Methods for Simulating Crane-deployment Plans used in Construction of Nuclear Power Plants

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ABSTRACT

To construct nuclear power plants no later than delivery dates for certain, Hitachi adopts the "open-top construction method." This method requires civil and mechanical installation works to be carried out concurrently. Therefore, civil and mechanical contractors must share cranes for carrying in materials such as rebar, piping components, and equipment. First, civil contractors make crane-deployment plans, which consist of crane locations, load capacities, and its operation schedule. Since it is difficult to estimate quantities of installation material exactly in an early construction-planning phase (in which the detailed design is not completed), plans are made on the basis of the planner's experiences, not quantitative evaluations. Due to such undefined conditions, it is often the case that actual utilization rates of cranes are larger than expected. To resolve this issue, scheduling extra day- and night-work shifts and increasing the number of cranes are typical solutions.

A simulation system for quantitatively evaluating the validity of crane-deployment plans was developed. It applies 4D simulation technology, integrating 3D models and a time dimension, to calculate utilization rates of cranes. To calculate utilization rates automatically and accurately, two functions were developed. The first function maps data between 3D objects and carry-in tasks by using a method called "fast geometric interference checking." The second one estimates installation material quantities in early construction-planning phases by using a statistical method called "random forests," which infers data from the results of previous projects. The result of verification tests based on previous construction data indicates that the proposed simulation system will significantly reduce the time required to create crane-deployment plans and improve their accuracies.

Keywords - Nuclear power plant; Construction; Crane deployment; Crane utilization; 3D-CAD; 4D-CAD; Interference check; Random forests

1 Introduction

A nuclear power plant (NPP) is composed of a lot of facilities classified into categories such as mechanical, electrical, and HVAC (heating, ventilating, and air conditioning). For example, the number of pieces of equipment reaches several thousand, and the total length of piping components reaches one-hundred-thousand kilometers. These facilities are complicatedly arranged in several-hundred areas surrounded by thick concrete walls. Therefore, as a project, constructing a NPP is so large that it needs several years and billions of dollars to complete, and any delay to the project causes a huge loss.

Hitachi adopts the "open-top method" of constructing a NPP [1][2]. As for this method, activities involved in constructing buildings and installing facilities are carried out concurrently at the construction site of a NPP. Although this method can reduce the construction period, it requires cranes to be shared between companies in charge of the two types of activities, namely, building frame work and equipment work. Therefore, properly drawing up plans for deployment of cranes, which contain the number of cranes, their locations, and a schedule to use them, is vital in regard to preventing delays of construction projects.

In terms of efficiency, the quality of plans for deploying cranes depends on a planner's know-how based on their experience. If the demands for cranes exceed the cranes' capacities, and delays are forecast, additional cranes must be deployed and overtime work must be scheduled. These measures, naturally, increase costs. To solve this problem, it is necessary to develop a system that can create robust plans without the need for skillful planners on the basis of rules extracted from previous statistics concerning construction data.

One of the ways to evaluate crane-deployment plans quantitatively is to estimate the utilization rates of cranes. It requires determining which cranes are assigned to each material. However, it is a problem that the number of materials used in constructing a NPP is too large to determine the assignments of cranes manually. Additionally, it is also a problem that the quantities of materials required and the number of facilities to be built is uncertain when a crane-deployment plan is created. This is because engineering of a NPP is not complete at that time owing to the concurrency between engineering and construction planning.

Researching methods for creating accurate crane-deployment plans effectively, Huang C. et al. have developed a planning method (which applies a mixed-integer linear-programming technique) for automatically creating deployment plans for tower cranes [3], and Lien L. C. et al. have developed a method that applies the "particle bee algorithm" [4]. These methods have been developed for planning construction of general buildings; therefore, if they are applied to construction planning of NPPs, linking materials to cranes requires a lot of time, and uncertainty of quantities of materials remains a problem. Additionally, it seems difficult to use these methods for interactive planning between a human and a computer because their aim is to create plans automatically.

