemes that are necessary to realize the distribution and utilization of 3D information in the life cycle of civil infrastructure projects in Japan, and to provide work items for proceeding with the planned development of such a platform. The 3D information utilization platform considered in this research is an environment that could be used not only by the Ministry of Land, Infrastructure, Transport and Tourism, but also by local governments and medium- and small-sized private businesses. Development of a successful 3D utilization platform would achieve practical and specific results in the construction of public works projects. In this paper, 3D information is defined as being distributed in accordance with International Organization for Standardization (ISO) standards and produced using 3D computer-aided design (CAD) software based on the concept of product data models.

II. Use Cases of 3D Information

A. Requirements for 3D Information in Life Cycle of Projects

In order for 3D information to be used in the life cycle of civil infrastructure projects, the ability to exchange and share such information between different software, to design structures in spatially distributed environments, and to apply information integrated construction such as machine guidance, machine control, and progress control of working form are required. 3D information is used to enhance the productivity of public works and to improve the quality and speed of construction. Also, the need for 3D information in design, construction, and visualization of maintenance is growing. Fig. 1 shows the conversion from two-dimensional (2D) to 3D information. However, the industry has not been able to produce sufficient momentum to enable the truly widespread use of 3D information. Therefore, it is necessary to clarify the incentives and benefits for project participants associated with using 3D information, and to maintain the institution and project environment.

B. Use Cases by Work Stages

Building upon simple and useful cases of how practitioners have implemented technologies in past construction projects is vital for gaining momentum in the future [2]. In this paper, various use cases related to surveying, planning, designing, constructing, operating, and maintaining roads, bridges, tunnels, underground structures,

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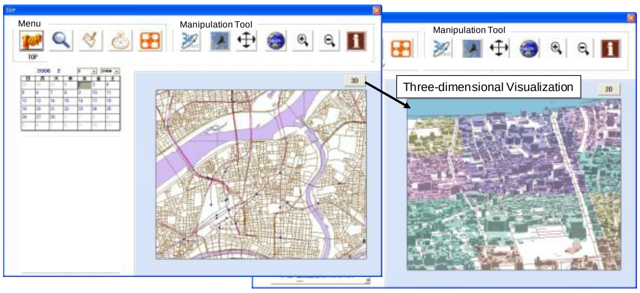

Fig. 1. Conversion from 2D to 3D information.

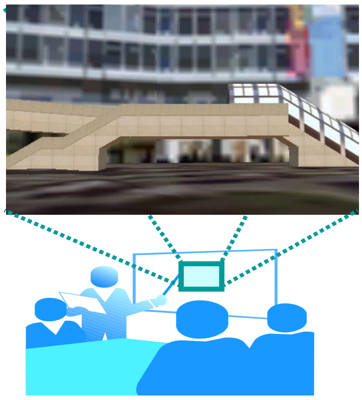

Fig. 2. Utilization of 3D information to explain projects to local residents.

rivers, planned urban areas, and landscapes are investigated from an examination of existing academic papers, reports, and Web pages.

1) Surveying Stage

3D surveying can be classified into aerial surveying and ground surveying. These technologies are used to collect 3D point group data and to construct 3D geometric shapes of civil infrastructure, smoothly and accurately.

2) Planning Stage

At the planning stage, 3D information is used to simulate costs, environmental impact, and disaster scenarios. Simulation examples are presented in [3, 4]. In these examples, 3D information is used for resident outreach, education, and public relations in general. Fig. 2 shows an example of 3D information used to explain a project to local residents.

3) Design Stage

At the design stage, 3D information is utilized in design using 3D CAD software. Examples include bridge design using a product data model [5], a collaboration and communication platform for stakeholder design/review meetings [6], and a virtual design and construction system [7]. In the future, 3D information will be used for planning routes and estimating supply quantities when designing roads and civil structures.

4) Construction Stage

In recent years, an increasing number of construction projects have adopted 3D or four-dimensional (4D) models to support management tasks [8]. 3D information is used as an observational method and as a model for distributing product data from design to manufacturing and information integrated construction with machine guidance, machine control, and progress control of working form. Systems that have been developed include Web-based 4D construction visualization in collaborative construction planning and scheduling [9], component-based integrated project management systems [10], a distributed collaborative 4D-based construction planning environment [11], interactive 3D CAD to control derrick crane operations [12], construction work control systems that consider temporal information [13], construction site image-processing software using 3D CAD [14], 3D graphics of underground infrastructure for augmenting site photos [15], and facility life-cycle management using 3D and 4D CAD [16]. Reference [9] note that visual presentation of the construction sequence is expected to help industry practitioners better understand the project schedule. 3D models help to determine overall site management strategies during the construction phase, the coordination of contractors, the planning of site logistics and access routing, and the timing of transferring completed parts of a facility between subcontractors [2]. In the future, to promote information integrated construction, 3D models and information generated at the design stage will be distributed at the construction stage.

