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Estimating Production Metric for Ship Assembly Based on Geometric and Production Information of Ship Block Model

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Abstract: To secure technological competitiveness in shipbuilding and offshore industries, the continuous application and development of various technologies is essential. Efficient scheduling in shipyards is an important management task, whereby materials and manpower are allocated at the appropriate time and to the correct workspace. Although some large shipyards ensure effective scheduling and production management through simulations employing advanced technologies, most shipbuilding industries, including small- and medium-sized shipyards, continue to use an index based on past experiences. However, this legacy index, termed the basic unit, involves poor engineering logic; therefore, it does not appropriately reflect a shipyard's working environment, which changes rapidly in response to technological developments. Although this has led to a demand for improvements in the basic unit, a clear solution has not been presented thus far. In this study, a method for calculating the man-hours required for assembly, which is the basis for preparing the basic unit, is proposed. First, the assembly process is analyzed, and individual activities involved in the assembly process are quantified and formulated into working hours, which is defined as a production metric. Based on a ship's computerized block model, the geometric properties and production information required for calculating the metric are generated automatically as far as possible; this is to establish a convenient production metric calculation system. The proposed method features complete applicability in new shipyards through a customization. It also serves as a tool for predicting the metric of new ships or comparisons with those of existing ships.

Keywords: production metric; man-hour estimation; CAD block model; shipbuilding assembly process

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1. Introduction

The shipbuilding industry exhibits unique characteristics that differ from those of other manufacturing industries, including the automobile and aircraft manufacturing industries. Ships, categorized as single products, are generally larger in scale than other products, and therefore, the scale of shipyards is also significantly larger than those of other industries.

Unlike industries following the "assemble to order" (automobile industry) or the "make to order" (aircraft industry) strategies, ship production is classified under the "engineering to order" strategy. During ship production, there is a significant difference between the manufacturing processes required for each component; this makes it difficult to apply automation to the entire process. Ship construction successively involves basic, detailed, and production design stages, each catering to the requirements of ship owners. The design, and thus the corresponding assembly process, often vary depending on the requirements of the ship owner, resulting in variability of the subsequent processes. Therefore, it is necessary to predict the changing schedule resulting from the variability.

From the perspective of manufacturing, the shipbuilding industry is defined as an assembly-intensive manufacturing industry that involves assembling a large number of components. As the numerous materials required for ship construction must be supplied in a timely manner, it is necessary to continuously supply these materials during ship construction. For this purpose, appropriate scheduling is required. In terms of shipyard assembly, scheduling refers to the process of coordinating the overall ship assembly schedule [1]. The various workshops in the shipyard possess different production capacities depending on the capabilities of their equipment. Therefore, load-leveling, achieved by allocating work quantities that correspond with the specifications of each workshop or workplace, is an important task during assembly scheduling.

Considering the ever-changing production processes and the resulting changes in the schedule, an index is utilized to determine, in advance, the amount of manpower, time, and materials required for fabricating a block. Based on this index, the production manager can inform suppliers about the appropriate quantities of materials and their delivery times, ensure that work is evenly distributed among the working groups, plan to utilize equipment efficiently, and assign the appropriate amount of manpower for each task. Currently, many shipyards use the concept of a "basic unit" that can be used for the index to calculate the required man-hours and the associated wages for block production.

The basic unit refers to factors that cause a change in the man-hours required for assembly; these factors depend on whether a steel plate is curved or flat, whether a butt or filet weld is required, and the workplace environment of the shipyard. Production managers typically predict the cost of assembling blocks by multiplying the basic unit with the block quantity and accordingly estimate the distribution of manpower and materials [2]. Basic information, such as the calculated man-hours and material quantity, is used as a guideline for the management of outsourced tasks as well as tasks performed inhouse.

However, the use of the basic unit involves clear limitations. The basic unit used in most shipyards comprises empirical values of past shipbuilding data. Therefore, the basic unit is only effective for blocks that are identical or similar to those built previously. Among the basic units, the use of factors considering the environment of the shipyard, especially the workplace, is also limited in terms of scalability. Shipyard managers agree that the basic unit is effective only when it is continuously updated based on the developments in fabrication methods, equipment, and environmental changes over time. Currently, however, small- and medium-sized shipyards are unable to procure and employ reasonable tools or methods for the renewal of the basic unit; thus, the use of basic units involves a fundamental limitation, in that it does not appropriately reflect real-world conditions.

Major large shipyards have consistently devoted efforts toward improving their basic units, and as a result, they have established a system that reflects the characteristics of their respective yards. The established basic unit system, which is the main indicator of shipyard characteristics, is classified as confidential, completely restricting external access. However, in the case of small- and medium-sized shipyards, there has been limited development in terms of establishing the basic unit. The approximate basic unit, which is typically based on past experience at the worksite, is implicitly operated by a few managers. Therefore, there is an urgent need for a general approach for the analysis and definition of basic unit systems.