On the other hand, 4D simulation technology has been applied to construction project for validating plans (such as construction schedules) instinctively has been researched extensively [5][6][7][8]. As a result of these researches, 4D simulation has become so prevalent that 3D CAD software includes a function for it. These researches applied 4D simulation technology mainly to visualization of plans; however, recently, Kang L. S. et al. developed a 4D-technology-based system for evaluating and visualizing risks involved in a construction project [9].

In this study, an efficient simulation system for evaluating and visualizing the validity of crane-deployment plans—on the basis of 4D simulation technology and a statistical method—was developed and tested.

2 Planning of crane deployment

2.1 Crane deployment

For constructing facilities in buildings in a NPP efficiently, it is important to deploy cranes properly. Two types of cranes are deployed during construction of a NPP: a tower type (which moves up and down while fixed in a stationary position) and a crawler type (which moves up and down and can move along the ground by caterpillars). As shown in Figure 1, the area in which a crane can operate ("operating area" hereafter) is modelled as a cylinder with radius equal to the operating radius of the crane. As shown in Figure 2, all materials and facilities must be covered by the operating areas of cranes. The number of cranes is also a key consideration. If it is too low, the utilization rates of the cranes will exceed their capacities. On the other hand, an excessive number of cranes incurs large costs and may cause physical interference between operating cranes. Additionally, the load limits of cranes must also be considered.

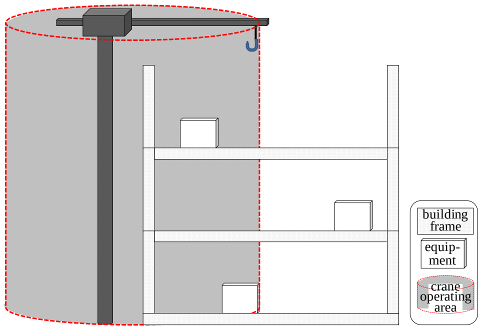

Figure 1: Image of an area in which a crane operates

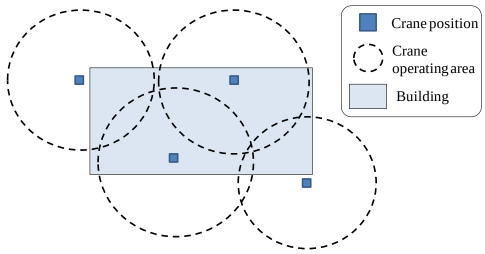

Figure 2: Image of a deployment of cranes

2.2 Carry-in schedule

A sequence of building frame work and equipment work, especially for carrying equipment and piping components in buildings, is shown in Figure 3 and Figure 4. In steps (1) and (2), floors and walls of areas are constructed. In step (3), facilities such as equipment and piping components are carried into those areas from above by cranes. In step (4), the ceilings are constructed. After step (4), the facilities are installed in those areas. The main reason for this sequence is that large facilities cannot be carried into areas through delivery entrances of the building after the ceilings of the areas are added. Although this sequence of building works and mechanical and electrical works in an area are conducted in series, such works in several areas are conducted concurrently.

