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ORIGINAL ARTICLE

Algorithm development for the spool installation sequence of outfitting works in offshore structure

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Abstract
In the early 2000s, shipyards in South Korea were the most competitive in the world for commercial vessels because of their accumulated production and quality management capabilities. In the mid-2000s, the rising trend of international oil prices and predicted market growth of offshore structures caused large shipyards in South Korea to start focusing on the construction of offshore structures. However, these shipyards suffered massive losses because they did not properly reflect the characteristics of offshore structures, which differ from those of commercial vessels. Such losses can largely be classified into engineering losses and production losses. This study aimed to address problems related to outfitting installation work from a production perspective. An algorithm was developed to define an efficient spool installation sequence and was verified through actual data of offshore structure. The developed algorithm should make it possible to plan spool installation work by determining an efficient spool installation sequence. In addition, the algorithm can assist in prompt decision making and eliminate wasted cost and time by providing with an efficient spool installation sequence.

Keywords Spool · Installation sequence · Interference · Offshore structure

1 Introduction

Until the mid-2000s, South Korea's shipbuilding industry had maintained world-renowned competitiveness based on its excellent ship construction technology for commercial vessels [1]. According to the shipbroker Clarkson PLC, South Korea has consistently had seven or eight of the world's top 10 shipyards based on compensated gross tonnage (CGT) each year [2]. However, the global financial crisis in 2008 depressed the international shipbuilding industry. This led to huge business losses and large-scale personnel reduction. Amid this depression, the demand for offshore structures started to increase owing to the rise in international oil prices and depletion of land resources. Large shipyards in South Korea started to construct offshore structures instead of commercial vessels because of the growth of the Chinese shipbuilding industry and positive prospects for the offshore structure market. However, those shipyards suffered massive losses because they could not reflect the characteristics of offshore structures, which differ from those of commercial vessels [3].

The losses of several domestic shipyards because of the construction of offshore structures can be largely divided into engineering losses and production losses [4]. From an engineering perspective, those shipyards have world-renowned construction capabilities, but their design capabilities are still insufficient. This makes the shipyards increase in cost and delay delivery.

The production losses are related to proportion of outfitting installation work to the overall workload of offshore structures compared to commercial vessels. For commercial vessels, the proportion of outfitting workloads such as spools and electrical equipment is relatively low compared to those of structural workloads corresponding to the hull. However, offshore structures have a high proportion of outfitting installation work. They include 5–10 times more outfitting structures than a liquefied natural gas carrier (LNGC), which has many outfitting structures for gas loading and unloading compared to other commercial vessels. Therefore, most of the outfitting installation work cannot be completed in the pre-outfitting stage, and a high proportion of outfitting

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installation work is performed in the post-outfitting stage, while the vessel is moored at a quay [5]. Furthermore, the relations among outfitting materials are complicated because those must be installed in restricted spaces. However, because engineering algorithm for detailed outfitting plans is not yet available in most shipyards, most of the outfitting work of offshore structures is carried out by the experience of field workers. For this reason, reworking may occur, and these problems cause schedule delays and lead to massive financial [6].

For detail outfitting planning, the installation sequence of outfitting materials must be defined first. Therefore, the present study aimed to define the installation sequence of outfitting materials. First, an algorithm was developed to define the spool installation sequence. Only spools were considered because they make up the largest proportion among outfitting materials. The algorithm uses the attribute data of spools and a 3D design model to define the installation ranking and the precedence relations. The algorithm was verified by application to offshore structure spool data.

2 Research review

Research on the material installation sequence of the shipbuilding industry can be divided into structures and outfitting. Representative research on structures includes Hong et al. [7] creating an erection sequence for the planning stage and Seo [8] optimizing the block assembly sequence planning by considering welding deformation. Studies on structures have been and are continuing to be actively conducted. However, the importance of outfitting has started to emerge as demand for offshore structures has increased. Studies on outfitting are still in the early stage and insufficient.

Rose et al. [9] focused on establishing an optimal plan within limited resource. They utilized a heuristic algorithm to find the optimal solution, where variables such as the constraints between outfitting materials, installation finish date, number of workers, and setup time were set. Their study is significant in that they proposed a planning methodology that reflects the characteristics of the shipbuilding industry, which has limited resources with regard to workers and working space. However, their work was limited in that the installation sequence must be determined first based on information related to outfitting materials.

Yan and Nienhuis [10] focused on determining the installation sequence of outfitting materials and establishing outfitting planning based on information related to outfitting materials. They used the attribute data of various outfitting materials to determine the installation sequence of outfitting materials. In addition, they proposed a methodology for outfitting planning based on installation constraints associated with the working space. Their study is significant in that they proposed a methodology to define the efficient installation sequence of outfitting materials. However, plans are established by grouping works that can be performed at the same time. Therefore, workers must select works that can be performed now, which requires subjective decision making. This means that their methodology is limited in that the precedence relations between spool installation works cannot be clearly defined during planning.

Kim et al. [11] proposed a methodology for defining the spool installation sequence based on the geometric relation of spools. This geometric relation is used to determine whether interference occurs and to define the installation sequence. Their study is significant in that they determined the spool installation sequence under the constraint of interference, which has the largest effect on the efficiency of spool installation work. However, their work was limited in that parameters and constraints other than interference were not sufficiently considered [11].

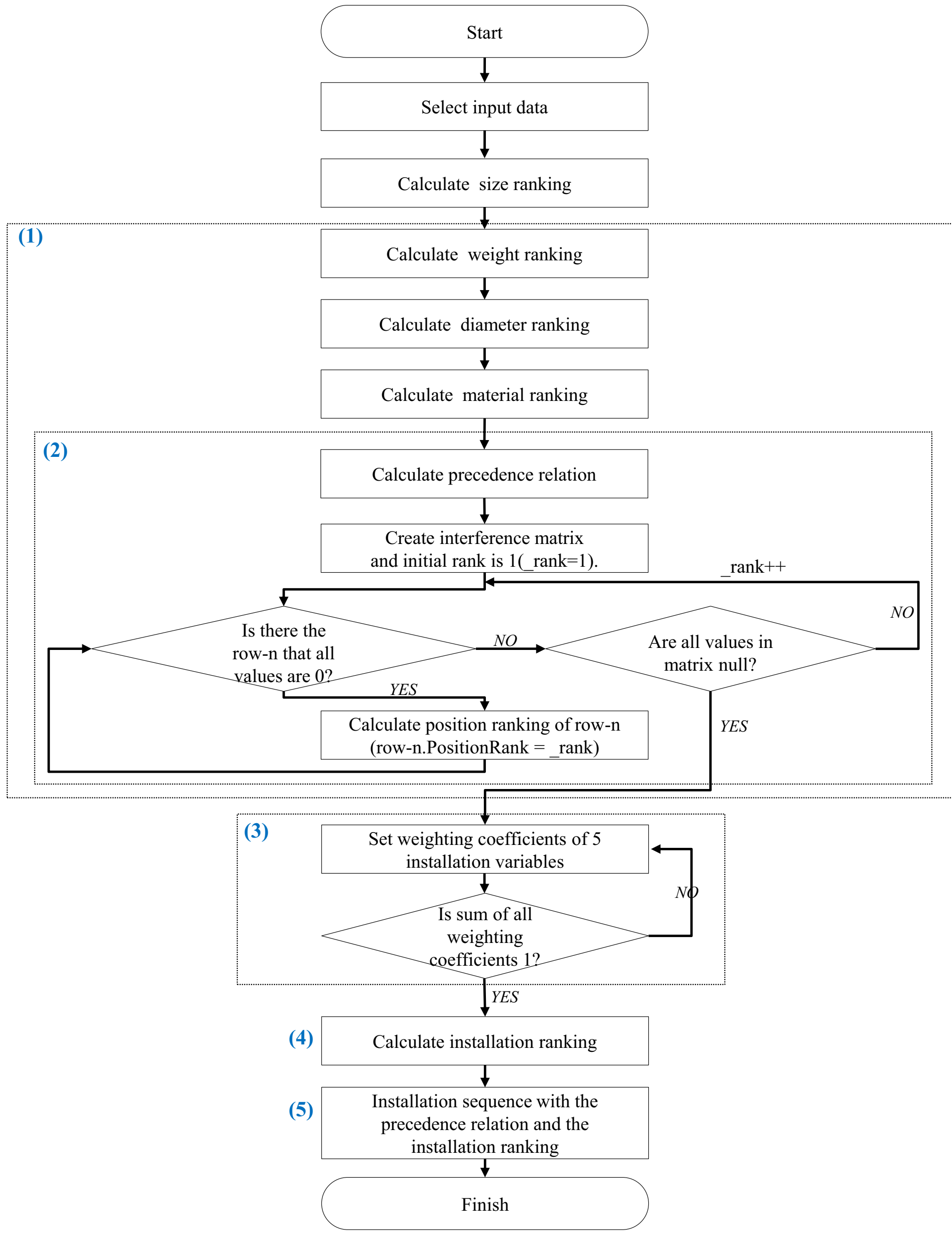
Choi et al. [12] developed an algorithm for determining the installation sequence of outfitting materials based on various attribute data. They tried to determine the efficient installation sequence of outfitting materials using data that can be confirmed during the design process. This study is significant in that they defined parameters that affect the installation sequence of outfitting materials. However, this work was limited in that preprocessing work was required to extract the coordinate information of outfitting materials and check the interference between outfitting materials. In addition, the possibility of simultaneous work was not considered.

