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Analysis on Hull Block Erection Process Considering Variability

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The hull block erection network process, which is performed during the master production planning stage of the shipyard, is frequently delayed because of limited resources, workspace, and block preparation ratio. In this study, a study to predict the delay with respect to the block erection schedule is conducted by considering the variability of the block preparation ratio based on the discrete event simulation algorithm. It is confirmed that the variation of the key event observance ratio is confirmed according to the variability caused by the block erection process, which has the minimum lead time in a limited resource environment, and the block preparation ratio. Furthermore, the optimal pitch value for the key event concordance is calculated based on simulation results.

Keywords: shipbuilding; block erection; discrete event simulation; block preparation ratio

1. Introduction

The shipyard is a production environment where the infinite capacity and fixed lead time assumptions of the material requirement planning system in the mass production industry cannot be applied. Because the production capacity of various resources such as labor workforce, production facility, and work space needs to be considered, and even if the same product is manufactured, the production lead time varies depending on the workplace and available manpower/equipment; a schedule is established based on the characteristics of this production environment (Woo et al. 2003). The biggest problem of the production management perspective in the shipbuilding production environment is that the production plan execution is inconsistent. Even if a production plan is established by considering finite capacity planning and varying lead time, it most likely will not be executed as planned because of various factors such as design change, procurement delay, and process delay. Therefore, the production management department is constantly operating a plan modification process that reflects the execution performance called the rolling plan every 2 or 4 weeks.

However, because of the negative problems such as the uncertainty of the estimated construction period and the contention of resources that are allocated to each activity, not only the credibility of the schedule management of the project decreases but also the temporal/economic loss can occur from the unexpected change of the schedule and the frequent rework, which adversely affects the productivity (Lee et al. 1997). It is necessary to predict the uncertain variables that affect the project schedule appropriately through simulation and reflect the variability in the plan in advance. Therefore, in this article, simulation is conducted by considering the variability of block erection process, which is the most important process in the shipbuilding production process.

The erection process is the process of completing the ship structure by assembling erection blocks in the dry dock or skid berth. In this process, managing and scheduling a dry dock or a skid berth, which is a workplace where the block erection takes place, skid birth, transporters and cranes for moving the blocks, welding equipment for the assembly work, and manpower are necessary (Lee et al. 2009). The importance of scheduling the block erection appropriately has been recognized consistently from the past.

In case of the block erection schedule, an initial schedule is established by considering the block erection network, construction method, and key event schedule, and the final schedule is determined by checking the critical path. However, the plan is frequently changed depending on whether the limited resource and the preceding block have been erected and/or whether the block has been prepared.

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Studies on the block erection process control using an optimization algorithm and simulation are as follows. For the optimization, Lee and Kim (1995), Bao et al. (2009), Yoon et al. (2010), Zhong et al. (2010), and Bao et al. (2014) used a genetic algorithm or a certain algorithm that combines genetic algorithm with other algorithms to study the optimal process planning by considering the construction period and the utilization of available resources at the process planning stage. Tokola et al. (2013) applied a mathematical model that considers block lifting and block assembly time to the block erection process analysis. Lim et al. (1997) conducted a study on simulation-based master production process planning method with constraints on the block erection process schedule, and the influence of the block erection schedule on the overall process load is analyzed by determining the load distribution for the schedule of master production processes. Kim et al. (2005) proposed a production simulation system for the shipyard and conducted simulations for various block erection methods for the erection process. Furthermore, many studies have been conducted, including a study where the production information is extracted from the design information and the assembly sequence of the block erection process is calculated to conduct simulation (Roh & Lee 2007), a study on the production support system for small- and medium-sized shipyards using simulation (Song et al. 2009), and a study that establishes a function deriving system for simulation of shipyard production system and applies the system into practice (Song et al. 2011).

However, in the case of optimization studies, it is possible to establish the optimized block erection plan if the working time is definite because of the constraint factors such as the block erection precedence relation and resource availability, but it cannot consider the influence when the variability is taken into consideration. Furthermore, existing simulation studies have focused more on 3D visualization, and therefore, there is a limitation in the analysis of the block erection process wherein the planning is considered.

In this article, a study on a fast delay estimation method that considers the block preparation ratio is conducted by using the discrete event simulation (DES) simulation for the block erection process. Specifically, the key event observance rate is quantitatively confirmed according to the variability caused by the block preparation ratio, and the optimum pitch value is estimated among the erection blocks for the key event concordance so that more efficient block erection planning and management are enabled.

The composition of this article is as follows. In Section 2, the erection process is analyzed and problem areas are defined. In Section 3, the framework and DES algorithm for fast DES simulation are described in detail. In Section 4, the simulation of the block erection process is conducted by considering the block preparation ratio and the result analysis is performed. Finally, Section 5 summarizes the contents of this article.

2. Analysis of the erection process and requirement

2.1. Erection process of target shipyard

In the *S* shipyard, which is the subject of this study, blocks are erected in the skid berth (Fig. 1). The skid berth method is a construction method using a skid rail, and this method can reduce the cost of the dock because the ship can be constructed in a flatland without dry dock. The main key events that are generally considered in the shipbuilding process using a dock are steel cutting (S/C), which indicates the start of the project, keel laying (K/L), which indicates the start of the docking operation, launching (L/C), which indicates the end of the process in the dry dock, and delivery (D/L), which indicates vessel delivery to shipowner. However, in the erection process with the skid berth, shifting (S/F) and load out (L/O) events are added between keel laying and launching. The S/F event moves a part of the ship, which is constructed at a place other than the erection place, on the skid rail. Because there is no need to complete the hull on the skid rail, the utilization of the skid can be increased and the production lead time can be reduced. L/O is the operation of moving a ship to the floating dock using a skid berth on which the hydraulic devices are placed. At this time, there is a difficulty in synchronizing the ballasting of the floating dock and the hydraulic device on the skid rail, which moves the hull from the land to the floating dock under hull-balancing conditions.