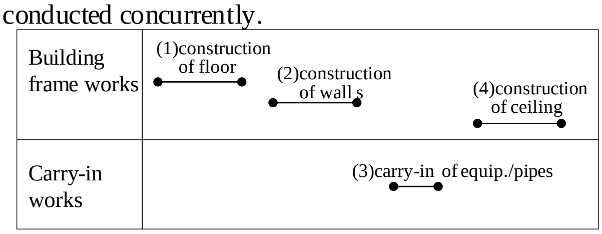

Figure 3: Construction steps performed in an area

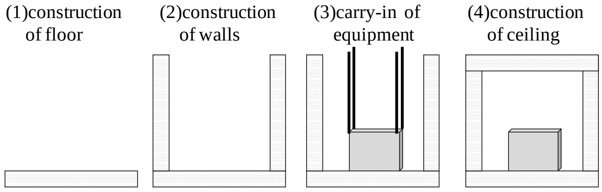

Figure 4: Image of construction sequences performed in an area

Materials and facilities to be carried into an area include structures, rebar, molds, and scaffolding as building works and equipment, piping components, operating platforms, metal components and fixtures to be installed, and scaffolding as mechanical and electrical works. Each activity in a work schedule has attributes to specify details such as building name, floor name, names of NPP systems, and drawing number. These attributes make it possible to relate activities to 3D objects. For example, as shown in Figure 5, it is supposed that activities take the same names as the areas in which each activity is conducted and that 3D objects take the same names as the areas in which they are placed. It is thus possible to create mapping between activities and 3D objects according to the area names that they have as attributes. However, it takes a lot of time to complete such mapping because the number of activities and 3D objects is huge.

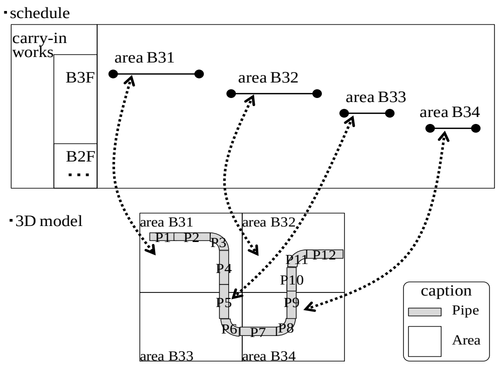

Figure 5: Mapping activities to 3D objects

2.3 Crane assignment

The number of cranes is limited by the space available in a construction site and by the delivery and operational costs of the cranes. Companies in charge of building works and mechanical and electrical works must therefore share cranes.

Operating areas of cranes must overlap as much as they can so that the dependency of each crane decreases and risks of delay can be reduced.

To calculate utilization rates of cranes, it is necessary to assign a crane to each 3D object. Figure 6 shows an example of the assignments. Pipe 1 can be carried by crane 1, and pipe 3 can be carried by crane 2. On the other hand, pipe 2 can be carried by both cranes 1 and 2. Therefore, pipe 2 must be assigned to either crane 1 or crane 2. However, these assignments also take a lot of time when they are conducted manually, because the number of 3D objects is extremely large.

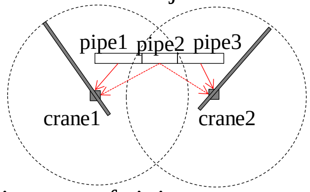

Figure 6: Assignment of piping components to cranes

2.4 Quantity of piping components

When utilization rate of a crane is calculated, the quantities of materials and facilities to be carried in are uncertain because detailed design of a NPP is not complete at that time due to the concurrency between design and construction planning. Figure 7 shows an example about piping components. The left side of the figure shows the pipe objects before engineering of spools is conducted. The right side shows the ones after spool engineering has been completed.

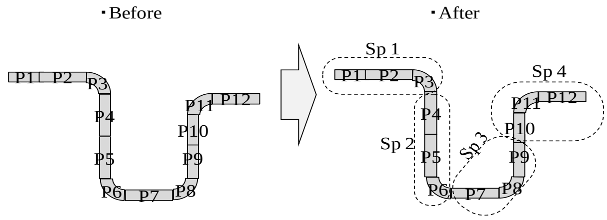

Figure 7: Image of pipe objects and spool objects

Quantities have been predicted on the basis of ones in a reference plant and the differences between the sizes of buildings (such as number of floors and floor space) in the current plant being constructed and the reference one. This method can precisely predict quantities when they are calculated in floor units. However, the prediction accuracy gets worse when quantities are predicted in more detailed units such as area. This is a problem in regard to predicting utilization rates of cranes because a crane operating area is smaller than the floor space.

3 System for simulating crane deployment

The purpose of this system is to improve the quality of crane-deployment plans. To solve the aforementioned problems, 4D simulation technology and a statistical method, called "random forests," is applied in the developed crane-deployment simulation system. The functions of the system are described as follows.