3 Algorithms for installation sequence with spool installation precedence relation and ranking

Determination of the installation sequence is necessary to establish an efficient plan for the spool installation. Multiple tasks are simultaneously carried out during the shipbuilding in a limited space depending on the allocated number of resources. Therefore, the sequential ranking alone is not adequate for establishing a installation plan. The purpose of this study is to define the installation sequence of spools by considering the precedence relation and the installation ranking. The precedence relation is defined in consideration of the occurrence of interference, and the installation ranking is defined in consideration of process parameters such as weight, diameter, volume, material, and positional relationship of the spools.

An algorithm for determining the installation sequence consists of 5 steps, and the first step is to calculate precedence relation. In (1) of Fig. 1, the calculation of the installation parameters for the decision of the installation

Fig. 1 Flowchart of the installation sequence algorithm



ranking is determined by considering the volume, weight, diameter, material, and position ranking; those are defined as the properties of the spools. During the calculation of (1), the position ranking, which is represented by (2), is determined based on the precedence relation and interference matrix. Details of (1) and (2) will be discussed in Sects. 3.2 and 3.3. (3) is the part that considers the weighting factors for the ranks determined for each of the five process parameters according to the working environment, (4) is the part that considers the calculation of installation ranking by considering the determined ranks and weighting factors, and details of (3) and (4) will be discussed in Sect. 3.3 and 3.4. Finally, in (5), the installation sequence is defined with the precedence relation and installation ranking, which will be discussed in Sect. 3.5.

3.1 Installation parameters

The process parameters that are considered in this paper are position, weight, diameter, size, and material of spools, and those are summarized in Table 1. The position constraints are described in detail in Sect. 3.2, and the weight, diameter, size, and material are described in Sects. 3.3.1–3.3.4.

Table 1 Process parameters for the calculation of installation ranking

Parameter	Description
Position	The position refers to the coordinate information for the spool installation location. The spool position can be used to determine whether spools interfere with each. The position is an important process parameter because interference is one of the most significant factors that affect the efficiency of spool installation work
Weight	Outfitting is divided into the pre-outfitting stage, which is performed in a shipyard, and the post-outfitting stage, which is performed after the ship is moored at a quay. For a heavy spool, installation in the pre-outfitting stage is more efficient because of work and space limitations in the post-outfitting stage, and additional resources such as cranes may be required
Diameter	Installing a spool with a large diameter first is efficient in terms of securing working space. In addition, when spools with the same diameter are grouped and installed together, the ready-to-install rate and efficiency are high. Therefore, the diameter was defined as a process parameter
Size	The size refers to the volume calculated from the length and diameter of a spool. For a larger spool, a wider moving path needs to be secured, and a broader working space is required. Therefore, the size is an important process parameter in terms of securing a moving path and working space
Materials	A spool consists of various materials depending on its use. In addition, different materials require different welding methods, which can result in different levels of difficulty for the installation work. Installing spools made of the same material at the same time is more efficient because of the high ready-to-install rate

3.2 Definition of precedence relation and position ranking

3.2.1 Interference constraint

In this paper, installation constraint means that the installation is impossible due to the interference between spools [12]. Interference is the factor that most significantly affects spool installation availability. That is, if there is interference between the two spools, it can be said that the two spools should have the precedence relation.

3.2.2 Interference check between spools

The interference check between spools should be performed first to define spools precedence relation. In general, the spools installation work is performed from spools closer to the installation. Therefore, the interference check between the spools is performed based on the vertically upward direction with respect to the installation surface. In other words, if the interference between spools occurs, spool that is closer to the installation surface can be defined as the pre-installation spool.

The algorithm of checking the interference between spools is shown in Fig. 2. The interference check between spools is performed with the 3D model. First, spool information is extracted from the 3D outfitting design model. After all spools are orthogonally projected onto a 2D plane based on the installation direction, the interference check is conducted. Therefore, the interference check is conducted in three steps to improve the computation speed.

First, the interference check is conducted between bounding boxes, which are also called the minimum bounding rectangles. If there is no interference between bounding boxes, there is no possibility of interference between the relevant spools. Second, an interference check is conducted between lines created based on the center coordinates of the spools. In this case, only spools with interference occur between bounding boxes are considered. If interference occurs between lines, the spools interfere with each other. Third, an interference check is performed between the meshes of spools. In this case, only spools with interference between bounding boxes and no interference between lines are considered. Therefore, the computation time can be shortened by minimizing the number of spools for which meshes are created. If interference occurs between the meshes, these spools interfere with each other.

It is possible to define the precedence relations between the spools through the process of performing the interference check as shown in Fig. 2, and the interference matrix.

3.2.3 Definition of precedence relation

Based on the calculation of the interference between spools, the precedence relation between spools is defined. For the two spools with interference, the precedence relation is defined considering the distances of the spools from the installation surface. In other words, the spool that is closer to the installation surface should be installed first, and the spool that is farther from the installation surface should be installed later. And, no precedence relation is defined between two spools without interference. If all interference checks are completed, then all precedence relations are defined. From this algorithm, precedence relation example of Fig. 3 can be calculated as Table 2. Detail description of the calculation is added in Appendix A.