Research using simulation technologies as a method for efficient scheduling has been conducted previously. In one such method, a simulation-based ship production model was created; subsequently, a virtual shipyard was created and a simulation of the erection process was performed to verify this model [3]. A process-oriented ship production simulation method that introduced the concept of virtual manufacturing, deviating from the existing resource-oriented technique to simulate the flow of production processes, was proposed [4,5]. Subsequently, a model capable of applying a process-oriented discrete event simulation was developed [6]. A method of measuring process capability by modeling an assembly plate for a new shipyard without using actual data was introduced by Sone et al. [7]. A case study of a machine-learning-based simulator capable of predicting the man-hours required for block erection by using the ensemble technique has also been introduced [8]. Although various simulation studies have been carried out, these previous approaches require accurate master data represented by the basic unit. Therefore, the importance of preparing an appropriate basic unit is further emphasized.

Thus far, very few reported studies have analyzed shipyard production processes and predicted the required material quantity and man-hours in a systematic manner. A study on calculating the welding amount using production information extracted from CAD data has also been introduced [9]; however, its results were limited to simple quantity calculations that could not account for the overall assembly process. A method of calculating the man-hours required for weekly and monthly process planning using regression analysis was also proposed [10]; however, this approach is significantly different from the approach proposed herein, which involves predictions for each unit process.

In this paper, we propose a method for calculating the required man-hours, called the production metric, via an engineering approach, as opposed to approaches based on past experiences or empirical results alone. Once the production metric is obtained, it is possible to logically calculate, compare, and evaluate the current basic unit of a shipyard; this also enables the production manager to solve potential problems at a site. The term production metric proposed herein refers to man-hours from a production perspective. This metric is defined as a generic concept that can express the difficulty of a specific task in relation to the material quantity. The terms "production metric" and "man-hours" are occasionally used interchangeably.

At its core, the proposed method involves extracting geometric and production information from a ship's CAD model, analyzing the assembly process based on work order, and logically calculating the man-hours required for the assembly process. For this purpose, geometric information such as the width, length, thickness, center of gravity, and directional vector are calculated from CAD data available at the design stage, and any additional production information required is extracted and processed if necessary. The procedure for assembling the constituent structural members of the block is sequentially arranged and simulated to numerically formulate the work procedure for each assembly process. Finally, all the work steps for each process are quantified, and the total production metric for the target block is calculated.

The ultimate goal of this study is to analyze activities occurring during the assembly process in a shipyard via a systematic approach and to numerically express the expected working time for each activity. As the time required for each activity is highly dependent on the work characteristics and practices of each shipyard, it is difficult to accurately calculate the actual man-hours required until the activities of the site are analyzed in detail. Even if they are identified, these characteristics or practices cannot be disclosed. Therefore, it is desirable to use the proposed production metric as a guideline for analyses of the working time required for the actual process, rather than directly comparing the results. Effective use of the proposed method is based on the premise of customizing the process of calculating the actual working time based on the practices of each workshop. However, to verify the validity of this method, the trend of the production metric is examined by comparing the results with those of a large shipyard.

The method proposed herein is based on the CAD model that includes structural design drawings. By comparing the man-hours obtained by applying the existing basic unit with the metric obtained via the proposed method, it is possible to identify current activities that can be improved. This approach can help production managers seeking to improve the current basic unit. If structural design drawings do not exist, however, it implies that data regarding the ship are unavailable. In such cases, the exact quantity of materials and the required man-hours cannot be obtained. Nevertheless, if an approximation of the man-hours required for a ship is needed in advance, the proposed method can be used indirectly.

The remainder of this paper is organized as follows. In Section 2, the overall description of the ship assembly process and the generation of input data, such as the geometric and production information, are presented. Section 3 explains the derivation of production metric for each activity involved in the assembly process. In Section 4, the production metric for a ship block model is calculated, and its validity is discussed.

2. Configuration of Production Metric Estimation System

2.1. Overall Assembly Process

The ship assembly process is typically divided into three consecutive construction stages: A sub-assembly, followed by a unit-assembly, and finally a grand-assembly [11]. A sub-assembly is an assembly process in which longitudinal members or stiffeners are welded on the base plate. A unit-assembly refers to the process of assembling sub-assembly blocks and associated structural members. Lastly, a grand-assembly involves integrating the unit-assembly blocks. Therefore, during the sub-assembly stage, the block has a relatively simple geometric shape, but the complexity increases as the construction stages progress.

To predict the man-hours required during the ship assembly process, it is necessary to first identify the characteristics of the assembly process. As ship assembly consists of a sequence of processes, the basic processes can be defined and classified as the representative unit process. Moreover, as there are numerous members or components with various shapes which further complicate the assembly process, it is important to accurately grasp information regarding the shapes of members and components in advance.