The first function maps data between 3D objects, carry-in tasks, and cranes by using a method called "fast geometric interference checking.” The calculation time is a significant problem described as following subsection. The second one estimates quantities of installation materials in the early phases of construction planning by using a statistical method, called “random forests,” which infers data from the results of previous projects.

3.1 System configuration

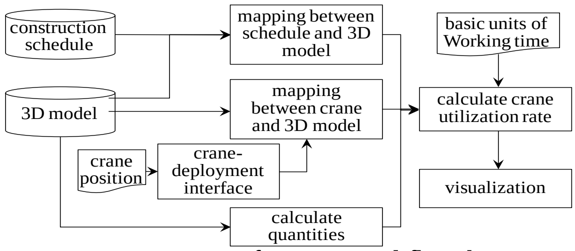

Figure 8: System configuration and flowchart

The configuration of the developed system is shown in Figure 8. The data input into the system include a construction schedule, a 3D model, crane position, and basic units of working time. The construction-schedule data includes name, start date, finish date, and attributes for specifying the details of the work (such as working area). The 3D model includes at least building frames, large equipment, and large diameter pipes (even if they have not been split in spools). The 3D-object data include parameters of shapes and attributes such as system name, drawing number, and weight. The crane-position data includes the coordinates of points at which cranes are deployed.

The function called “mapping between schedule and 3D model” connects activities and 3D objects by matching their attributes. The function called “mapping between crane and 3D model” connects cranes and 3D objects that they can carry into buildings.

The function called “calculate quantities” predicts and calculates quantities of concretes, rebar, equipment, and piping components on the basis of the 3D model and data from previous projects. The function called “calculate crane utilization rate” predict utilization rates of cranes, and the function called “visualization” visualizes the predicted utilization rates in the form of 2D or 3D graphs. Utilization rate means operating times of cranes in a particular period in units of months or weeks. It is calculated from “basic units of operating time,” which means the operating time taken by a crane to carry one of materials or facilities into a building. These values are defined for each kind of material and facility.

3.2 Crane-deployment interface

This system has an interface that enables users to deploy cranes on a 3D model easily. An image of the interface is shown in Figure 9. Users can add and delete cranes with their name and specs (such as operating radius) and modify their positions and specs. Cranes can be deployed one by one manually using this interface or automatically using an input function for text data (whose format is shown in Table 1). As for the 3D models of cranes, some templates have been created and will be attached to the 3D model of a NPP at each position of the cranes.

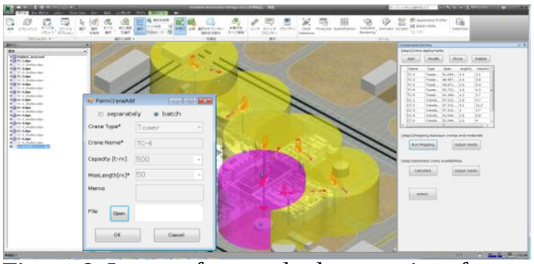

Figure 9: Image of crane-deployment interface

Table 1: Data format for crane deployment

Crane name	X (m)	Y (m)	Z (m)	Max radius (m)	Spec (t・m)
TC-1	-45	2	0	60	900
TC-2	-15	-20	0	50	400
TC-3	30	100	0	55	450

3.3 Mapping between cranes and 3D objects

To determine which 3D objects are located within the operating area of each crane, interference-checking functions, provided by commercial 3D-CAD software, can be used. For example, operating areas of cranes can be modelled as cylinders, and interference checking between the cylinders and the 3D objects composing a NPP can be performed. However, this checking takes a long time to calculate possibility of interferences. This is because the interference-checking function considers precisely detailed shapes of 3D objects. This calculation time is a significant problem when several deployment plans must be evaluated. Therefore, a fast interference-checking method using an “axis-aligned bounding box” (AABB) was developed.