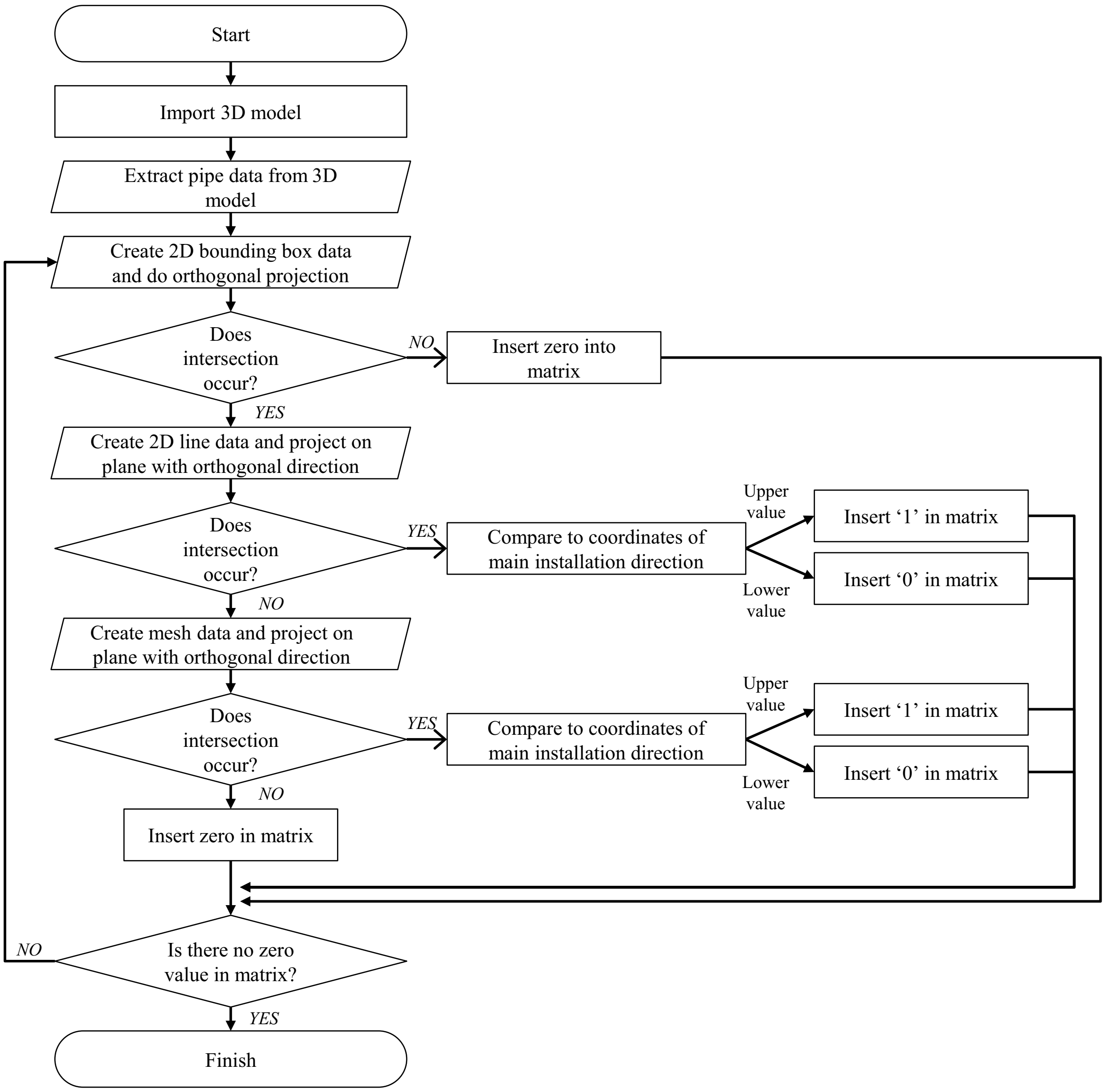


Fig. 2 Flowchart of the interference check algorithm between spools

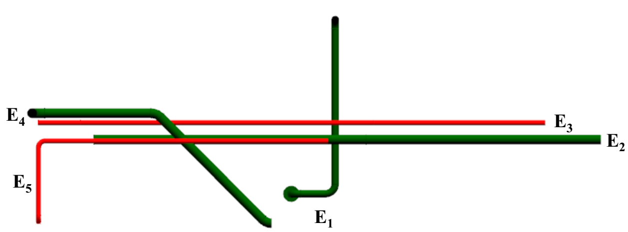


Fig. 3 Sample model consisting of 5 spools

Table 2 Precedence relations of spools in the sample model

Precedence spool	Next spool
E_1	E_2
E_1	E_3
E_2	E_4
E_2	E_5
E_3	E_4
E_3	E_5
E_4	E_5

3.2.4 Interference matrix

The interference matrix is a mathematical model proposed by Yan and Nienhuis [10] to determine the disassembly sequence of an assembled product. In this paper, the interference matrix is used to calculate the position ranking. The interference matrix can be generated based on the result of the interference check calculation. The difference between the precedence relation and the position ranking is that the precedence relation is an interference check between any two spools and is defined only when interference occurs. The position ranking is calculated by generating an interference matrix based on the result of the interference check between all spools and using the completed interference matrix. Equation 1 shows an interference matrix, where $E_{1\mathrm{r}}$ is the first element of the reference because the subscript r means the reference. $E_{1\mathrm{C}}$ is the first element for comparison because the subscript c means comparison. The reference elements are arranged in the left column, while elements to be compared are arranged in the top row in the same sequence. When a reference element and another element are checked for interference, 1 is entered into the matrix if interference occurs, and 0 is entered if interference does not occur. When the values in the row of the reference spool are 0, this means that the spool of the relevant column can be installed. The values in the reference column and row are then deleted, and the position ranking for the reference spool is provided. Through this process, the installation ranking according to interference can be calculated.

$$\mathrm{A_k} = \begin{array}{c} \\ E_{1r} \\ E_{2r} \\ \cdots \\ E_{ir} \\ \cdots \\ E_{nr} \end{array} \begin{array}{c} \begin{array}{cccccc} E_{1c} & E_{2c} & \cdots & E_{ic} & \cdots & E_{nc} \end{array} \\ \begin{bmatrix} a_{11} & a_{11} & \cdots & a_{11} & \cdots & a_{11} \\ a_{21} & a_{21} & \cdots & a_{21} & \cdots & a_{21} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{i1} & a_{i1} & \cdots & a_{i1} & \cdots & a_{i1} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n1} & \cdots & a_{n1} & \cdots & a_{n1} \end{bmatrix} \end{array} \tag{1}$$

3.2.5 Calculation of position ranking

Using the interference matrix in Sect. 3.2.4, the ranking of the positional relationship can be calculated. In other words, the position ranking indicates the installation sequence according to the interference of the spools. Calculation example of position ranking is described as follows with sample model in Fig. 3. The result of the interference matrix for the spools of the sample model is shown in Eq. 2.

First of all, since the values in the first row of the interference matrix are all zeros, E_1 does not interfere with any spools. Therefore, the position ranking of E_1 is defined as the first, and all values in the first row and the first column are eliminated (step 1). From step 1, it can be found that the second row and the second column are all zeros. Therefore, the position ranking of E_2 and E_3 is defined as the second, and the values of the second row, the third row, the second column, and the third column are eliminated (step 2). Similarly, since the values of the fourth row are all zeros, the position ranking of E_4 is defined as the third, and all the values of the fourth row and the fourth column are eliminated (step 3). Finally, since the values in the fifth row are all zeroes, the position ranking of E_5 is defined as the fifth, and all values in the fifth row and the fifth column are eliminated (step 4). If all the values in the interference matrix are empty, the calculation of position ranking is completed. The final position rankings of the five spools are shown in Tables 3 and 4.

$$\mathrm{A_k} = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \tag{2}$$

3.3 Calculation of ranking by process variable

3.3.1 Weight ranking

The weight ranking is calculated by giving priority to heavy spools. Spools are classified into five groups by summarizing their weight information entered into the algorithm. The first priority is given to the group with the highest weight. The lowest priority is given to the group with the lowest weight. The weight ranking of the spools is calculated based on the five groups.

Table 4 Position ranking of the sample model (Fig. 3)

Element	Position ranking
E_1	1
E_2	2
E_3	2
E_4	3
E_5	4

Table 3 Calculation steps of position ranking

$$\mathrm{A_k} = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} & & & & \\ & 0 & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 \\ & 1 & 1 & 0 & 0 \\ & 1 & 1 & 1 & 0 \end{bmatrix} \end{array} \quad \text{step 1}$$

$$\mathrm{A_k} = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} & & & & \\ & & & & \\ & & & & \\ & & & 0 & 0 \\ & & & 1 & 0 \end{bmatrix} \end{array} \quad \text{step 2}$$

$$\mathrm{A_k} = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & 0 \end{bmatrix} \end{array} \quad \text{step 3}$$

$$\mathrm{A_k} = \begin{array}{c} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{array} \begin{array}{c} \begin{array}{ccccc} E_1 & E_2 & E_3 & E_4 & E_5 \end{array} \\ \begin{bmatrix} & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \end{bmatrix} \end{array} \quad \text{step 4}$$

3.3.2 Size ranking

The size ranking is calculated by giving priority to large spools. The spool volumes are calculated based on the length and diameter information entered into the algorithm. The calculated volumes are then classified into five groups. The first priority is given to the group with the largest size. The lowest priority is given to the group with the smallest size. The size ranking of the spools is calculated based on the five groups.