2.2. Requirements analysis

The block preparation ratio, which indicates whether or not a particular erection block can be erected according to the planned date is a random variable that includes information on completion of the preceding process, movement of the erection block, and preparation for the erection. The block preparation ratio is a normal distribution type, in which the scheduled date of each erection block is the average and the deviation across blocks is the standard deviation. In this process, the scheduled date for the erection means the earliest start (ES) time that is calculated in the critical path method (CPM) technique, which indicates the earliest time that the corresponding block can be erected. Table 1 shows the deviation of the block preparation ratio according to the block characteristics. The deviation is a result of the performance data analysis of the subject shipyard and is used to calculate the block preparation ratio. The block preparation ratio (B_R) can be calculated as equation (1), in which the mean of the normal distribution is ES of each erection block.

$$B_R \sim N(\mu, \sigma), \tag{1}$$

where μ is the mean of ES time of each block and σ is the deviation of ES time of each block.

Through the simulation, it should be possible to confirm the planned key event observance rate, the optimal pitch value for obeying the key event schedule, block stock period as well as schedule delay, and the total period of the erection process based on the previously defined block preparation ratio and the erection network, which is established in the master production planning stage. These are summarized in Table 2.

For the erection, the erection of the next block can be performed when the predetermined work of the preceding block is processed, rather than the erection of the next block being performed after the

NOMENCLATURE

CPM = critical path method
DES = discrete event simulation
DEVS = discrete event system specification
ES = earliest start
MRP = material requirement planning

Fig. 1 Block erection on skid in S shipyard (http://www.isungdong.com)

preceding block is completely erected. The start date indicates the start date of the specific block, and the next block start date indicates the start date of the next block. At last, the finish date means the date on which the block is completely erected. The pitch of an erection block consists of standard pitch and buffer. During the standard pitch, a certain amount of work will be performed so that the next block can be started. However, an erection block may have some buffer time because of the work sequences in the erection network.

For example, in Fig. 2, blocks A, B, and C are erection blocks, and once blocks A and B start to be erected and a certain amount of work (in case of the subject shipyard: joint part tack welding) is completed during each standard pitch period, the erection process for the next block can be launched. In the case of block C, of which blocks A and B are the preceding blocks, it can be launched on July 10, when the tack welding of blocks A and B is completed. In the case of block A, although the standard pitch is 5 days since it can be found that the spare buffer is 4 days by understanding the precedence relation, the work schedule can be determined by considering the load condition and the working environment according to the given buffer period. Likewise, the period from the start date of the block to the start date of the next block is defined as a pitch of the erection block, and the erection pitch consists of the standard pitch, which is predetermined for each block, and the spare buffer, which is generated according to the precedence relation of activities in the erection network. Such indices will be derived through DES simulation of the erection process in this research.

Table 1 Deviation of block erection date

Type		Block	Block code	Deviation (sample)
Total	Curve block	Engine room	E	11.4
Total	Curve block	After	A	10.7
Total	Curve block	Hopper	H	8.4
Total	Curve block	Forward	F	17.1
Total	Curve block			13.8
Total	Flat block	Bottom	B	2.8
Total	Flat block	Side	S	11.2
Total	Flat block	Deck	D	12.0
Total	Flat block			8.8
Total				12.9

3. Process-centric DES simulation

3.1. Process-centric DES algorithm

The shipyard production simulation consists of a discrete event, which is different from the continuous objects used in the mechanical analysis. So the shipyard production simulation modeling can be performed through the DES. In this study, the process-oriented modeling methodology (Lee et al. 2014), which is well known to reflect the production characteristics of the shipyard, is used. Process-centered modeling methods are defined based on the flow between processes, relationships between processes and products, and relationships between processes and resources. The processes of the ship and offshore plant construction are expressed through the flow of process model entities, and the information on materials, equipment, and facility required for the process are expressed in connection with the process model entity. This is the best structure to express the shipyard production process by considering the reality of the shipyard where the proportion of line production factories with automated equipment is low and facilities are used differently depending on the situation. Therefore, engineers at a shipyard who are not accustomed to simulation can also perform modeling without additional training.

The atomic model of the simulation is defined based on the DES specification (DEVS) formalism (Hong et al. 1997), which is one of the widely known DES formalisms. The equation that represents the atomic model in the DEVS formalism is as follows. Each variable

Table 2 Input and output data of the simulation model

Data		Description
Input	Block preparation ratio	A random variable containing information such as completion of the preceding process, block transportation, and block setting
	Block erection network	Network-like workflow diagram with block erection sequence
Output	Observance ratio of key event	The rate at which key events begin on the planned start dates
	Schedule delay and stock period	Schedule delay and stock period of each erection block
	Optimized pitch	The optimized pitch of block erection process

represents the state transition and time advance in the input, output, and internals.

$$M = (X,\ Y, S, \delta_{\text{int}}, \delta_{\text{out}}, t_{\text{a}}, \lambda),$$

where X: the set of input ports and values, Y: the set of output ports and values, S: the set of states, $\delta_{\text{int}} : S \to S$, the internal transition function, and $\delta_{\text{out}} : Q \times X \to \text{S}$, the external transition function.

$$Q = \{(s, e) | s \in S, 0 \le e \le t_{\text{a}}(s)\} : \text{ the total state set},$$

where e: the time elapsed since the last transition, $\lambda : S \to Y$, the output function, and $t_{\text{a}} : S \to R^{+}_{0,\infty}$, the time advance function.

In the DEVS formalism, the model where two or more atomic models are connected is called a coupled model, and this model can be expressed in the following form (Kim 1995).

$$\text{DN} = (X,\ Y, M, \text{EIC}, \text{EOC}, \text{IC}, \text{SELECT}),$$

where X: the set of input ports and values, Y: the set of output ports and values, and M: the set of all components in DEVS,
$\text{EIC} \subseteq \text{DN.IN} \times M\text{.IN}$: the external input coupling relation,
$\text{EOC} \subseteq \text{DN.OUT} \times M\text{.OUT}$: the external output coupling relation,
$\text{IC} \subseteq M\text{.IN} \times M\text{.OUT}$: the internal coupling relation,
SELECT : $2^{M} - \varnothing \to M$: tie $-$ breaking selector.