An image of an interference check between 3D objects in a crane operating area and piping components is shown in Figure 10.

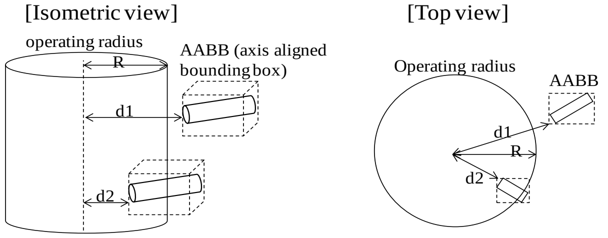

Figure 10: Image of interference checking using an axis-aligned bounding box

When the distances between the center axis of a cylinder and the intersection points of the edges of the AABB are smaller than the crane radius, the 3D object and the crane are considered to be interfering.

$$\min_{k \in E_i} d_k < R \qquad (1)$$

E_i : set of intersection points between edges of AABB for object i

d_k : distance between center axis of a cylinder and an intersenction point k in E_i

3.4 Mapping between schedule and 3D model

To link activities of construction schedules with 3D objects, the matching of their attributes can be used. For example, they can be linked on the basis of matching names of areas in which activities are performed with names of areas in which 3D objects are located.

Additionally, a function for attaching an attribute such as an area name on the basis of simple input data, in the case that 3D objects have not been given an attribute, was developed. The input data is a text data in which area names are manually assigned to each voxel separated by baselines of a building. Then, the voxels with their area names are linked to 3D objects by a fast interference check using AABB. As a result, each 3D object is given the area name where it is located.

3.5 Quantity of 3D objects to be carried in

It is often the case that 3D objects and quantities cannot be linked easily because of a lack of attributes for construction works due to uncompleted detailed design of a NPP. As for piping components, before detailed design involving welding points and piping spools are completed, it is impossible to count the number of spools, which is equivalent to the quantity of piping components to be carried into buildings. In this case, it is necessary to predict the number of spools on the basis of the length of the piping objects, which have not been spools, and other attributes such as radius. This prediction method is described in detail in the next section.

As for equipment, the quantities are counted on the basis of attributes such as equipment ID, names of parts of equipment, and volumes of 3D objects composing equipment. As for materials for building works (such as rebar), their quantities are predicted on the basis of the space and volume of objects composing building frames.

3.6 Prediction of quantity of piping spools

The statistical method for predicting quantities of piping spools that are not grouped by spools is described in detail as follows.

The input parameters for this method are length of the piping object, length of the piping line to which the pipe object belongs, pipe radius, type of building in which it is located, the name of the NPP system that it belongs to, and number of bends in the piping line. The output parameter is average length of spools in a piping line. To determine the quantity of a pipe object, the actual length of the object is divided by the predicted average length of spools. "Random forests" (RF) [9] is applied for determining the relationship between the input parameters and the output parameters. RF is an "ensemble learning technique" that uses several learning algorithms as weak learners and merges their predictions to predict something accurately. It uses decision trees (or regression trees) as weak learners.

An image of a decision tree (regression tree) is shown in Figure 11. This technique classifies input data (training data) into multiple groups by using a tree structure. The root node of the tree holds all the training data. The child nodes of the root node are separated by the number of bends (which is one of the parameters of the training data). The thresholds using the separation are determined by an algorithm such as C4.5 and CART, which is based on entropy of information. Leaf nodes hold the distribution parameters such as a mean value and a variance of training data classified in each node. The decision tree allows both qualitative data and quantitative data.