3.3.3 Diameter ranking

The diameter ranking is calculated by giving priority to spools with large diameters. The diameter of a spool ranges from 3.81 [cm] to 76.2 [cm]. The diameter is important because different diameters require different work hours. The diameters were classified into the five groups given in Table 5. The first priority is given to the group with the largest diameter. The lowest priority is given to the group with the smallest diameter. The diameter ranking is calculated based on the five groups.

3.3.4 Material ranking

Table 6 presents the four materials typically used for spools. Different materials require different welding methods, which results in different levels of work difficulty. Therefore, priority is given to spool materials with high difficulty. The first priority is given to copper nickel (CN), followed by low-temperature carbon steel (LTCS), stainless steel (SS), and carbon steel (CS). The material ranking is calculated based on the four groups.

Table 6 Classification of material ranking

Material (abbreviation)	Material	Material ranking
CS	Carbon steel	4
CN	Copper nickel	1
LTCS	Low-temperature carbon steel	2
SS	Stainless steel	3

3.4 Weighting factors of each process parameters and installation ranking

Through Sects. 3.2.5 and 3.3, the ranking of five process parameters is calculated. The importance of these process parameters can vary depending on the working environment and input resources of the spool installation compartment. Therefore, the weighting factors of each process parameters were applied to each process parameter by considering the relative importance.

This study used the analytic hierarchy process (AHP) to set the weighting coefficients. The AHP method is used to systematically analyze parameters for decision making when there are multiple or complicated parameters [10]. In this method, a paired comparison is performed first to assess the relative importance of parameters. In this study, the AHP scale in Table 7 was used for the paired comparison. Because the paired comparison cannot exclude subjective decisions, effective results can be obtained when experts in the relevant area are available. The calculation of each weighting factors is added in Appendix B.

Equation 3 calculates the final score of the ith spool by applying the ranking and weighting factors of each process parameter calculated, where n is the number of process parameters. The score is calculated based on the ranking of each process parameter. The final installation ranking is calculated by giving priority to spools with low ranking scores:

$$S_i = \sum_{k=1}^{n} \left(\text{Rank}_k \times \text{Weighting coeff.}_{,k}\right). \tag{3}$$

3.5 Definition of installation sequence

3.5.1 Installation sequence based on installation ranking and precedence relation

The algorithm sequence in Fig. 1 was used to calculate the precedence relation in Sect. 3.2.3 and the installation sequence in Sect. 3.5. The calculated precedence relation

Table 5 Classification of diameter ranking

Diameter ranking	Range of diameter (in)
1	$D < 2$
2	$2 \leq D < 5$
3	$5 \leq D < 10$
4	$10 \leq D < 15$
5	$15 \leq D$

Table 7 Values of each level of importance for the calculation of AHP

Value	Level of importance
1	Equally important
3	Slightly more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important

and the installation sequence are the final results of the algorithm developed in this study. In other words, the installation sequence is produced in two tables, and the reason for being divided into two types can be explained through the characteristics of the shipbuilding industry. In shipyards, several works are performed simultaneously, and several vessels are constructed at the same time. In other words, not only one resource is inserted to perform a task, but a plurality of tasks is performed simultaneously according to the number of input resources. Therefore, the spool installation ranking calculated in Sect. 3.4 alone has a limit in establishing a reasonable plan that reflects the characteristics of the shipbuilding industry. The installation sequence is each spool's priority calculated based on the properties of the spools. Therefore, with the installation ranking alone, it is difficult to consider the possibility of simultaneous work as well as the precedence relations among spools. For example, when Spool 1 and Spool 2 are ranked first and second, and there are two resources available, a plan may be made to install both spools simultaneously if only the installation ranking is considered. However, if the two spools are close, the two spools may not be able to be installed at the same time. Therefore, the precedence relations among spools must be specified to reflect the characteristics of shipyard. As a result, in order to develop a reasonable spool installation plan, it is necessary to define an installation sequence that considers precedence relation.

3.5.2 Resolving priority conflict with precedence relation

At this point, there can be a conflict between the installation ranking determined in Sect. 3.4 and the precedence relation due to interference constraints. For example, in the case where the installation ranking of spool A is the first and the that of the spool B is the second, if spool A interferes with spool B, the installation and position ranking for the two spools will collide. When this happens, it can be defined that spool B should be installed before spool A, taking into account the precedence relation. If the precedence relation is considered alone, installation sequence cannot be established. Therefore, the installation sequence considering various variables is also important. However, if interference occurs, it may be necessary to remove and re-install the previously installed spools inability to secure the movement route of the spools. Therefore, in this paper, the installation plan for the spools is established by considering the effects of interference as the top priority, and if there are many spools that can be installed simultaneously, the plan can be prioritized according to the installation sequence and the number of resources.

A planning method when there is a conflict between precedence relation and installation ranking will be explained based on the sample model of Fig. 3. The result of installation ranking is shown in right column of Table 8, where it can be found that the installation sequence and the position ranking (precedence relation) from Table 4 have difference priorities. In the installation ranking, the priority of E_4 is higher than that of E_2, but in the precedence relation, E_2 should be installed before E_4. Based on these two results and the characteristics of the working environment, interference has the highest priority. Therefore, in such a case, a plan should be established so that E_2 is installed before E_4 in consideration of interference constraints, which change the installation ranking as the number with bracket in Table 8.

The result of installation sequence is the installation ranking and precedence relation both together. When establishing a spool installation plan based on the installation sequence, the process model is first constructed through the precedence relation. After that, the installation plan will be established by considering the installation ranking and available resources. The installation process drawn from the results of position ranking (precedence relation) in Table 8 can be schematized as shown in Fig. 4. On the other hand, if there is only one resource available, installation process will be drawn as Fig. 5.

E_1 without preceding spool installation is installed first. Also, since E_1 is only pre-installed spools, E_2 and E_3 can be installed after E_1 is installed. However, if only one resource is available, the priority is decided according to the installation sequence. It was found that the installation sequence of E_2 is the fourth, and the installation sequence of E_3 is the second. Therefore, E_3 is installed first, and then, E_2 is installed. Therefore, after E_3 is installed, E_2 is installed. After that, E_4 is installed, and then finally, E_5 is installed. In this way, the installation sequence can be applied to establish a spool installation plan.

Table 8 Position ranking and installation ranking of the sample model

Element	Position ranking (from Table 4)	Installation ranking
E_1	1	1
E_2	2	4 (3)
E_3	2	2
E_4	3	3 (4)
E_5	4	5