The atomic process model used in this study can be defined as follows by applying the process-oriented modeling methodology based on the coupled model of the DEVS formalism.

$$\text{Process Based Coupled Model} = \left(X,\ Y, M_{\text{process}}, \text{PIC}, \text{POC}, \text{IC}, \text{SELECT}\right),$$

where X: input events set, Y: output events set, MProcess: process-centric sub-model set, PIC: process input coupling relation, POC: process output coupling relation, ICProcess: internal coupling relation of each process, and SELECT: internal model logics for external events.

To construct a simulation model using the atomic model described above, a method of connecting the atomic models and the process logic in-between the model is also necessary. The method of modeling the simulation elements of process units in a network diagram format is efficient; on the other hand, it is able to directly use the process information that is used in the production site. Therefore, it is intuitive for the workers to understand. Also, if the product information and equipment information, which include information such as specification, weight, and schedule are linked based on the process, it is possible to construct a simulation model that reflects the characteristics of shipyard production. Figure 3 and Table 3 summarizes the concept of the network diagram-based simulation model proposed in this study.

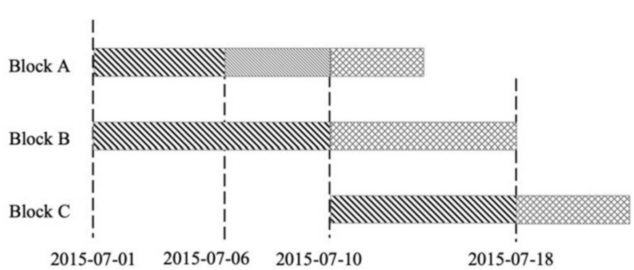


Fig. 2 Explanation for the pitch of block erection

3.2. Framework for process-centric DES algorithm

To support production management activities using simulation, concrete components and a framework that integrates the components from the information viewpoint are needed. The required simulation framework in this study is based on the DES algorithm. This framework would enable production management support through the 6-factor information model, KPI (Key Performance Index), and function definition process of the simulation algorithm.

Many simulation framework studies of shipbuilding activities have been conducted, including a study on production management system requirements for small and medium shipyards (Woo et al. 2009), a study on establishing a block ship assembly plan for a medium shipyard, verifying the established plan (Woo & Song 2014), a study on the framework for the shipyard production and logistics simulation (Woo et al. 2010; Woo et al. 2017) (Fig. 4), and a study on the six-factors of shipbuilding (Lee 2013). In this article, based on the simulation framework proposed in Woo et al. (2017), a system for erection simulation is defined.

4. Modeling of erection process for DES simulation

4.1. Analysis of block erection network

In this article, the abovementioned simulation modeling method is used to model the block erection process based on the erection network which is established in the master production planning stage. First, the erection network, which includes the start date of the erection blocks and key events and the erection sequence, is analyzed for the simulation. The activity inside the network consists of a minimum start date, a maximum start date, an erection block name, a forward pitch, and a reverse pitch. The minimum start date indicates the ES date of the block and is equal to the ES time in the CPM technique (Wiest & Levy 1969). The maximum start date indicates the start date of the latest start (LS) of the block, which is the same as the LS time. The forward pitch indicates cumulative pitch from keel laying and the reverse pitch indicates the degressive pitch from the load out. Figure 5 shows the erection network diagram of a certain vessel of the S shipyard to be modeled.

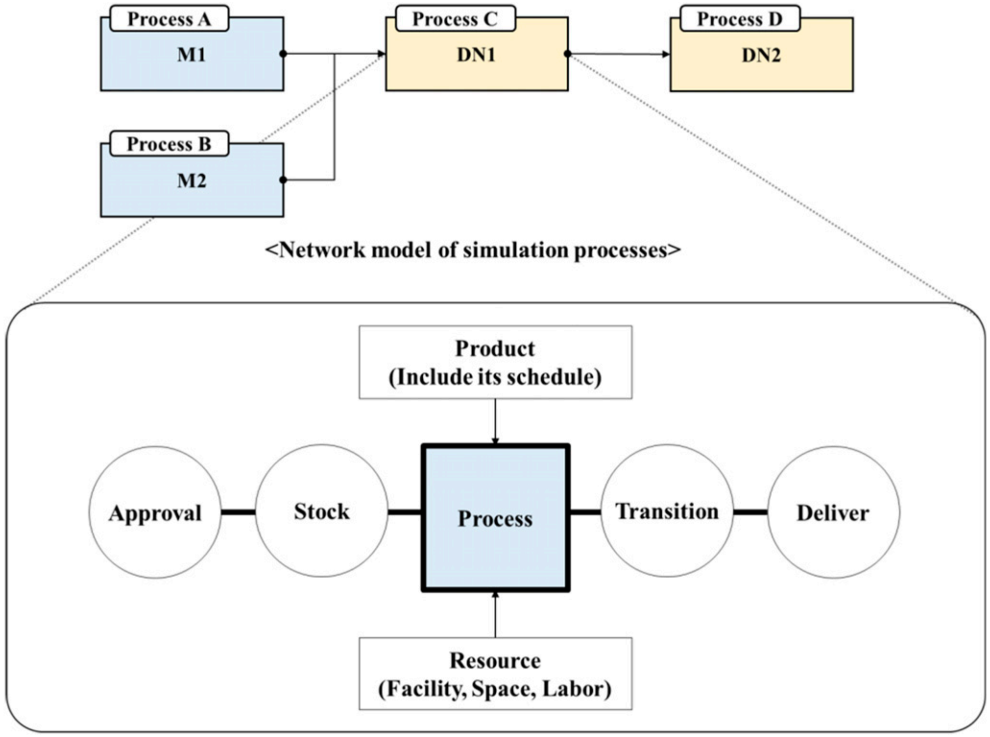


Fig. 3 Configuration of process-centric entity

4.2. Generation of input data for DES simulation

To generate input data for the DES simulation of the block erection process, the information of ship number, activity code, preceding activity, and pitch are extracted from the erection network data of a vessel in *S* shipyard. Next, the start date of each activity is calculated through the CPM analysis. After that, simulation input information is generated by reflecting the block preparation ratio which is calculated based on the start date of each activity and deviation across the blocks. The process of generating input data is seen in Fig. 6, which is automatically generated by a developed macro program. In addition, it is calculated by using the normal distribution for the block preparation ratio, and herein the requirements of the shipyard are reflected for a case where the block preparation ratio is negative or is more than twice the average. That is, a logic is added to set the value to zero for negative numbers and to limit the maximum value to twice the pitch when the value is more than twice the pitch.