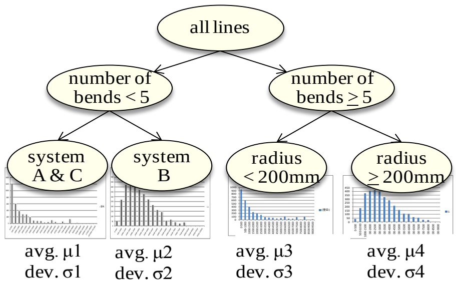

Figure 11: Example of a decision tree (regression tree)

Sequences of learning and prediction by RF are shown in Figure 12. First, bootstrap samples are created from learning data by random sampling with replacement. Second, decision trees are created from each bootstrap sample. In this step, RF does not necessarily use all the parameters that are used to classify learning data in nodes of a tree. That is, RF can randomly select parameters to be used when it creates a decision tree from each bootstrap sample. Finally, it merges the results of predictions by all decision trees (as weak learners) on the basis of accepting a majority or taking an average.

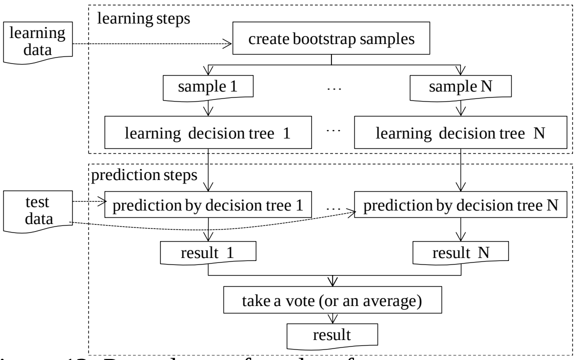

Figure 12: Procedures of random forests

3.7 Calculation of crane-utilization rate

To calculate utilization rates of cranes, the following data are used: schedule data, mapping data between schedules and 3D objects and between 3D objects and cranes, quantities to be carried into buildings, and basic units of operating time of cranes to carry each material and facility into buildings.

An image of the algorithm for calculating utilization rates is shown in Figure 13. In step1, the input data is united on the basis of object ID as a key. In step2, the carry-in quantity of each 3D object is equally assigned to cranes that are linked to the 3D object.

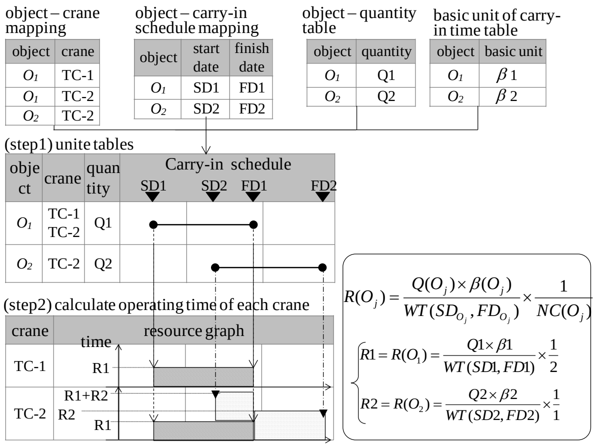

Figure 13: Image of the process for calculating operating times of cranes

The carry-in quantity of a 3D object, "Oj" hereafter, assigned to each crane, is defined as follows:

$$R(Oj) = \frac{Q(Oj) \times \beta(Oj)}{WT(SD_{Oj}, FD_{Oj})} \times \frac{1}{NC(Oj)} \quad (2)$$

where $Q(Oj)$: Carry-in quantity of Oj,
$\beta(Oj)$: Basic unit of time to carry a unit quantity of Oj,
SD_{Oj}: Start date of carrying Oj,
FD_{Oj}: Finish date to carrying Oj,
$WT(SD_{Oj}, FD_{Oj})$: Number of working days between SD_{Oj} and FD_{Oj},
$NC(Oj)$: Number of cranes that can carry Oj.

After the assignments of all 3D objects are completed, utilization rates are calculated from the sum of the quantities assigned to each crane.

3.8 Visualize utilization rate

This function is to visualize the utilization rates by graphs represented by 2D and 3D. 2D graphs of crane-utilization rates are shown in Figure 14. The horizontal axis means date, and the vertical axis means crane-utilization rates in units of [hours/day] and [hours/month]. In this figure, the two line graphs represent transitions of utilization rates of two cranes, called "TC-1" and "TC-2". This graph confirms the validity of the crane-deployment plan. If the peaks of utilization rates of cranes exceed the limits, the plan of crane deployment should be modified from the viewpoint of number of cranes, their positions, and carry-in schedules.