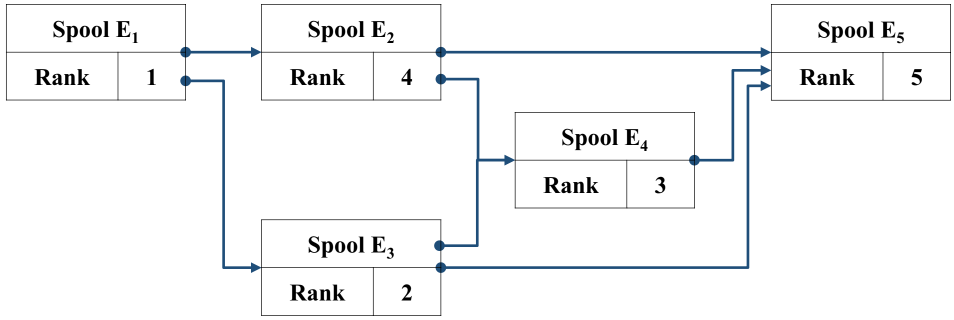


Fig. 4 Process model of spools in the sample model

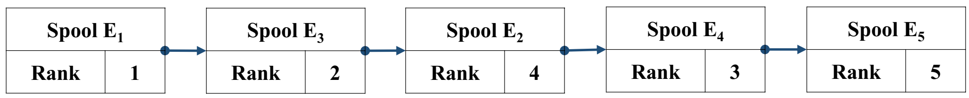


Fig. 5 Process model with only one resource available

Table 9 Attributes of the spool model

Spool name	Weight (kg)	Material	Diameter (in)	Size (mm^3)
E9B-24IN-S1	285	CN	24	12,603,023
E9B-6IN-S5	201	SS	6	6,982,941
E9B-6IN-S4	84	SS	6	6,762,128
E9B-6IN-S6	48	SS	6	7,124,747
E9B-3IN-S1	58	SS	3	1,022,144
E9B-3IN-S3	61	SS	3	1,392,486
E9B-3IN-S2	42	SS	3	1,138,501
E9B-3IN-S4	29	SS	3	1,452,880
E9B-4IN-S1	72	SS	4	2,887,528
E9B-1.5IN-S1	14	SS	1.5	378,271
E9B-4IN-S2	39	SS	4	2,917,155
E9B-3IN-S6	121	SS	8	7,811,494
E9B-3IN-S5	115	SS	8	8,103,210
E9B-8IN-S3	107	SS	8	4,051,605
E9B-8IN-S2	67	SS	3	1,486,939
E9B-8IN-S1	69	SS	3	1,523,403
E9B-6IN-S2	183	CS	6	3,686,960
E9B-6IN-S1	192	CS	6	6,275,936
E9B-3IN-S7	74	SS	3	1,664,830
E9B-6IN-S3	81	CS	6	6,568,158

Table 10 Weighting coefficients for the algorithm validation

Process parameter name	Weighting coefficient
Position	0.6
Weight	0.05
Size	0.05
Diameter	0.2
Material	0.1

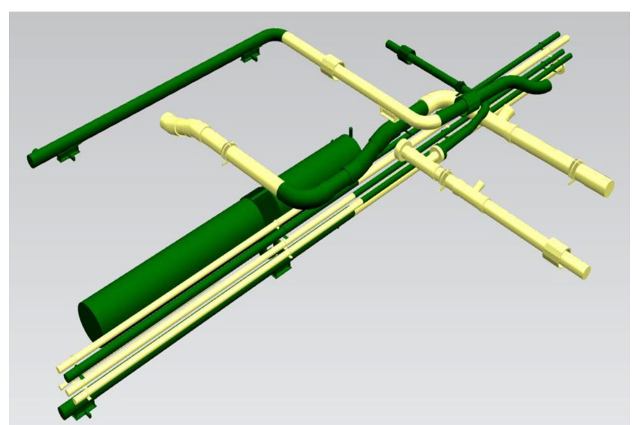


Fig. 6 3D model of given spools for the algorithm validation

4 Example of developed algorithm

4.1 Result of installation ranking and precedence relation

The developed algorithm was validated with the actual data of an offshore structure. Data for one section of an offshore structure composed of about 240 spools were used, and a sample model consisting of 20 spools was extracted to visually validate the results of the algorithm. Table 9 presents the attribute data of the spools. For the interference check between spools, the 3D outfitting design model file in the JT format was used. The weighting factors of each process parameter were defined as given in Table 10, and detail calculation procedure is added in Appendix B.

Figure 6 shows the spool model extracted as sample data. After the orthogonal projection of the spools of this model onto the *X*–*Y* plane, an interference check was conducted with bounding boxes first, as shown in Fig. 7a. Figure 7b,

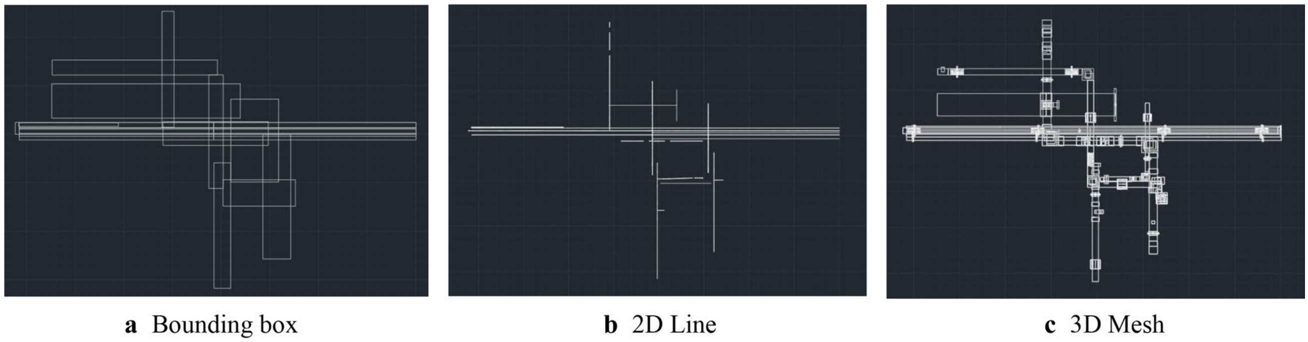


Fig. 7 Orthogonal projection of spools onto the *X*–*Y* plane for the interference check with bounding boxes

c shows the following interference checks with lines and meshes, respectively. Table 11 presents the calculation process for the installation ranking, which was calculated based on the ranking and weighting coefficient of each process parameter. The installation ranking was calculated by prioritizing spools with low scores. Table 12 presents the precedence relation between spools by the constraint of interference.

To give an example of using the result of Table 11 and Table 12, let us explain 'E9B-4IN-S1' and 'E9B-1.5IN-S1'. The two spools have different value of each process parameter, but the installation rankings of the two spools are the same (ranking is 150 in Table 11). However, the precedence relations of the two spools are different as shown in Table 12, where precedence relation of two spools is not defined. 'E9B-4IN-S1' is defined as the follow-up installation work of 'E9B-3IN-S4' and 'E9B-1.5IN-S1' is defined as the follow-up installation work of 'E9B-6IN-S5'. Therefore, although the final installation ranking of the two spools is equally calculated, the two spools are defined as follow-up installation work of the different spools, and the actual installation sequence of the two spools is defined according to the working condition at work site. For example, if 'E9B-3IN-S4' was already installed and 'E9B-6IN-S5' was not installed, it is possible to determine the installation sequence of the two spools

Table 11 Calculation result of the installation ranking

Spool name	Position ranking	Weight ranking	Size ranking	Material ranking	Diameter ranking	Score	Installation ranking
E9B-24IN-S1	1	1	1	1	1	1	1
E9B-6IN-S5	1	1	2	3	2	1.45	8
E9B-6IN-S4	1	2	2	3	2	1.5	12
E9B-6IN-S6	1	3	2	3	2	1.55	14
E9B-3IN-S1	1	2	5	3	4	2.05	36
E9B-3IN-S3	2	2	4	3	4	2.6	127
E9B-3IN-S2	2	3	4	3	4	2.65	131
E9B-3IN-S4	2	4	4	3	4	2.7	137
E9B-4IN-S1	3	2	3	3	3	2.95	150
E9B-1.5IN-S1	2	4	5	3	5	2.95	150
E9B-4IN-S2	3	3	3	3	3	3	153
E9B-3IN-S6	4	1	2	3	1	3.05	155
E9B-3IN-S5	4	1	2	3	1	3.05	155
E9B-8IN-S3	4	1	3	3	1	3.1	159
E9B-8IN-S2	3	2	4	3	4	3.2	167
E9B-8IN-S1	3	2	4	3	4	3.2	167
E9B-6IN-S2	5	1	3	4	2	4	200
E9B-6IN-S1	5	1	3	4	2	4	200
E9B-3IN-S7	5	2	4	3	4	4.4	219
E9B-6IN-S3	6	2	2	4	2	4.6	225

Table 12 Calculation result of the precedence relations of spools

Precedence spool	Next spool
E9B-6IN-S6	E9B-6IN-S3
E9B-6IN-S6	E9B-6IN-S2
E9B-3IN-S7	E9B-6IN-S3
E9B-8IN-S1	E9B-6IN-S1
E9B-8IN-S2	E9B-6IN-S2
E9B-8IN-S3	E9B-3IN-S7
E9B-8IN-S3	E9B-6IN-S3
E9B-24IN-S1	E9B-8IN-S1
E9B-24IN-S1	E9B-6IN-S2
E9B-6IN-S5	E9B-1.5IN-S1
E9B-1.5IN-S1	E9B-3IN-S5
E9B-6IN-S1	E9B-3IN-S2
E9B-4IN-S1	E9B-8IN-S2
E9B-4IN-S2	E9B-6IN-S2
E9B-3IN-S4	E9B-8IN-S2
E9B-3IN-S4	E9B-6IN-S2
E9B-3IN-S4	E9B-4IN-S2
E9B-3IN-S4	E9B-4IN-S1
E9B-3IN-S4	E9B-3IN-S5

because ‘E9B-4IN-S1’ can be installed and ‘E9B-1.5IN-S1’ cannot be installed.