5) Operation and Maintenance Stage

Few examples exist in the literature of 3D information being used at the operation and maintenance stage. Reference [17], present the utilization of information through the life cycle of civil infrastructure by analyzing construction projects. The few systems that have been developed include a virtual reality system for use in routine bridge inspection [18] and a 4D information management system for road maintenance [19]. Fig. 3 shows example simulation results in a road operation and maintenance system. Road administrators can manage the repair plan along a project timeline. Civil infrastructure construction project participants are thus able to share the simulated results of the construction.

In the future, 3D information is expected to be used for visualization of public utilities' infrastructure buried beneath roads, observation using 3D sensing technology, road maintenance management, and 3D simulation. Utility industries can visualize gas and water supplies, and sewage lines, and can manage the condition of underground pipelines using 3D CAD and 3D information.

TABLE I: WORK ITEMS FOR USING 3D INFORMATION

Work Item	Contents and specifications
Establishment of standards for exchanging 3D information	Standards for exchanging 3D information based on ISO Specifications for producing 3D information
Revising relevant systems	Revising common specifications in design work Revising control criteria in civil engineering work and construction
Designing work process models	Constructing future work process models Evaluation and spread of work process models
Providing a 3D information utilization platform	Development of viewer for 3D information Dissemination to local governments
Construction of a civil infrastructure data model	Civil infrastructure data model (CiDM) with definition of attributes
Development of 3D CAD engine	3D CAD engine Domain-specific 3D CAD software

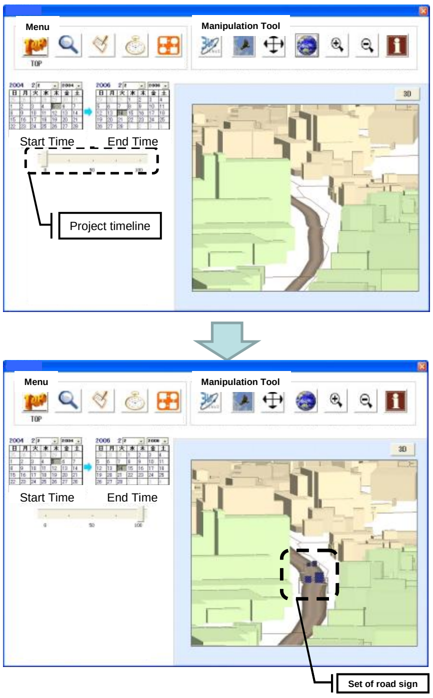

Fig. 3. Simulation results using 3D information.

III. Policy Issues and Research Topics for the Distribution and Utilization of 3D Information

A. Policy Issues

In this section, policy issues and research topics for the distribution and utilization of 3D information during the civil infrastructure life cycle are proposed. A summary of these issues and topics are listed in Table I. Based on this list, necessary work items are clarified to create a distribution and utilization platform for 3D information.

1) Establishment of Standards for Exchanging 3D Information

3D information to be exchanged and shared between different software platforms and between project participants should be standardized based on international de jure standards, since interoperability and compatibility are important in developing a platform for sharing civil infrastructure information. Therefore, when defining the rules of information exchange and sharing, using existing standards and specifications is useful. This paper proposes the use of business process standards, information infrastructure standards, and information sharing standards for defining 3D information.

Business process standards are standards that relate to business processes and to the management and creation of information shared between companies and government agencies. These standards involve business processes, quality management, and project management.

Information infrastructure standards relate to the system infrastructure for exchanging and sharing information. These standards include infrastructure requirements for middleware and platforms, operating systems, security, databases, communication networks, and information exchange media.

Information sharing standards concern information to be exchanged and shared between companies and government agencies. These standards include requirements for information sharing systems and middleware, document structure, application system data, text data, and drawings.

In Japan, the SCADEC exchange format—a 2D CAD data exchange format—is standardized through ISO10303 Part 202 [20] (also known as the "standard for the exchange of product model data") developed by the ISO. However, 3D information falls outside the scope of this Japanese construction for CAD data exchange. Instead, ISO 10303 Part 203 standardizes the exchanging and sharing of 3D information [21].