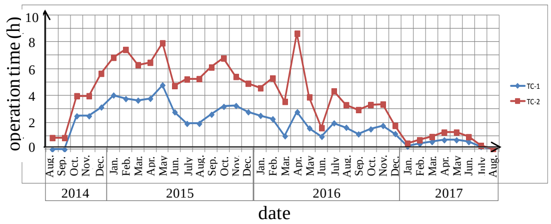

Figure 14: Graphs of operating times of cranes

To modify the position of a crane, a function for visualizing the utilization rates of the crane at several positions near the current one was develop. Bar charts representing utilization rates of a crane at several positions near the current one on the x-axis are shown in Figure 15. The *z*-axis represents the value of utilization rate. A value of "0" means the utilization rate at the current position. The *z* value is positive if the utilization rate is larger than that at the current position. The absolute value on the *z*-axis becomes larger in accord with the absolute value of the difference between a selected position and the current position.

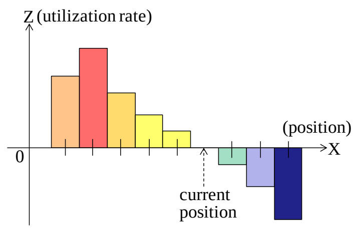

Figure 15: Bar graph showing operating times at each position of a crane

An actual visualization of this method is shown in Figure 16. The 3D objects of bar charts show utilization rates of a crane around its current position. This visualization helps to modify the position of a crane whose utilization rate is low (or high) to one where it will become higher (or lower).

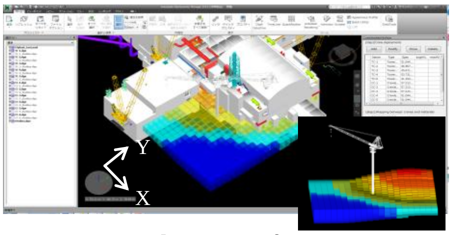

Figure 16: 3D visualization of operating times of a crane at several positions around the current one.

Additionally, if the range of positions is expanded to cover the whole site of a NPP, as shown in Figure 17, the visualization helps not only modification of crane positions but also initial planning of crane positions.

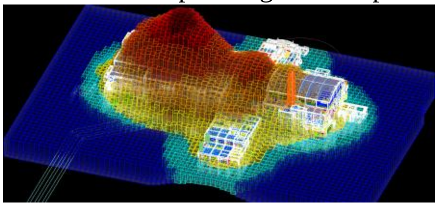
Figure 17: 3D visualization of operating times of a crane at the whole site of a NPP.

An image of the steps for determining deployments of cranes by using this visualization is shown in Figure 18. Step (1) shows a scene in which the position of crane "TC-1" is being considered by visualizing its utilization rates. Step (2) shows a scene in which the position of "TC-2" is being considered by visualizing its utilization rates after "TC-1" has been deployed. In this manner, the height of bar graph becomes lower around the positions of cranes that have been deployed.

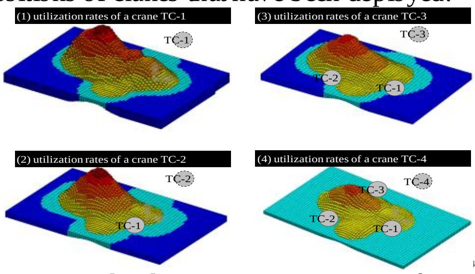

Figure 18: Graphs showing operating time of cranes

4 Experiments and discussion

The simulation system was developed as an add-on program for Navisworks (2014 Manage), and it was validated through computational experiments performed in the following environment: CPU: Intel Core i7-3930K 3.20 GHz; OS: Windows 7 Professional; and Graphics: NVIDIA Quadro 2000D. The targets quantitatively evaluated were the speed and accuracy of calculation by a function for mapping data between a crane and 3D objects and the accuracy of the function for predicting quantities of piping spools. Data of previous projects was used for the experiment.