To verify the results with ‘E9B-8IN-S3’ and ‘E9B-3IN-S4,’ the position ranking of ‘E9B-8IN-S3’ is 4 and the position ranking of ‘E9B-3IN-S4’ is 2, but the installation ranking of ‘E9B-8IN-S3’ (137) is higher than that of ‘E9B-3IN-S4’ (159) in Table 11. And there is no precedence relation between two spools as shown in Table 12. This is because the installation ranking of ‘E9B-8IN-S3’ is higher than that of ‘E9B-3IN-S4’ and there is no direct precedence relation between the two spools. That is, if there is no interference between the two spools, the installation sequence may differ from the sequence by interference. Assuming ‘E9B-8IN-S3’ is larger and heavier than ‘E9B-3IN-S4,’ it may be reasonable that the installation ranking of ‘E9B-8IN-S3’ is higher than that of ‘E9B-3IN-S4,’ even if the position ranking of ‘E9B-3IN-S4’ is higher than ‘E9B-8IN-S3,’ since ‘E9B-8IN-S3’ requires a wider workspace and additional resources, such as a overhead crane.

4.2 Why installation ranking and precedence relation needed

To make sure that the installation sequence should include precedence relations as well as the installation ranking, the results should be divided into following four cases.

Case 1: Position ranking only.
Case 2: Installation ranking only.
Case 3: Precedence relation only.
Case 4: Installation sequence and the precedence relation.

In case 1 where only the position ranking is considered, spools that can be installed are grouped according to the interference ranking, as shown in Fig. 8. In this case, there is a limitation that the spool in the following group can be installed only after the installation of all spools in the preceding group is completed since the precedence relation between spools is not defined.

In the second case where only the installation ranking is considered, a process model can be created as shown in Fig. 9. Since only the installation ranking is considered, it can be defined that the next spool can be installed after an installation spool with a higher installation ranking is

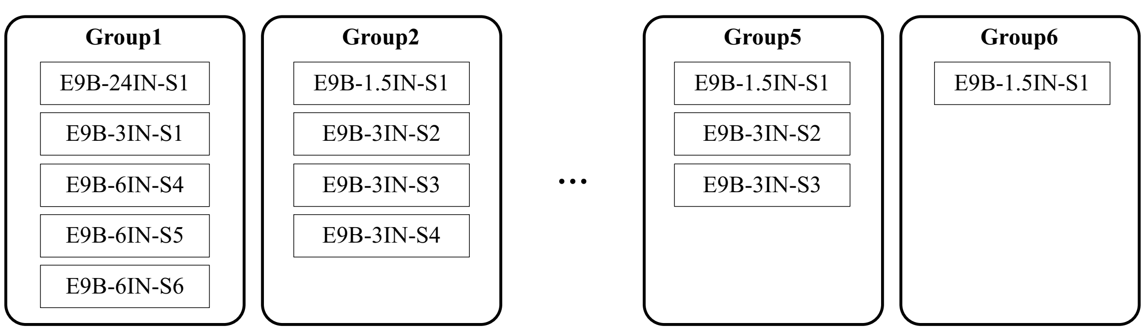


Fig. 8 Process model with position ranking only

Fig. 9 Process model with only installation ranking

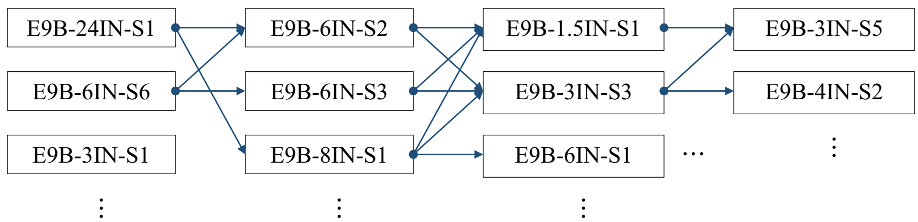


Fig. 10 Process model of case 3 (precedence relation only) and case 4 (installation ranking and precedence relation)

completed. In this case, however, parallel installation process cannot be considered since it is defined that only one task is performed at a specific time.

In the third case where only the precedence relation is considered, a process model can be created as shown in Fig. 10. As such, the process model in consideration of the connection relations between the spools is good because this model allows parallel installation process. However, in this case, it is difficult to determine the priority of the installation order when the number of resources is less than the number of the spools that can be installed.

The case 4 is that takes into account both the installation ranking and precedence relation. In this case, a process model can be created as shown in Fig. 10 same with the one of precedence relation. The difference from the third case is that when the number of allocated resources is smaller than the number of the spools that can be installed, the priority of spool installation can be determined with the installation ranking.

As a result, it is confirmed that the installation sequence has to be determined by considering both the installation ranking and precedence relation. With those ranking and relation, a more reasonable installation sequence can be established.

5 Conclusion

This study focused on solving the problem with spool installation sequence, which has a high proportion of outfitting work in construction of offshore structures. For the resolution of sequence problem, algorithm was developed for the calculation of the installation sequence.

In detail, installation ranking and precedence relation were calculated and two factors are combined into installation sequence. Position, weight, size, diameter, and material property of each spool are considered for the calculation of installation ranking. Also, for the precedence relation, the 3D model of each spool is used for the calculation of positional ranking and precedence relation of each spool.

Finally, the developed algorithm was verified with the spool data of an actual offshore structure.

As a future study, an installation planning algorithm that could consider resource availability will be developed with the proposed algorithm.

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Appendix A: Example of precedence relation

To explain the process of defining precedence relation through Fig. 3, the sample model consisting of five spools is projected on a two-dimensional plane with respect to the installation surface and viewed from the top. It was found that all spools interfere with one or more spools. E_1 is located closest to the installation surface, and no interference with other spools was found. E_1 collided with E_2 and E_3. Since E_1 is located closer to the installation surface, it can be defined that E_1 should be installed before E_2 and E_3. In addition, since it was found that E_4 interferes with E_2 and E_3, E_2 and E_3 can be defined as the spools that are installed before E_4. The precedence relation that is defined based on the interference check operation is shown in Table 2.

Table 13 Calculation process for the weighting coefficients with the AHP method

	Position	Weight	Size	Material	Diameter	Sub-value	Geometric mean	Weighting coefficient
Position	1	9	9	7	5	2835	4.90	0.60
Weight	1/9	1	1	1/3	1/5	0.01	0.37	0.05
Size	1/9	1	1	1/3	1/5	0.01	0.37	0.05
Material	1/7	3	3	1	1/3	1.43	0.84	0.10
Diameter	1/5	5	5	3	1	15	1.72	0.20

Table 14 List of functions for the application

Function ID	Name	Description
F-001	Selection of spool data	Spool data list is available and viewable
F-002	Setting of weighting coefficients	Weighting coefficients are viewable, available, and changeable
F-003	Calculation of installation ranking	Installation ranking can be calculated based on process parameters and weighting coefficients
F-004	Request of resultant data	Resultant data are available and viewable
F-005	Export of resultant data	Resultant data can be exported with Excel