2) Revising Relevant Systems

In this section, by targeting common specifications in design work and control criteria in civil engineering and construction, existing issues are identified and solutions are proposed for the relevant systems. 3D design drawings must continue to utilize 3D information. In common design work specifications, no rules exist for making drawings. Standards are thus required not only to make drawings to particular specifications, but also to define which 3D drawings should adhere to these specifications. In addition, drawing data should be exchanged based on 3D information exchange standards.

Automated quantity calculation is an effective use of 3D information. However, a definition is necessary of the 3D information generated using 3D CAD that can be used for quality calculations in a control criterion in civil engineering work and construction.

3) Designing Work Process Models

It is important to explore ways to integrate the exchange of 3D-model-based information into the work and business processes of the construction industry [2]. Processes should be created as future work process models for total optimization based on the system architecture fully optimized in the life cycle. A work process model that employs 3D information and future work processes has previous been constructed [22], [23]. Activity diagrams generated in unified modeling language (UML) were used to construct this model, and the work processes that should be transformed as a result of 3D information were identified [22], [23]. These work processes were modeled as a "utilization scenario" by analyzing road maintenance flow. To create the model, the temporal information flows were constructed using a UML sequence diagram.

4) Providing a 3D Information Utilization Platform

To provide a 3D information utilization platform, development of a viewer for 3D information, training for 3D CAD software operators, and dissemination to local government (as discussed in Section IV) are required. A 3D information viewer displays both 3D geometric models and attributes generated by 3D CAD for easy understanding. In Japan, few 3D CAD operators are currently found in civil infrastructure projects. Therefore, students majoring in civil engineering at universities should study 3D CAD operation and learn to generate 3D models and information.

B. Research Topics

1) Constructing a Product Data Model

A wide variety of construction projects, for example, those for roads, buildings, and rivers, generate information on geometric shape and attitude [24]. In civil infrastructure

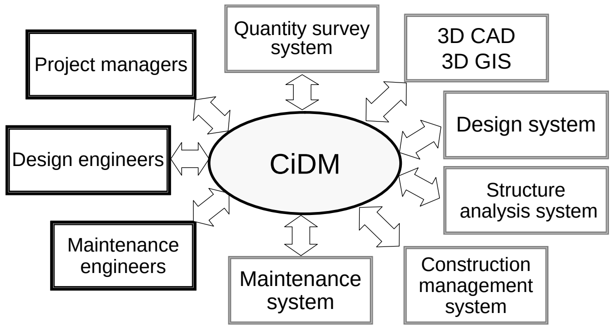

Fig. 4. Interoperability of life-cycle information through CiDM.

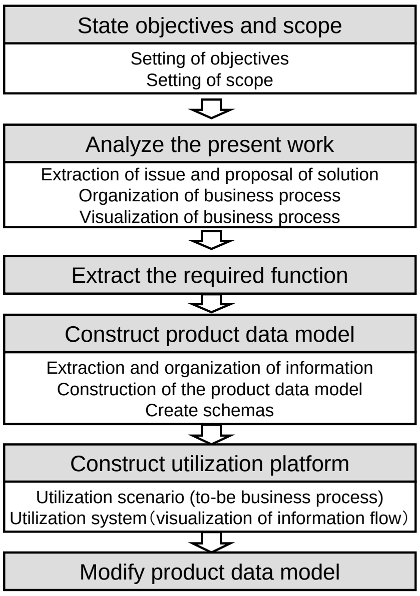

Fig. 5. Construction method of CiDM.

construction projects, generated information should be exchanged and shared between project participants on an ongoing basis. In standardizing 3D information, a product data model must be constructed to define and organize the life-cycle information. In this paper, product data models of civil infrastructure are referred to as the “civil infrastructure data model” (CiDM). Project participants, stakeholders, and computer software can share and utilize the standardized information by using CiDM, as shown in Fig. 4. A product data model is defined by its method of representing the product and shape information over the life cycle of structures. A product data model contains the product’s attributes from documents, CAD data, drawings, design calculations, and other resources so that construction project participants can access this information.