This paper proposes a method that automatically extracts necessary information regarding the structural members from a block model and calculates a quantity measuring the required man-hours. If the appropriate amount of man-hours is predicted in advance by using the proposed method, it is possible to secure a workspace for ship construction as early as possible and also set up the overall construction schedule, enabling the provisioning of appropriate material quantities and the required manpower. Figure 1 shows the data flow of the complete production metric estimation system. The naval architects prepare the CAD model, the node tree of the model, and joint information. The production manager inspects the results of production metric estimation for the further scheduling and production management.

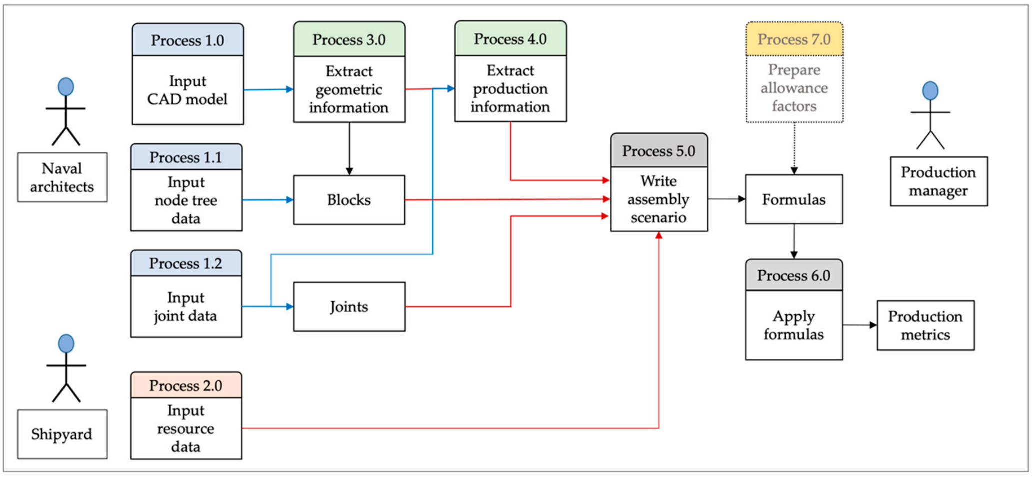

Figure 1. Data flow of production metric estimation system.

2.2. Three-Dimensional Product Models and Block Types

Three-dimensional (3D) CAD data modeled in the design phase are used to represent the construction blocks of a ship. The example shown in Figure 2 represents the midship block of a container vessel.

Blocks at the final design stage are extremely complex because they include multiple objects such as pipes, ladders, supporting structural members, and a number of outfitting equipment, in addition to the hull plates and associated components. The existence of these additional objects usually causes a change in the assembly sequence. In this study, only the purely structure-oriented parts, which are required in the assembly shops, are considered; the remaining parts are excluded through preprocessing.

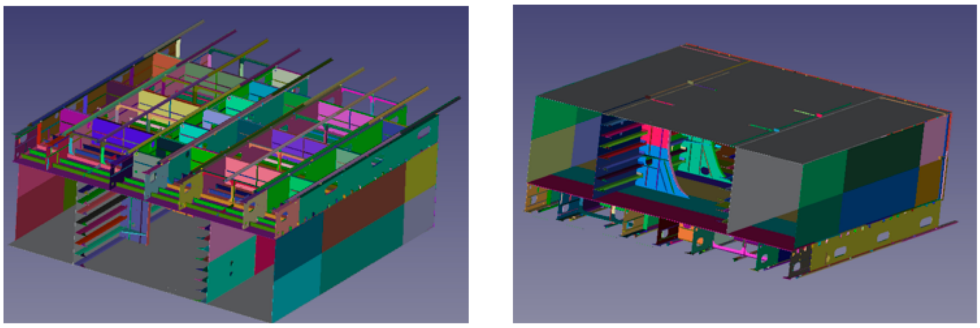

Figure 2. Computerized model of a block: Bottom (**left**) and top (**right**) iso-views.

In this study, blocks were classified into L1, L2, and L3 levels according to their size, shape, and functionality. It is difficult to standardize block division methods because they differ depending on the environment, capability, and design practices of shipyards. Therefore, we apply rules to categorize the blocks by considering the shape similarity, work type, and complexity of each block. The L1-level refers to blocks in which longitudinal and small members are assembled on the base plates. The L2-level corresponds to blocks in which the L1-level blocks are combined. Finally, the L3-level denotes blocks containing multiple L2-level blocks appended by some L1-level blocks. Blocks divided into the L1 and L2 levels correspond to the sub-assembly and unit-assembly blocks, respectively, but do not necessarily coincide. All representative block types defined in this study are shown in Figure 3.