Table 3 Description of logical parts of each process entity

Logic	Description
Approval	To check whether the product can enter the process based on availability of required resource
Stock	Triggered when the product is determined to enter the process
Process	To determine the working time of the entered product considering the resources
Transition	To select the next process
Deliver	Triggered when the product is about to move to next determined process

4.3. DES simulation modeling

Modeling and simulations are performed using the process-centric DES algorithm proposed in Section 3.1. The developed program consists of an adapter that automatically generates input data necessary for modeling from the erection network data in a shipyard, a modeler that can automatically perform modeling using input data, a simulator that can perform simulations based on user settings, and a reporter that can confirm simulation results and detailed analysis results. Table 4 shows the modeling adapter and the automatic modeling result (in the upper section) and the process logic and script code of each activity (in the lower section) in the developed program. Figure 7 shows a DES simulation environment equipped with these functions.

As for resource constraints, one transporter and one overhead crane are considered as required resources, which reflects the real production environment in the target shipyard. Bottom blocks are erected using the transporter and the remaining blocks except for the bottom block, a condition of using the overhead crane is applied to the model. Furthermore, in the case of the crane and the transporter, the logic is defined so that it can be used to erect the trailing block after 4 hours from the start of the erection.

4.4. Logical modeling

Block preparation ratio enables the user to check the possibility whether the erection process can start on the scheduled date by calculating the production completion date of the corresponding block. For the block preparation ratio, the initial scheduled date is the average, and the logic is implemented using the normal distribution that has the block variation of Table 1. Because each block

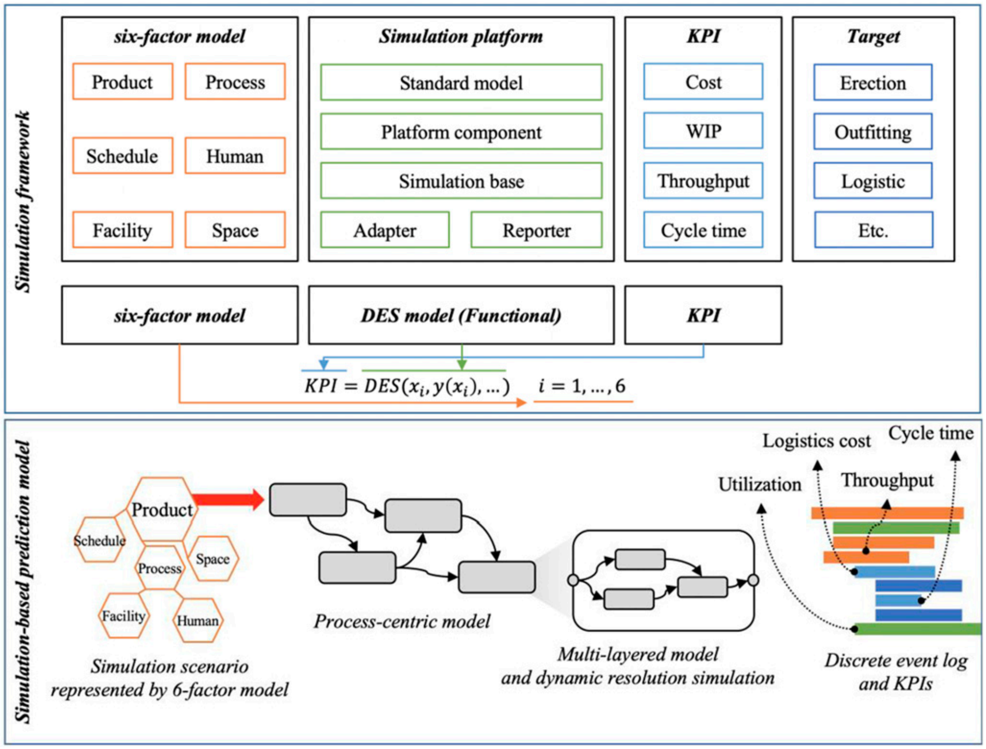


Fig. 4 Simulation framework for shipbuilding realization (Woo et al. 2017)