4.1 Mapping between a crane and 3D objects

Calculation times of the function for mapping between a crane and 3D objects are listed in Table 2. In the table, times calculated by the native function for interference checking in Navisworks are compared with those obtained by the proposed method based on AABB. The proposed method reduces the calculation time from 527 s (by the native function) to 0.62 s.

Table 2: Calculation time of mapping

	Native function of Navisworks	Proposal method
Calculation time (s)	527	0.62

As for this result, considering the number of cranes in a NPP is between 10 and 15, it takes about 10 s to calculate the mapping for a crane-deployment plan by the proposed method. This is significantly quicker than the two hours taken by the native function. Based on this method and parallel computing (multi-thread programming), it takes about 25 min to create Figure 17 where the site was split at 5m intervals and the number of crane positions was about 10,000.

The evaluated accuracies of the mapping function are listed in Table 3. The accuracy was evaluated in terms of the difference between the mapping results calculated by the native function and the proposed method. Cover rate (CR) and wrong-detection rate (WDR) were determined from the following equations:

$$CR = \frac{A}{A+B} \quad (3)$$

$$WDR = \frac{C}{A+C} \quad (4)$$

Here, *A* is the number of common mapping results given by both the native function and the proposed method, *B* is the number of mapping results given by the native function excluding *A*, and *C* is the number of mapping results given by the proposed method excluding *A*. Note that larger CR is better, and smaller WDR is better.

Table 3: Accuracy of mapping

	Cover rate (%)	Wrong detection rate (%)
Equipment	99.1	0.11
Pipe	99.6	0.05
Building frame	99.8	0.22

As shown in Table 3, CRs were confirmed to be over 99% and WDRs were confirmed to be under 0.22% in the case of each method.

As for the influences of these errors, the error in operating time of each crane is calculated to be lower than 30 min/month, which is considered to be small enough to be ignored.

4.2 Prediction of quantities of piping spools

To validate the function for predicting quantities of piping spools, a previous project was used for learning data, and another one was used for test data. As for methods used, a method using average length of spools in a building, a method using average length of spools composing each NPP system, and the proposed method were experimentally compared.

Two types of results on accuracy of prediction of pipe quantities are listed in Table 4. The left column is the average error rate between total pipe quantities in each building in terms of actual ones and predicted ones. The error rate of the proposed method is 2.1%. The right column is the average error rate of a pipe quantity in each area. The error rate of the proposed method is 20.7%.

Table 4: Accuracy of prediction of pipe quantities

Method type	Average error rate for buildings (%)	Average error rate for areas (%)
Average length in each building	3.8	35.0
Average length in each NPP system	6.5	33.8
Proposed method	2.1	20.7

5 Conclusion

A simulation system for evaluating plans for deploying cranes was developed. It applies 4D simulation technology to calculate utilization rates of cranes. To calculate utilization rates automatically and effectively, two functions were developed. The first function maps data between 3D objects, cranes, and schedules by using a method called "axis-aligned bounding box." The second function estimates quantities of installation material required in the early construction-planning phases by using a statistical method called "random forests". The simulation system including these two functions was developed as an add-on program for "Navisworks" (produced by Autodesk). The two methods were confirmed to be effective by verification tests. According to the results of these tests, the calculation time of the first function for linking data between a crane and 3D objects in a NPP model was 0.62 s, compared with 527 s for the native function of Navisworks. As for the second function, the average error rate of a total quantity of piping spools in each building was 2.1%, compared with 3.8% by a method using average length of piping spools in each building (data of a previous project). The average error rate of a quantity in each area was 20.7%, compared with 35.0% by the method using average length. These results indicate that the proposed simulation system will significantly reduce the time required to create crane-deployment plans and improve their accuracies.

The company names and product names described in this paper are trademarks or registered trademarks of their respective companies.

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