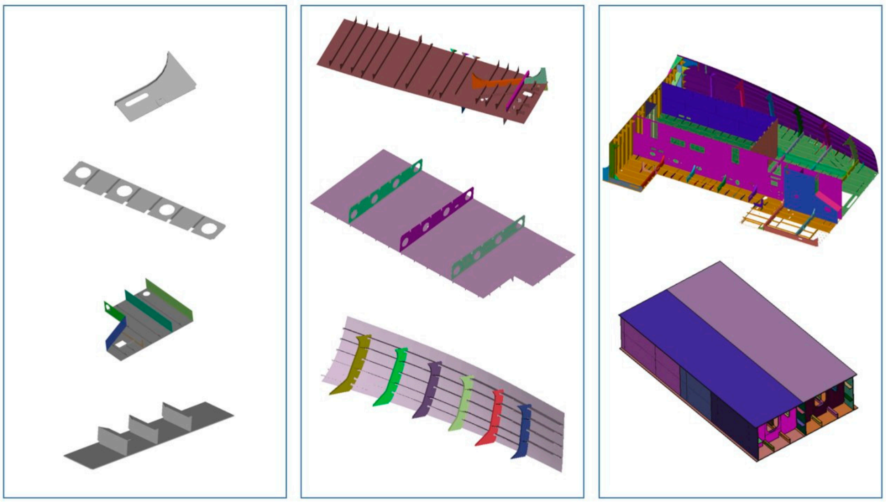

Figure 3. Three types of assembly blocks: L1 (**left**), L2 (**middle**), and L3 (**right**).

The CAD file format generally adopted by the design department of a shipyard is a special format mainly used by the shipbuilding CAD system. The CAD file contains not only the geometric data of the hull, but also production information such as the node tree and welding information. Cases requiring a file conversion often arise when delivering the CAD file to other departments or organizations; however, during a file conversion, some of the contents of the file can be altered or lost. Therefore, when using the CAD file from a shipyard, it is necessary to verify the data in the CAD file. In this study, to standardize the working process, the CAD files are first converted to STEP [12], a standardized format, and correction is subsequently performed, if necessary.

2.3. Derivation of Geometric Information

For the assembly process, we regard the blocks or structural members as the main objects that are moved, placed, and assembled through human intervention. Assuming that the production metric calculation is based on the geometric shape information of these blocks, it is necessary to collect their geometric information in advance.

Geometric information of the blocks should be obtained from the block models provided at the design stage. As block models have different sizes and division methods, the types and storage methods of geometric information are normally different. It is inefficient, and occasionally even impossible, to manually grasp the necessary information from a complex model. Therefore, functions are required to automatically extract the necessary geometric information from a computerized block model.

To process the CAD model, various tasks for manipulating the geometric shape, such as functions to read, write, analyze, extract, and visualize specific data, are required. In this study, OpenCASCADE [13] was utilized. OpenCASCADE is a powerful CAD/CAM/CAE kernel and a development platform composed of reusable C++ libraries. As it is open-source, it is suitable for the initial work required for system construction.

As the shapes of the extracted members are different, a representative description for every extracted member is desirable. A bounding box is used to represent the shapes of the members or components used in the block, the entities of which are summarized in Table 1. The area of a member is defined by the largest among the faces constituting the shape, and the aspect ratio is used to characterize the geometric shape.

Table 1. Geometric attributes of extracted structural members.

Name	Symbol
Centroid of bounding box	C
Length of bounding box	L
Breadth of bounding box	B
Thickness	T
Area	A
Weight	W
Aspect ratio	AR
Normal vector of largest face	**N**

The geometric information obtained from a CAD model is classified into basic geometric information directly extracted from the model and extended geometric information based on design knowledge. Basic geometric information includes the intersection length, welding length, common surface, and common vertex extracted from two neighboring members, in addition to the entities described in Table 1.

Intersections generated by overlapping members are important for assembly. The intersection lengths and endpoints are calculated directly or by using the function provided by OpenCASCADE.

Computerized block models are often imperfect. In such cases, either no intersection is found, or some of the information of the intersection is lost, resulting in an inaccurate intersection. This problem is regarded as model imperfection and not a problem of the intersection itself. Imperfect models are often encountered in shipbuilding CAD models; thus, they need to be corrected by applying additional algorithms during the intersection operation step.

In this study, an intersection is classified into three cases based on the relationship between two neighboring members: (1) The two members intersect, (2) the two members are in contact and have a common surface, and (3) the two members are separated (although this case should be recognized as an intersection owing to characteristics of the ship assembly structure). The first two cases can be easily solved using a general intersection algorithm, as shown in Figure 4. The third case, however, is regarded as an error mainly caused by modeling or file conversion. To resolve this problem, we add a heuristic algorithm that considers an intersection if the minimum distance between the two members is less than 2 mm.