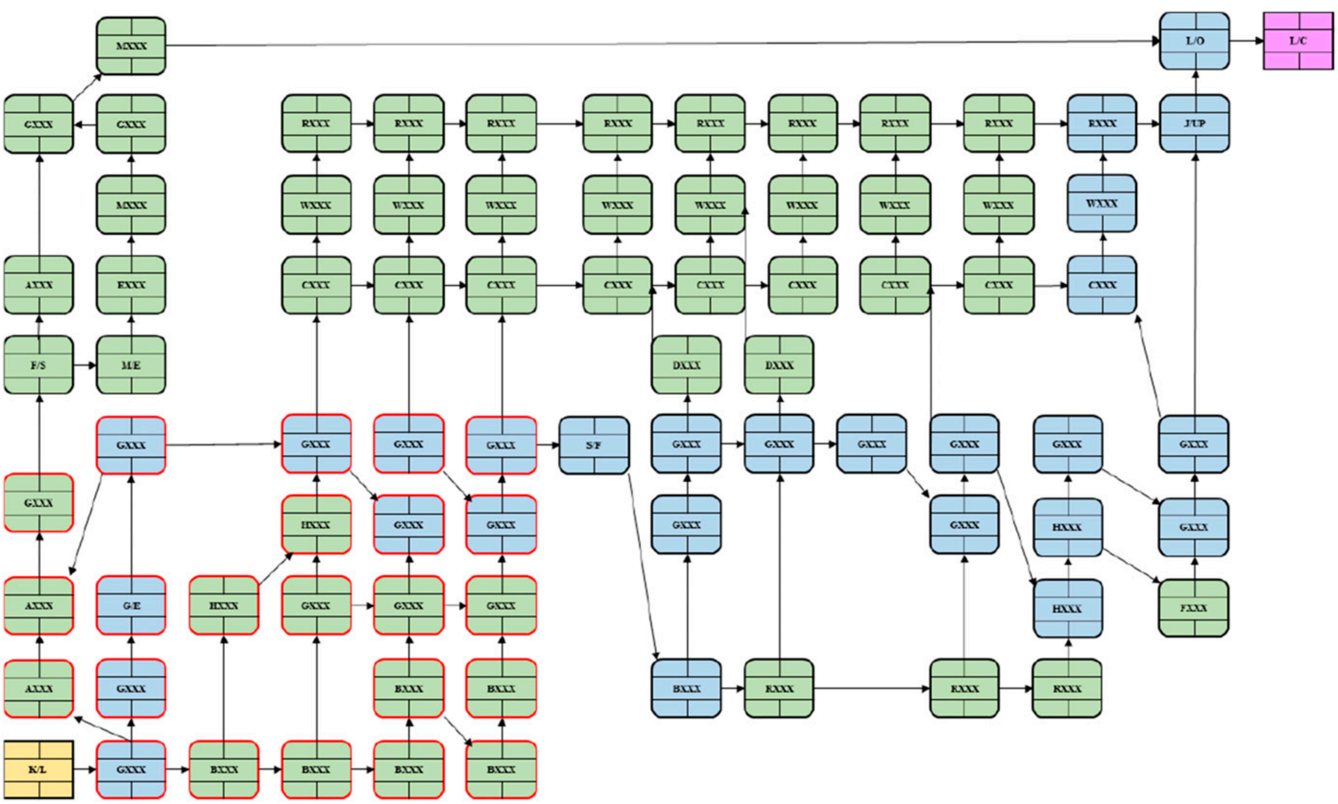


Fig. 5 Erection network diagram

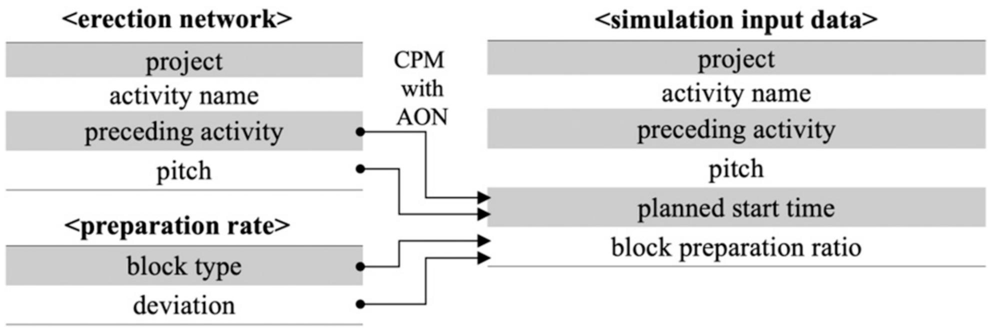


Fig. 6 Generation process of input data in the program

preparation ratio has an independent relationship with each other, even if a task is delayed because a preceding block is not prepared, the block preparation ratio of the corresponding erection block is not affected. This is because the block preparation ratio is calculated based on the forward pitch that can be obtained through the erection network. Figure 8 shows an algorithm that calculates the block preparation ratio, the start date, the stock of the block, and the delay time of the block erection.

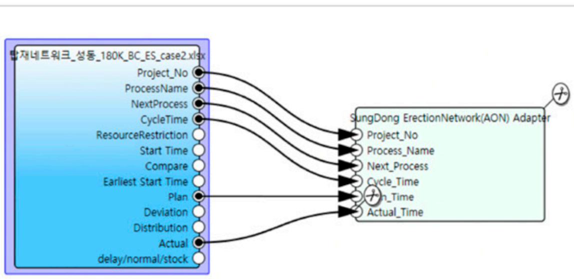
The existence of the preceding block of the blocks that are established in the planning stage is checked and the erection plan dates are calculated to calculate the forward pitch. The block preparation ratio is calculated by using the forward pitch and the deviation across blocks, and the date of calculated block preparation ratio is compared with the ES time on the simulation to judge whether or not the corresponding block is stock or delayed. Figure 9 and equations (2) and (3) show how to determine the block reservation rate, the planned time, and the actual time of the block.

$$B_R \sim N(\mu, \sigma),$$

$$d_W = t_S - B_R, \quad \text{when } t_S > \mathrm{BR}, \tag{2}$$

$$d_D = t_S - t_P, \tag{3}$$

Table 4 Simulation modeling



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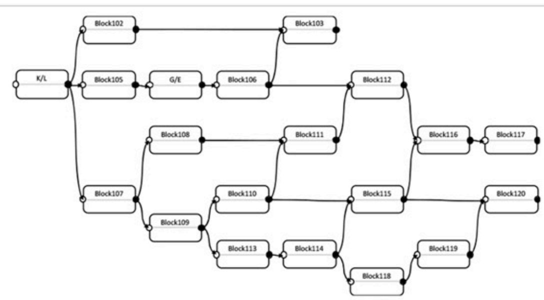
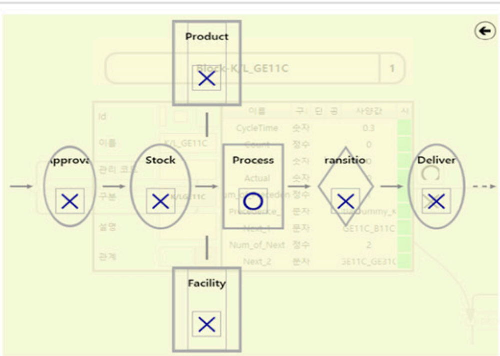