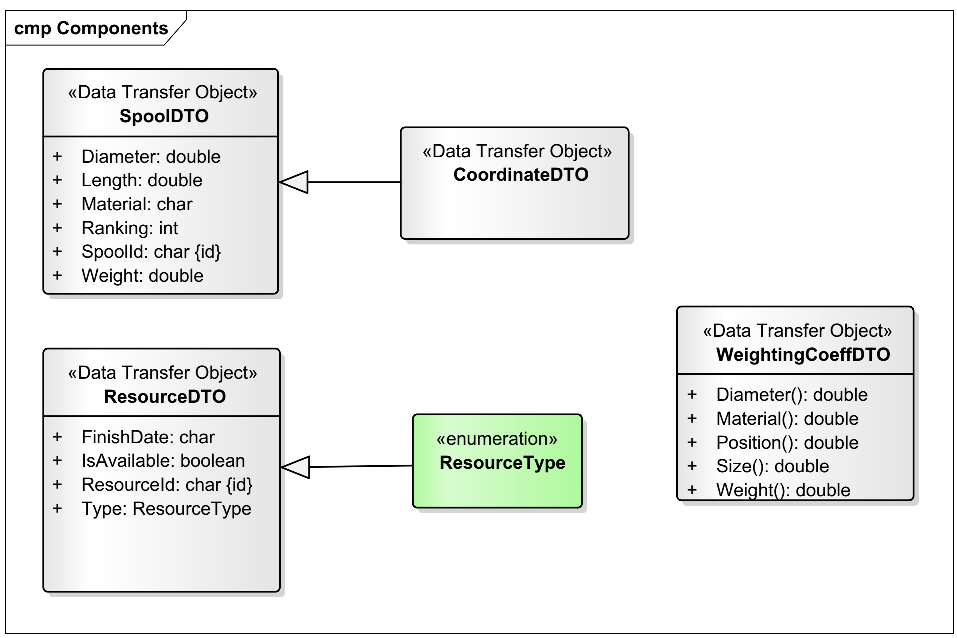

Fig. 11 Structure of data transfer objects

Appendix B: How to calculate weighting factor

Table 13 presents an example to explain the process for setting the weighting factors of each process parameter with the AHP method. A paired comparison is performed for each parameter. For example, the position information is given 9 points when judged to be 'Extremely more important' than the weight information. The weight information is given the reciprocal score (i.e., 1/9 points). Because the same values have the same relative importance to each other, a paired comparison between the same values gives 1 point to each parameter. When the paired comparison is completed for all parameter pairs, all values are entered as given in Table 13. In this case, the values in each row are multiplied to obtain the sub-value. For example, the position is given the sub-value 2835 because its comparison to the other parameters results in the values 1, 9, 9, 7, and 5. The geometric mean is calculated from the sub-value. The geometric mean is the *n*th root of the product of n positive numbers. In this instance, *n* is the number of parameters. Because five parameters were considered in this study, the geometric mean is the fifth root. Therefore, the geometric mean of the position is 4.90. Finally, the weighting coefficients can be calculated from the obtained geometric means. The sum of the geometric means for all process parameters is 8.22. Therefore, the final weighting coefficient of the position is 4.90/8.22 = 0.60.

Appendix C: Application development

An application was developed for the implementation of installation sequence algorithm. Table 14 defines the required functions based on the developed algorithm. The functions are divided into those that the user sets up, those for calculating the installation sequence, and those for which the user can check the required output data. A data transfer object (DTO) structure was designed for developing the functions, as shown in Fig. 11.

SpoolDTO consists of spool attribute data and the data for calculating the spool installation sequence, *ResourceDTO* is for resources required for spool installation works, and *WeightingCoeffDTO* contains the weighting coefficients of the process parameters.

Figure 12 depicts the business component model of the application. It shows the overall structure and relations between components. Because the application was developed based on the model–view–controller (MVC) structure, the business component model consists of the model, view, and controller layers. The components in the model layer control data. The components in the view layer visualize data for the user. The components in the controller layer not only serve the most important function but also facilitate the data flow between model layer and view layer. In the model layer, the end of the component's name is 'Info.' In the controller layer, the end of the component's name is 'Mgr.' The business component model is divided according to the roles of the included functions. Calculation components such as *CalculatinMgr* include the functions required to calculate the spool installation sequence. Setting components such as *SettingMgr* and *SettingInfo* contain the