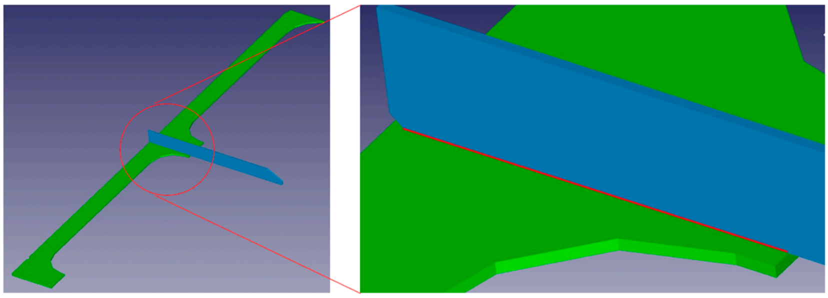

Figure 4. Example of intersection of two members.

Extended geometric information consists of the properties to which additional algorithms and operations are applied based on basic geometric information. An example of extended geometric information is the factor used to determine the role of a member. At this time, it can be determined whether a given member is a base plate or a structural member by using the aspect ratio of the breadth and the length of the member. The values obtained by multiplying the aspect ratio with the area of the member are listed in ascending order, and the point where these values change sharply is set as the threshold. Members with values lower than this threshold are determined to be structural members, whereas those with values exceeding the threshold are determined as the base plates.

2.4. Derivation of Production Information and Provision of Resource Information

The geometric information described in the previous section is insufficient for calculating the production metric. Apart from geometric information, a process for obtaining production information is also required. It is inefficient, or occasionally impossible, for the user to provide all necessary production information directly. Therefore, this study considers extracting as much production information as possible from the computerized model, and if this extracted information is insufficient, additional methods to fabricate production information are provided. Nevertheless, information that cannot be obtained from the computerized model, such as welding posture or work efficiency, needs to be manually provided by the user.

Different types of welding information can be generated based on the intersection characteristics of neighboring members in the computerized block model. First, an intersection line is extracted to calculate the welding length, and the joint type, defined as a filet or butt joint, is determined by considering the normal vector of the two intersecting members. In addition, the thickness and joint type of the two intersecting members are used to determine the welding method and bevel. Three types of bevels—single V-groove, Y-groove, and double V-groove—are considered depending on the thickness of the member. Furthermore, the calculation of the leg length is described in Appendix A as an example of deriving production information.

As the working time may vary depending on the shipyard environment or equipment specifications, shipyard resource information must be provided, in addition to the production information. The resource information considered in the developed system includes the shipyard layout, workplace locations, welding machine specifications, speed and allowable load of the means of transportation (such as trailers and transporters), speed and allowable load of the cranes, and movement speed of the workers.

2.5. Variability of Input Values

As the manufacturing process in the shipbuilding industry is not standardized, work factors such as work activity, equipment, workshop size, and layout differ. In addition, even with the same factors, the results or performances often tend to differ depending on the work environment, worker capabilities and conditions, and workload of a workshop. In particular, when workers are involved, variability according to the workers' status becomes an important factor. Therefore, the variability of each input value and its result should be considered.

To consider the variability of input variables, the range of the variables should be determined. For this purpose, a reliable method involves setting the maximum and minimum values for each task, and within this range, values corresponding to the current situation can be interpolated. In practical scenarios, however, it is difficult to determine the maximum and minimum values. Although a survey can provide these results, it is impossible to collect sufficient samples within a short period of time. In this study, the Westinghouse rating system [14,15] was used as a tentative method for evaluating workability.

The Westinghouse rating system analyzes work based on four factors: Skill, effort, environment, and consistency. Despite being an old concept, owing to which the values for each factor are somewhat impractical, the approach itself is noteworthy. This rating technique is a system that evaluates the current worker's ability by comparing the performance of the worker being observed with that of a normal worker.

In the shipbuilding industry, it is assumed that working time is significantly affected by the will and skill level of the worker, and the surrounding environment. With regard to detailed processes, such as the adjustment step included in the setting process, it is known that the working time for unskilled workers can be up to twice that of skilled workers. This study applied the Westinghouse rating system to reflect the variability in working time.

For example, if a worker with the attributes {skill = good, effort = excellent, condition = good, consistency = excellent} performs tack welding, which requires 15 min under normal conditions, the working time is shortened to 12.8 min, as follows:

- Normal tack welding time = 15 min
- Good skill (C1): +0.06
- Excellent effort (B2): + 0.08
- Good condition (C): 0.00
- Excellent consistency (B): 0.03
- Total score: 0.17
- Observed tack welding time = Normal time/(1+Westinghouse total score) = 15/(1.0 + 0.17) = 12.8 min

Here, each factor is selected from Table 2. In this example, the difference between the performances of the two workers is 15%, and this difference is reflected by the variability in welding speed.