<activity network model>



<process logic configuration>

```
var _productKey;
var _next;
var _processName = get("Process", null, "Name");
var _NumOfNexts;
var _NumOfPre;
var _cycletime = get("Process", null, "CycleTime");
var _now = getNowFrom()/3;

if (_processName != "InitialDummy_K/L")
{
    _NumOfPre = get("Process", null, "Num_of_Precedence");
    for (var i = 0; i < _NumOfPre; i++)
    {
        _productKey = getAssigned("Product", 0);
        deliver(_productKey);
    }
    var _actual = get("Process", null, "Actual");
    if (_now < _actual) _cycletime = _cycletime + (_actual - _now);
}
```

<process logic script>

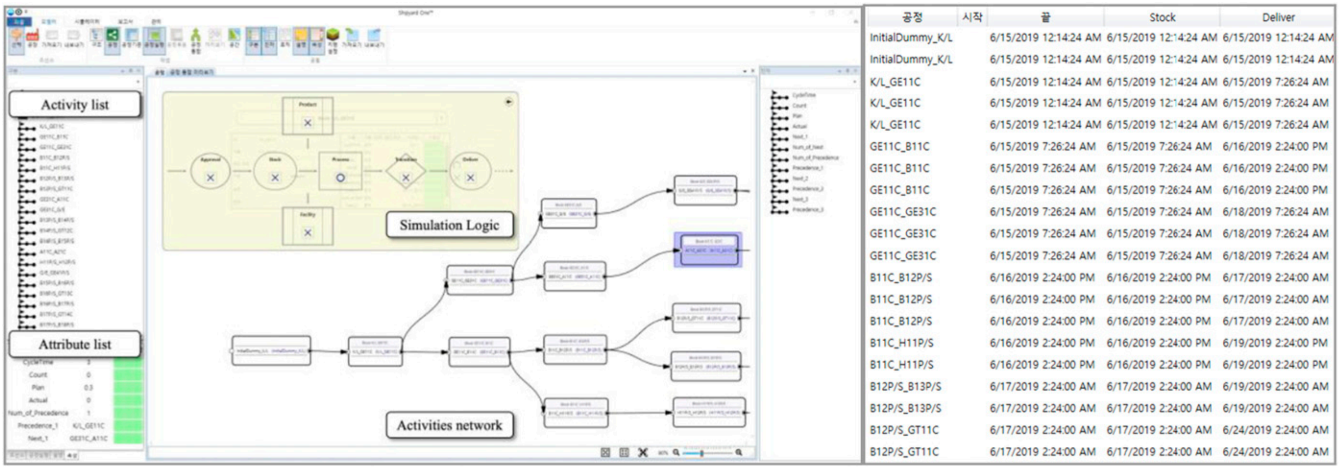


Fig. 7 DES simulation environment for block erection process (left: modeling environment, right: result of each activity)

where t_S: simulated start time of the activity, t_P: planned start time of the activity, t_F: simulated finish time of the activity, d_W: stock waiting duration of the activity compared to t_S, and d_D: delay duration of the activity compared to t_P.

As a result of analysis of the erection network, the ES time of the "A00" block is "2." Assuming that a value of "−1" is obtained when the block preparation ratio is calculated by considering the deviation of the corresponding block; this means that the block is already stocked 3 days before the ES time of the corresponding block. On the other hand, in the case of the "B00" block, the ES time shows "6," and assuming that the value of "7" is obtained when the block preparation ratio is calculated by considering the variability, it means that the corresponding block can be started when "6," but the erection process is delayed by "1" because the block is not prepared until "7." For the "C00" block, the ES time for simulation is "11" and assuming that the value of "9" is obtained when the block preparation ratio is calculated by considering the variability, which means that the corresponding block has already been completed when it is "9" and is stock for "2" before "11," which is the minimum start time. Besides, because the schedule of "B00" is delayed "1," which results in 1 day schedule delay of follow-up "C00" from planned start time "10" to simulated start time "11."

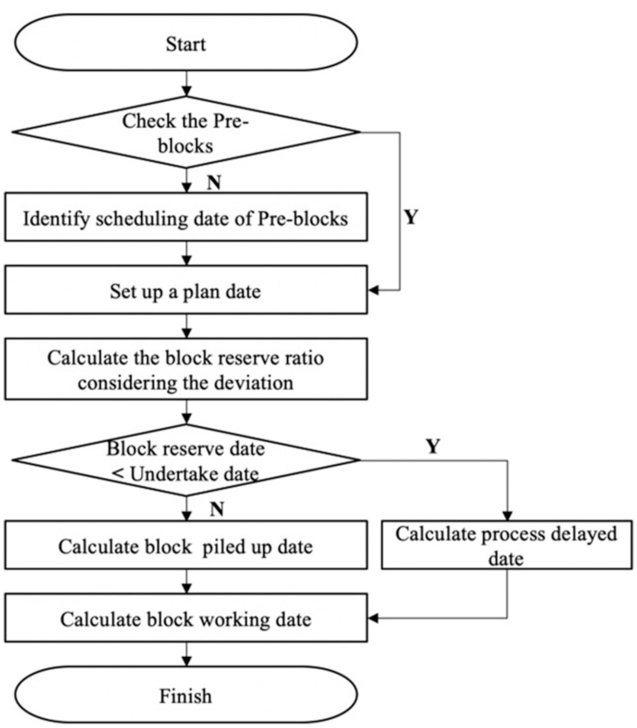


Fig. 8 Algorithm of each activity for DES simulation

5. Results analysis

Table 5 shows the input data required to perform the simulation of the block erection process. The activity code, preceding activity, and pitch are extracted from the erection network, and the planned start date (t_P) is calculated through the CPM. The block preparation ratio (B_R) is determined using normal distribution of the planned start date and deviation (σ) data defined by block type.

Based on the abovementioned data as input information, simulations are performed in the DES simulation environment which is defined and well-described in Section 4. Table 6 shows the simulation results. The simulation results can confirm records such as the planned start date (t_P), block prepared date (B_R), simulated start date (t_S), simulated finish date (t_F), and facilities used for each activity in the erection network by each simulation case.