Product data models for civil infrastructure are made by various organizations and research institutions [25]-[31]. However, if the same information is stored in accordance with different data models, this could lead to problems with information compatibility in the future. Data models that have already been constructed by various methods are difficult to standardize into a uniform format. Therefore, according to the objectives of the various types of civil infrastructure, standardization of the functions that must be fulfilled by the data models, and the types and items of information to be maintained can be considered. The proposed method for standardizing the functions required to be fulfilled by CiDM is shown in Fig. 5, in addition to the

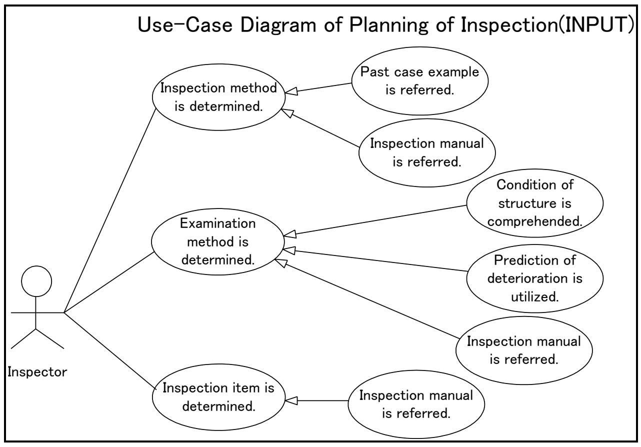

Fig. 6. Use case diagram of required function.

types and items of information to be maintained. This method was developed after a survey and analysis of existing methods for constructing product data models, under the assumption that the models will be applied to all types of civil infrastructure. The method of developing product data models is as follows.

1) State objectives and scope: Set the objective for constructing the data model. Establish the scope of work to be analyzed, and any points to be emphasized, such as the reduction of work or the utilization of information in downstream processes. Clearly identify the target users, such as managers and contractors. With respect to the objectives, identify problem points and devise measures to solve them. Establish an analysis method of modeling in order to arrange the methods that use the relevant work processes and information. Support tools for analyzing or re-constructing the present status of work include the integrated DEFinition method (IDEF), EXPRESS-G (ISO10303: Industrial automation systems and integration—Product data representation and exchange), and UML.
2) Analyze the present work: Identify the scope of the activities, the responsibilities of the organizations or managers of the system, and the arrangement of the work items. Arrange the workflow to encompass the work items, and visualize the flow using the established analysis method.
3) Extract the required functions: Extract the required functions based on the perspectives of those engaged in this type of work. An example of a use case diagram for required functions in inspection planning is shown in Fig. 6.
4) Construct the product data model: Extract information of high importance based on the analysis of work processes. Arrange the information according to the determined analysis model, and construct the data models. Verify the attributes of the created product data models and the relationships between product data models. Fig. 7 shows the conceptualization of a product data model for roads and bridges, and Fig. 8 provides an example of a completed product data model for roads and bridges. The model consists of structural and work information that describes the project using class diagrams.
5) Construct a utilization platform: Construct future business processes as a utilization scenario of the

product data model and visualize information flow as a utilization system.

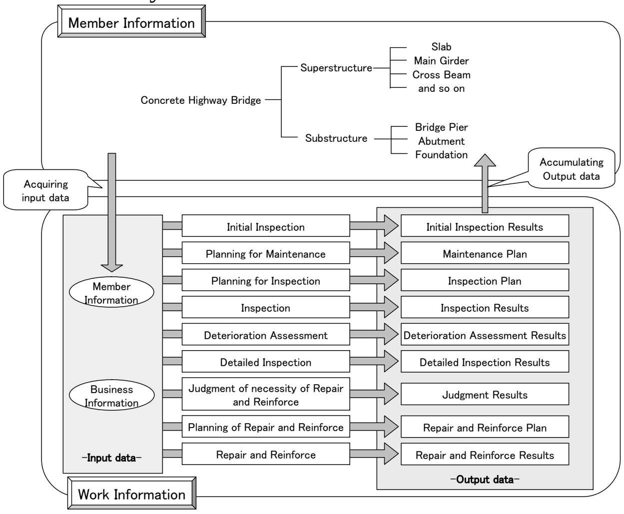

Fig. 7. Conceptualization of a product data model for roads and bridges.

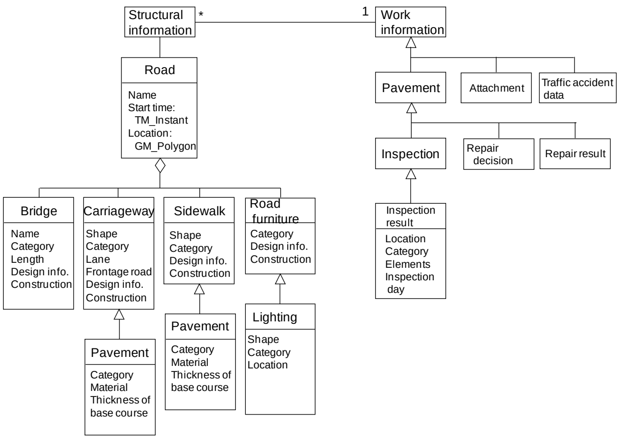

Fig. 8. Example of a product data model for roads and bridges.