Table 2. Factors of Westinghouse rating system.

Westinghouse Rating System											
Skill			**Effort**			**Environmental Condition**			**Consistency**		
Super	A1 A2	0.15 0.13	Excessive	A1 A2	0.13 0.12	Ideal	A	0.06	Perfect	A	0.04
Excellent	B1 B2	0.11 0.08	Excellent	B1 B2	0.10 0.08	Excellent	B	0.04	Excellent	B	0.03
Good	C1 C2	0.06 0.03	Good	C1 C2	0.05 0.02	Good	C	0.00	Good	C	0.00
Average	D	0.00	Average	D	0.00	Average	D	0.00	Average	D	0.00
Fair	E1 E2	−0.05 −0.10	Fair	E1 E2	−0.04 −0.08	Fair	E	−0.03	Fair	E	−0.02
Poor	F1	−0.16	Poor	F1	−0.12	Poor	F	−0.07	Poor	F	−0.04

3. Derivation of Production Metric

3.1. Components of Production Metric in Assembly Process

The production metric was defined as an index for man-hours from a production perspective. To consider the production metric in terms of engineering, it is necessary to prepare the data and formulas required for each process. For example, when moving and positioning a member to a work position, a series of processes including lifting, lowering, and securing the member is applied. If a formula is established to calculate the working time of each process, the required number of man-hours can be determined by substituting necessary data in the formulas.

Detailed assembly processes include transportation, alignment, setting, tack welding, turnover, welding, and grinding, as shown in Figure 5. In the proposed approach, when analyzing the block assembly process, we first consider the theoretically derived sequential work procedures, while referring to current practices carried out at the shipyard's assembly site. First, the assembly order, defined as Priority #n, is determined between (1) two neighboring base plates, (2) a base plate and structural members, and (3) structural members. In principle, the work entailed in each assembly sequence is performed in order of the joint name. With regard to welding, auto carriage (AC) welding is performed first, followed by CO_2 welding.

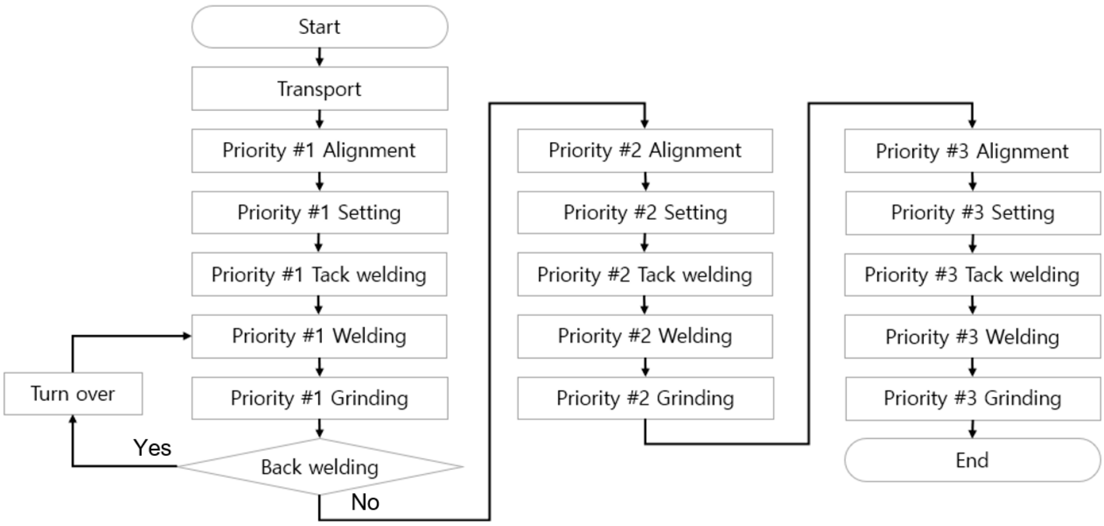

Figure 5. Assembly procedure: Priority #1 for assembly between base plates, priority #2 between base plate and structural members, and priority #3 between structural members.

3.2. Transportation

Transportation refers to the process of transferring members from the stockyard to the workplace. The first step in the analysis of the transportation operation involves defining the means of and basic operations for transportation. Trailers are the main means of transportation in most shipyards. Transportation is divided into a lifting process, where members in the stockyard are loaded onto a trailer; the traveling process, where the loaded members are transported to the worksite; and the lowering process, where the members are unloaded at the worksite. A forklift is used to load and unload the members onto the trailer in groups by placing them on a pallet. The members to be transferred are grouped according to the allowable load of the forklift, and the number of lifting and lowering operations is determined according to the number of groups. After collecting the necessary data, a basic formula dividing the path with the speed is applied to obtain the detailed metric for each process.