5.1. Observance ratio of key event

To confirm the observance ratio of key events, the planned start date and the simulated start date of each key event are compared as seen in Table 7. Because the block prepared time is determined based on a randomly generated block preparation ratio, it is confirmed that the block prepared date, stock duration, and delay duration of each case are different even for the same block, which also affects the start dates of the key events. The result shows that the start dates of the key events, except for K/L, are delayed by

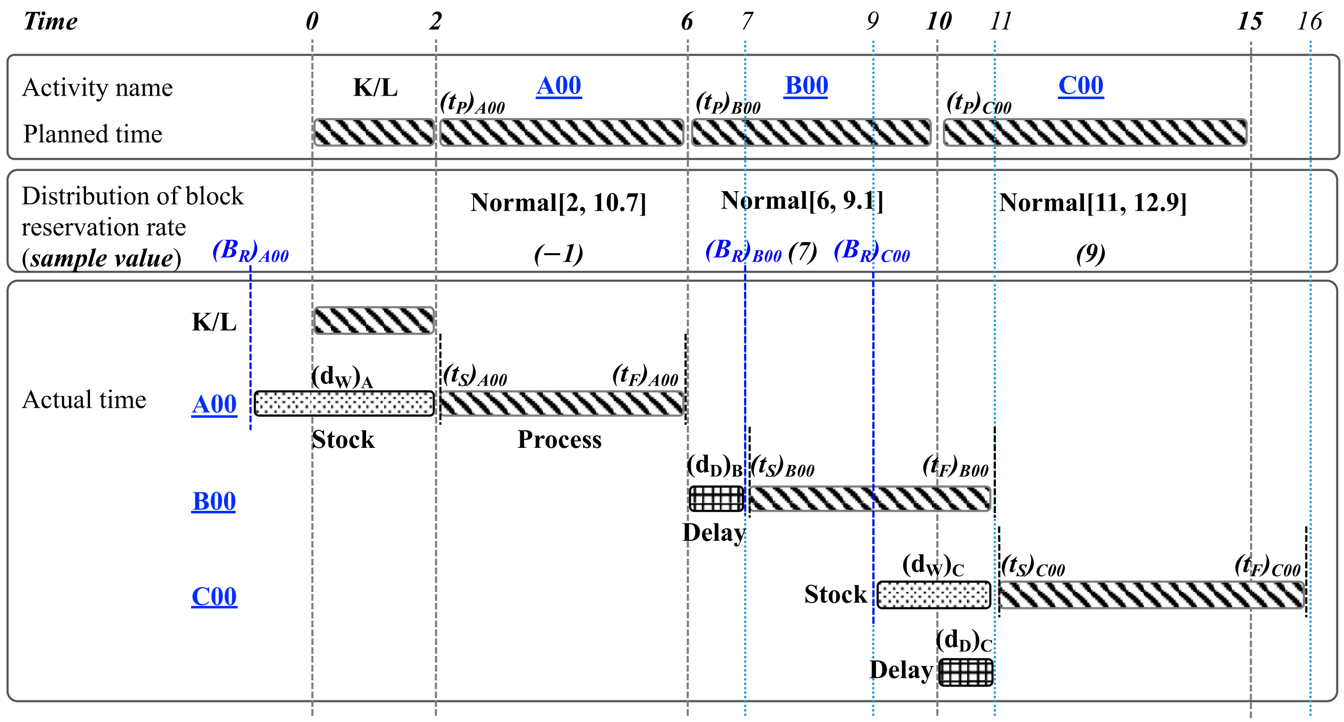


Fig. 9 Explanation for the logic of B_R, d_W, and d_D

approximately 20 days and confirms that they are similar with the confirmed delay durations from the performance data of S shipyard. The analysis result of the observation ratio against the plan for the start dates of the key events shows that 32% of the schedule is met within 5 days of delays in the shipyard. Twenty-one percent of the key events are delayed from 10 to 20 days and 48% are delayed more than 20 days.

5.2. Stock waiting and delay analysis

When the block preparation ratio is considered, the delay by each erection block is accumulated as the erection process progresses, thereby increasing the total lead time of erection process. Figure 10 shows stock wait duration (d_W) and delay duration (d_D) of each block through simulations considering the block preparation ratio.

Table 5 Input data for modeling simulation (selected)

Activity name	Preceding activity	Pitch	t_P	σ	B_R
K/L	–	.3	0	0	0
B12P/S	B11C	2	1.6	2.8	1
A11C	GE11C	3	4.3	10.7	8.6
GT13C	B16P/S	2	13.2	12.9	11.3
D32P/S	D31P/S	25	18.3	12.0	23.1
H22P/S	G21P/S	2	41.3	8.4	34.9
A51C	F/S	.3	41.3	10.7	48.7
C07C	C08C	5	45.3	13.8	51.8
R07P/S	W07P/S	.3	51.3	12.9	40.5
W02P/S	C02C	1	55.3	12.9	44.6

Unit: day

Regarding the stock wait duration, 72% of the erection blocks are expected not to exceed 5 days, yet 28% of the blocks are expected to be more than 5 days. In the case of scheduled delays, with respect to plan, approximately 41% of the blocks are expected to be less than 5 days, which is an allowable observation ratio criterion, while the remaining 59% are delayed by more than 5 days. Therefore, if the process is progressed according to the initial plan, it will adversely affect manpower scheduling as well as construction.

5.3. Pitch control based on simulation results

It is possible to calculate the improved pitch (P_O) with the following equation (4) by reflecting the stock and delay by activity in the erection network which is identified from 10 repetitive simulations.

$$P_O = \frac{\sum_{i=1}^{10} (t_F - t_S)_i}{10}, \tag{4}$$

where i: simulation case no., P_O: optimized pitch of the activity, t_S: simlation start time of the activity, t_F: simulated finish time of the activity.