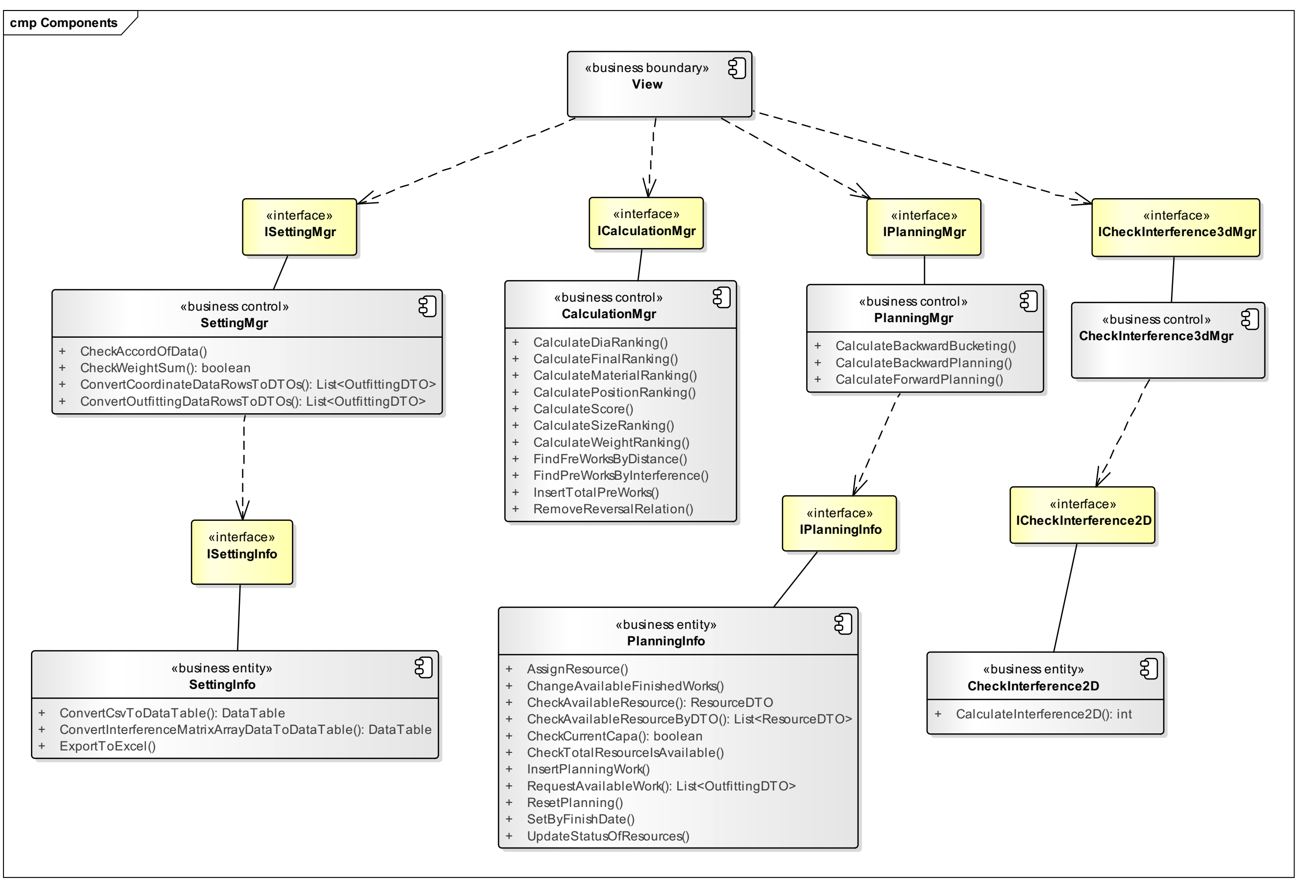

Fig. 12 Business component model

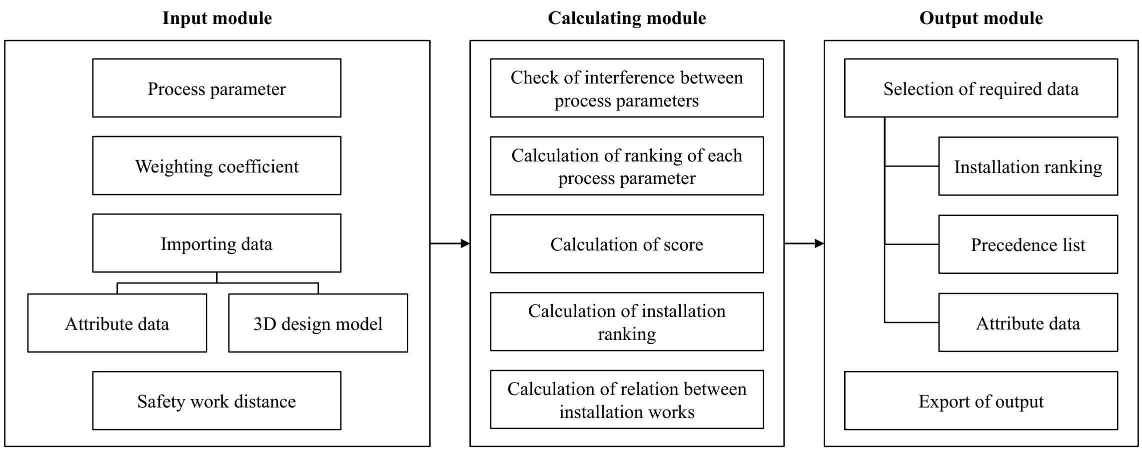

Fig. 13 Structure and main features of the developed application for defining the spool installation sequence

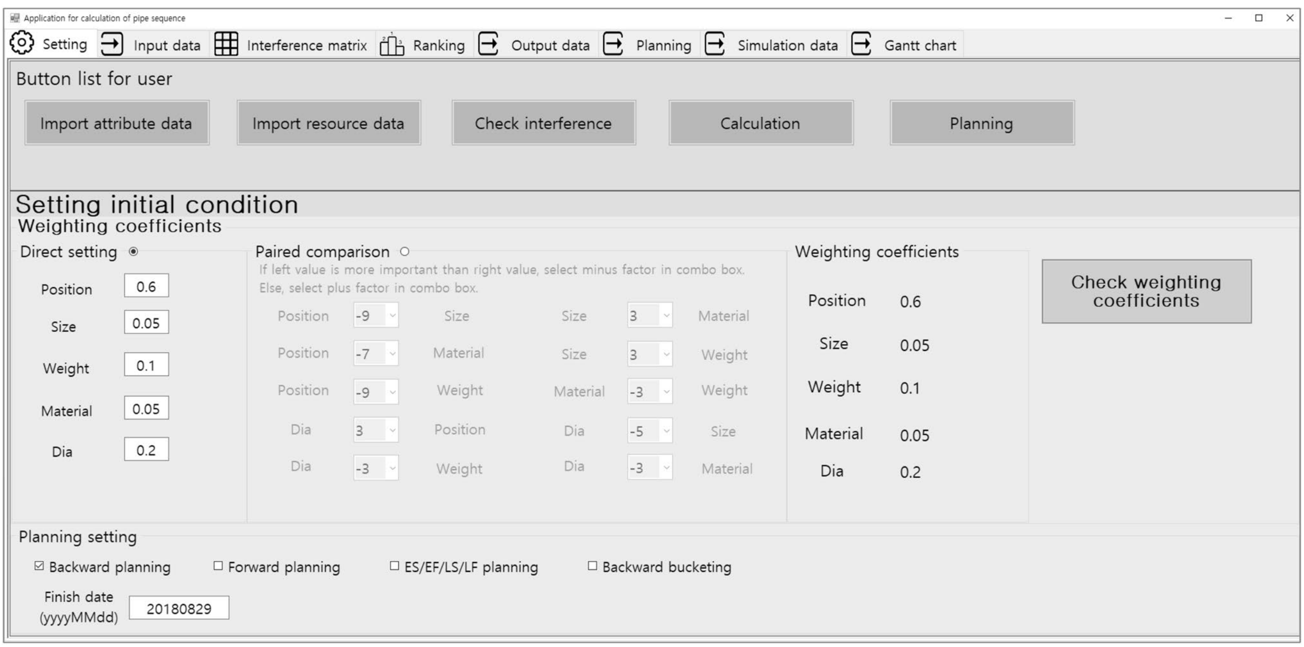

Fig. 14 Setting view of the developed application

function for controlling and processing data. Interference check components such as CheckInterference2DInfo and CheckInterference3DMgr include the function for checking interference between spools.

The application was developed based on the designed business component model and DTO structure. The application consisted of three modules, as shown in Fig. 13. The input module imports spool attribute data and the 3D outfitting design model and sets the process parameters, weighting coefficients. The calculation module calculates the ranking of each process parameter and the installation ranking of each spool. The precedence relations between spool installations are defined based on the interference and distance constraints. The output module selects and exports required data such as the installation ranking, list of preinstalled spools, and spool attribute data. Figure 14

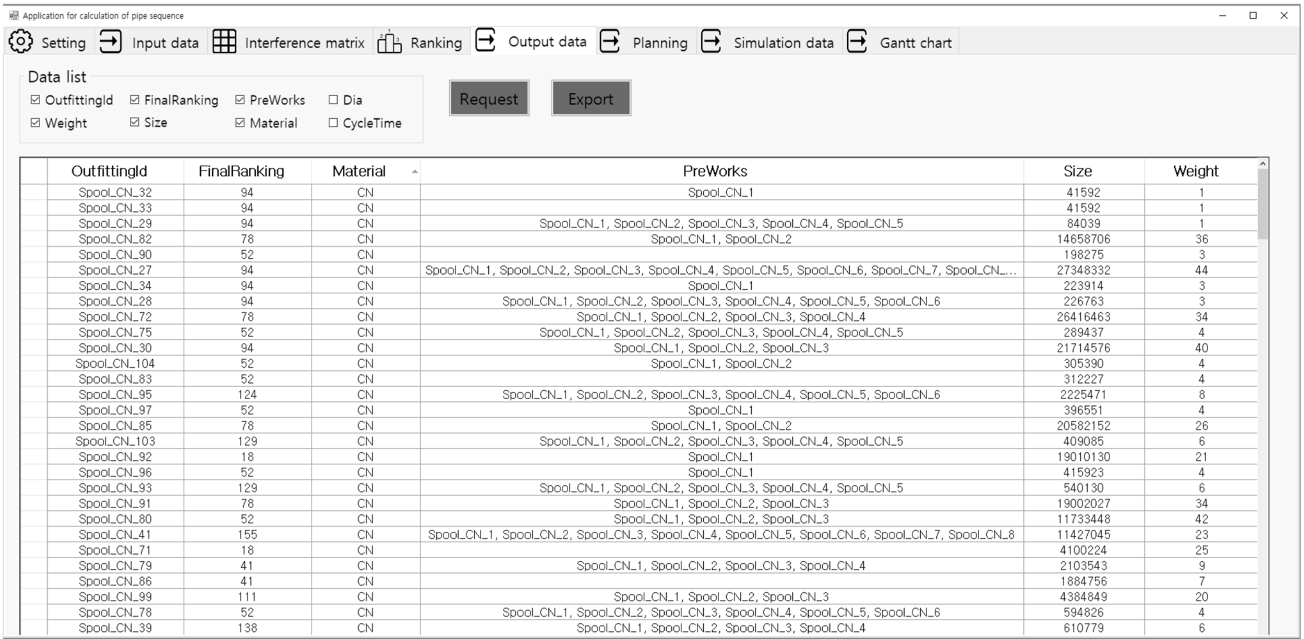

Fig. 15 Results view of the application

shows the setting view of the developed application, in which it is possible to import the spool attribute data and 3D model and set the weighting coefficients. Output data such as the installation ranking and precedence relation are calculated by clicking the 'Calculation' button and are shown in Fig. 15.

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