6) Modify the product data model: Set the objectives for creating schemas and determine the encoding method. Create schemas in accordance with the determined encoding method. Verify whether the created schemas can be used in accordance with the objectives. Use extensible markup language (XML) or EXPRESS (ISO10303) to create the schemas. The constructed XML data of objects can be exchanged between any systems. Modify the data models as necessary to improve or amend them in response to changes or additional information.

Meanwhile, building information modeling (BIM), a 3D object-oriented CAD technique, is among the most promising developments in the architecture, engineering, and construction (A/E/C) industries [32]. BIM covers geometry, spatial relationships, geographic information, and building component quantities and properties. With BIM technology, an accurate virtual model of a structure is constructed digitally. This technique is effective for building an environment where various types of construction enterprise information are used in an integrated manner [33]. The product data model is similar to BIM, as both have data on geometry, spatial relationships, and attributes.

2) Developing 3D CAD Engine

There are no domestically produced 3D CAD engines in Japan. For realizing such a 3D CAD engine, both a 3D CAD engine and domain-specific 3D CAD software will be developed. Reference [34] suggest that the construction industry needs a tool that can generate, manipulate, and link

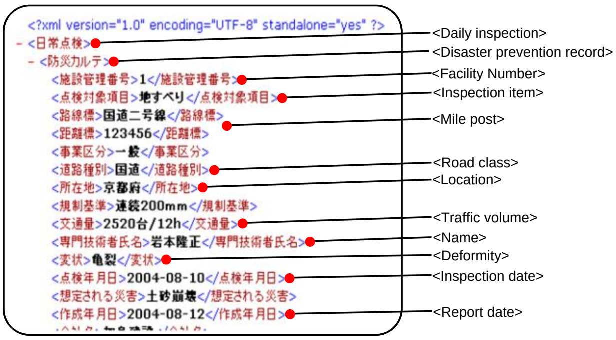

Fig. 9. Example of XML data (in Japanese).

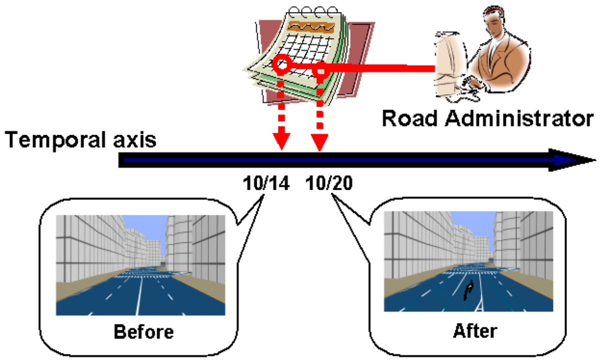

Fig. 10. Simulation of 3D information along temporal axis.

schedules and 3D components in a single environment. Despite much research having been conducted, 4D CAD technology is not commonly used in the construction industry anywhere in the world [35]. These tools are somewhat difficult to use and the visualization they provide is not easily customizable. These tools are based on object-oriented concepts and are used primarily for planning, design, and appraisal types of analyses [36]. Furthermore, 4D CAD models have a single level of detail that hinders collaboration among general contractors and subcontractors. Fig. 10 shows a simulation of a 3D geometry model using the temporal sequence for road maintenance. Considering past case studies, 3D CAD software should have the following functions: generating 3D geography data; inputting 3D geography data and verifying particular data attributes; generating 3D simulation data using 3D geography and design data; conducting longitudinal design and calculations of earth volume using 3D geography and design data; and outputting machine control data using 3D design data.

IV. Utilization of 3D Information in Local Government

The 3D information distribution and utilization platform considered in this research is an environment that could be used not only by the Ministry of Land, Infrastructure, Transport and Tourism, but also by local governments and medium- and small-sized businesses. In Japan, it is difficult to use 3D information in the product data models and the business process models used by local governments and small- and medium-sized businesses. The feasibility of local government and construction companies applying 3D data was investigated in Iwate Prefecture. Awareness of the ability to submit deliverables in electronic form is not high among some local governments, so implementing work processes using 3D information in construction projects would still seem to be difficult. Therefore, the merits of using 3D information should be widely communicated. I propose a revolution for utilizing 3D information in three areas: people—users should have literacy of 3D and engineer-generated 3D models in 3D CAD; Systems and rules—data exchange standards and quantity calculation standards are required; and software—3D CAD engine and domain 3D CAD software are necessary.

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