The metric required for transportation is expressed in Equation (1), which is closely related to the layout of the shipyard. Therefore, information regarding the order of sub-processes and shop layout is required. As the use of GPS has recently been simplified, this technology, which can measure the transportation time between shops, has emerged as the basis for measuring transportation processes in real time.

$$\text{Transportaton} = \text{Loading} + \text{Securing} + \text{Transporting} + \text{Unbinding} + \text{Unloading} \quad (1)$$

3.3. Alignment

Alignment is the process of moving members transferred to the workshop to a marked joint line. To move a member, consecutive steps including binding the member with a clamp, lifting it using a crane, moving it down to the joint line, and releasing the clamp are required. The main equipment used is a hoist or overhead crane.

The metric for alignment is calculated by considering the lifting, traveling, lowering, clamp fixation, clump disassembly, and other sub-processes, similar to the calculation of the transportation metric. The formula for calculating the alignment metric is shown in Equation (2):

$$\text{Alignment} = \text{Securing} + \text{Lifting} + \text{Transporting} + \text{Lowering} + \text{Unbinding} \quad (2)$$

It should be noted that no obstacles should block the movement of a member. If the assembly unit is complex, a function to check interference should be provided.

3.4. Setting

Setting refers to a series of processes in which a member or block is lifted using a crane, moved to the target position, lowered again, positioned according to the marking line, and fixed with a mounting device. The member is fixed with a clamp or wire tied with a lug and then moved. To fix a member at a specific position, it is necessary to align it in the same direction as the centroid and the direction vector of the target member. At this time, an adjustment process for fixing the member is required. The movement of the member involves lifting, traveling, and lowering; each metric is similar to the corresponding one used for alignment.

During the setting process, the adjustments require a considerable amount of time. An adjustment is a significantly difficult process to approach mathematically, because the process varies depending on the weight of the member or block. For this reason, quantifying the adjustment is barely feasible, even in large shipyards. Therefore, in this study, the minimum and maximum times required for adjustment are determined through field interviews, and the logic of configuring the time linearly according to the block size is established. Equation (3) is the formula used to calculate the setting metric:

$$\text{Setting} = \text{Securing} + \text{Lifting} + \text{Transporting} + \text{Lowering} + \text{Adjustment} + \text{Fixing} + \text{Unbinding} + \text{Unfixing} \quad (3)$$

3.5. Tack Welding

Tack welding is a process of simply welding only a part of the welding line, such that the members placed at certain positions do not fall before the main welding process. After the welding machine is prepared, the worker moves to the welding line of the parts to be temporarily joined, and tack welding is performed at regular intervals. Once this welding process is completed, the finishing process is commenced. The formula for tack welding is expressed in Equation (4):

$$\text{Tack welding} = \text{Preparation} + \text{Welding} + \text{Finishing} \quad (4)$$

As the time required for preparation cannot be quantified, it is substituted with a specific value. To obtain the metric for the tack welding process, it is necessary to determine the tack welding length, as shown in Figure 6.

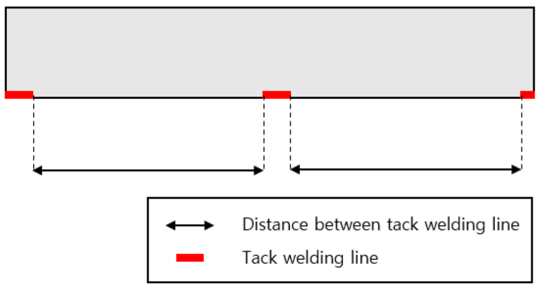

Figure 6. Tack welding distance and length.

In this study, the tack welding length was calculated by multiplying the intersection length of the joint with the tack welding ratio. The intersection length can be extracted from geometric information, and the value of the tack welding ratio is one generally used at shipyards.

3.6. Turnover

The turnover process refers to the process of overturning an assembly when an additional operation is required at the backside of the assembly. In this study, rotation includes both the process of simply flipping the panel and the process of rotating the block in the air using wires. Equation (5) presents the formula of the turnover process, which is expressed by the sequential processes of lifting, rotation, and lowering the assembly:

$$\text{Turnover} = \text{Securing} + \text{Lifting} + \text{Rotation} + \text{Lowering} + \text{Unbinding} \tag{5}$$

The detailed procedure for turnover is summarized in Table 3.

Table 3. Detailed procedure of turnover process.

Sequence	Block Level	Process	Device	Equation
Securing → Lifting → Rotating → Lowering → Unbinding	L1	Securing	Clamp	Clamp installation time
		Lifting	Crane	Length/Lifting speed
		Rotation		Length/Rotating speed
		Lowering		Length/Lowering speed
		Unbinding	Clamp	Clamp uninstallation time
	L2, L3	Securing	Lug	Lug installation time
		Lifting	Crane	Length/Lifting speed
		Rotation		Length/Rotating speed
		Lowering		Length/Lowering speed
		Unbinding	Lug	Lug uninstallation time

The turnover process generally differs depending on the resources owned by the shipyard. The structural mechanics of rotating the assembly also affects the work time, although this factor is not considered in the present study.