Table 8 summarizes the delay (d_D) reduction effect employing the improved pitch. The average delay for the initial plan is 19.05 days because of the influence of the block preparation ratio, yet it is confirmed that the average delay for the improved plan employing the improved pitch which reflected the simulation result is reduced to 7.3 days. Hence, it is possible to eliminate unnecessary waiting and management in terms of such process delays and manpower operations. As a result, it is expected that productivity of the erection process can be enhanced.

Table 6 Simulation result in the program for a simulation case (selected)

Activity name	Next activity	t_P	B_R	t_S	t_F	Facility
K/L	GE11C	2019-06-15	2019-06-15	2019-06-15	2019-06-15	Transporter
B12P/S	B13P/S	2019-06-16	2019-06-16	2019-06-16	2019-06-18	Transporter
A11C	A21C	2019-06-18	2019-06-15	2019-06-20	2019-06-23	Transporter
D32P/S	GS13P/S	2019-06-26	2019-07-01	2019-07-17	2019-07-19	Crane
GT13C	GS15P/S	2019-06-29	2019-06-30	2019-07-02	2019-07-13	Transporter
C07C	C06C	2019-07-21	2019-07-16	2019-08-13	2019-08-14	Transporter
H22P/S	H23P/S	2019-07-30	2019-08-13	2019-08-13	2019-08-15	Crane
A51C	GM15C	2019-07-28	2019-08-07	2019-08-07	2019-08-08	Crane
R07P/S	R06P/S	2019-08-03	2019-08-06	2019-08-19	2019-08-19	Crane
W02P/S	R02P/S	2019-08-09	2019-08-03	2019-08-30	2019-08-31	Crane
						(Unit: day)

Table 7 Comparison result of key event schedule

	K/L		S/F		L/O		L/C	
Case	Plan	Actual	Plan	Actual	Plan	Actual	Plan	Actual
1	2019-06-15	2019-06-15	2019-07-19	2019-07-29	2019-08-21	2019-09-11	2019-08-23	2019-09-14
2	2019-06-15	2019-06-15	2019-07-19	2019-08-06	2019-08-21	2019-09-17	2019-08-23	2019-09-18
3	2019-06-15	2019-06-15	2019-07-19	2019-08-06	2019-08-21	2019-09-08	2019-08-23	2019-09-09
4	2019-06-15	2019-06-15	2019-07-19	2019-08-13	2019-08-21	2019-09-15	2019-08-23	2019-09-16
5	2019-06-15	2019-06-15	2019-07-19	2019-08-11	2019-08-21	2019-09-17	2019-08-23	2019-09-18
6	2019-06-15	2019-06-15	2019-07-19	2019-08-01	2019-08-21	2019-09-17	2019-08-23	2019-09-18
7	2019-06-15	2019-06-15	2019-07-19	2019-08-10	2019-08-21	2019-09-13	2019-08-23	2019-09-14
8	2019-06-15	2019-06-15	2019-07-19	2019-08-05	2019-08-21	2019-09-10	2019-08-23	2019-09-11
9	2019-06-15	2019-06-15	2019-07-19	2019-08-06	2019-08-21	2019-09-13	2019-08-23	2019-09-14
10	2019-06-15	2019-06-15	2019-07-19	2019-08-08	2019-08-21	2019-09-18	2019-08-23	2019-09-19

6. Conclusion

In this article, a simulation study is conducted using DES algorithm by considering the variability and resource constraints for the erection process. The block preparation ratio is applied as the most important factor of variability, and the existing actual data are reflected. Through the simulation, it is confirmed that the erection schedule is delayed because of the block preparation ratio, and the simulation result is more consistent with the performance data of the shipyard.

Using the simulation results can be categorized into two main categories which are the prediction of the block erection schedule and the prediction of the block stock duration according to the production schedule. In terms of predicting the block erection schedule, improved lead time predictions can reduce losses due to frequent delays and plan changes. In addition, it can be used as a supplementary means to examine the utilization of the limited stock area in the shipyard, because it can provide insight about the space consumption due to variability during the erection process.

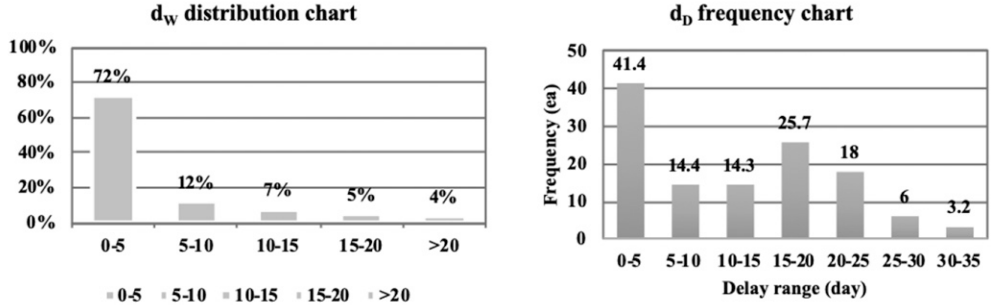


Fig. 10 d_W distribution chart (left) and d_D frequency chart (right)

Table 8 Decrease of d_D after pitch revision (partly selected)

Activity list	Start date of each activity			d_D of each activity		
	Initial t_P	Improved t_P	Simulated t_S	Initial d_D	Improved d_D	Reduction rate (%)
K/L	2019-6-15	2019-6-15	2019-6-15	0	0	0
B12P/S	2019-06-16	2019-06-16	2019-06-18	2	1.4	30
A11C	2019-06-19	2019-06-21	2019-06-22	3	.8	73
GT13C	2019-06-28	2019-07-01	2019-07-04	6	3	50
D32P/S	2019-07-03	2019-07-14	2019-08-13	41	29.2	29
A51C	2019-07-26	2019-08-02	2019-08-09	14	6.7	52
H22P/S	2019-07-26	2019-08-14	2019-08-26	31	11.9	62
C07C	2019-07-30	2019-08-12	2019-08-20	21	7.2	66
R07P/S	2019-08-05	2019-08-21	2019-08-21	16	.1	99
W02P/S	2019-08-09	2019-09-02	2019-09-07	29	4.7	84
L/C	2019-08-23	2019-09-15	2019-09-22	30	6.9	77

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