3.7. Welding

Welding refers to directly bonding solids by applying heat and pressure to same or different types of materials. This is a dominant process because it directly affects the structural integrity of the assembled structure, and thus, its application range is sufficiently wide to account for a majority of the working time required for the assembly process.

The welding process, whose formula is shown in Equation (6), includes a preparation step, the main welding time, and the finishing process. The method for calculating the welding metric is essentially the same as that for the tack welding metric:

$$\text{Main welding} = \text{Preparation} + \text{Welding} + \text{Finishing} \tag{6}$$

The preparation step refers to the time required to prepare the welding machine and move it to the welding position. This preparation time is generally short for L1-level blocks. However, for L2- or L3-level blocks, where the size of each block is larger and the interiors of the blocks are complex, a considerable amount of time is required for preparation. Thus, coordinates from the worker's starting position to the welding position are compared to compute the distance.

To determine the welding time, welding volume was utilized. The welding volume, as described in Appendix A, was calculated using production information, including the joint type, welding length, bevel, leg length, and welding machine type. After determining the type of welding machine, the appropriate current and voltage are set by considering the thickness of the joint members. The welding time is then calculated using the relationship between the current, voltage, and welding speed. Furthermore, corresponding factors for flat, vertical, and overhead working positions are multiplied with the metric to reflect the difference in postures. These factors are obtained via analyses of the worker's posture. Table 4 shows detailed formulas for calculating the metric of the welding process for L1-, L2-, and L3-level blocks.

Table 4. Detailed procedure of main welding process.

Sequence	Block Level	Process	Tool	Activity
Preparation → Welding → Finish	L1	Preparation	Human	(Target location − Start location)/Moving speed +(Target height − Start height)/Climbing speed
		Welding	Welding machine	Welding volume * Joint length/Welding speed
		Finishing	Human	(Start location − Target location)/Moving speed +(Start height − Target height)/Descending speed
	L2, L3	Preparation	Human	(Target location − Starting location)/Moving speed +(Target height − Start height)/Climbing speed
		Welding	Welding machine	(Welding volume * Joint length/Welding speed) * Space factor
		Finishing	Human	(Start location − Target location)/Moving speed +(Start height − Target height)/Descending speed

3.8. Grinding

Grinding is the finishing process that is used to smoothen a welded surface. Thus far, there has been no reported approach for calculating the time required for grinding. As grinding is proportional to the weld length, the method of simply multiplying the welding time with a certain factor is widely used as a general rule. In this study, the grinding factor, which is generally used in shipyards, is multiplied with the welding time to determine the grinding time.

4. Application of Production Metric

The developed production metric calculation system was tested on a block located at the center of a container vessel. The shape of the block is shown in Figure 2, and a portion of the basic geometric data of the members extracted from the model is shown in Figure 7.

Production information that cannot be obtained from the block, such as the node tree, welding information, and shipyard resources, is processed using a file or a method requiring direct inputs from the user.

To calculate the production metric for each block, the block corresponding to the route code is used. The route code refers to a block classified by considering the properties of the block or the assembly stage. This classification method, which is used in some large shipyards, is not standardized, but it is an accepted approach for representing a block as an execution plan unit. The production metric calculation proposed in this study was developed to be essentially independent of the block classification method. However, for a comparative analysis of the results, the block corresponding to the route code was targeted. Some results of the calculated metric are presented in Table 5.

```
LB6Q
Part: _14_SR3S_S11_001
     L:700.011    B:100.001    T:12.025    W: 657.340    C: (263362.637, -2697.623, 14093.083)  N: (-0.892, -0.451, 0.000)
Part: _14_SR5S_S11_001
     L:6047.000   B:150.000    T:12.000    W: 8392.829   C: (260865.485, -4399.000, 8291.952)   N: (0.000, -1.000, 0.000)
Part: _14_SR5S_S1_001
     L:6047.000   B:150.000    T:12.000    W: 8392.829   C: (260865.485, -3559.000, 8291.952)   N: (0.000, -1.000, 0.000)
Part: _14_SR3S_S1_001001
     L:6049.500   B:150.000    T:12.000    W: 8396.362   C: (260866.497, -4399.000, 14081.952)  N: (0.000, -1.000, 0.000)
Part: _14_SR3S_S1_002
     L:6049.500   B:150.000    T:12.000    W: 8396.362   C: (260866.497, -3559.000, 14081.952)  N: (0.000, -1.000, 0.000)
Part: _14_SR5S_S5_001
     L:1783.350   B:163.027    T:12.010    W: 2222.154   C: (263656.016, -3128.795, 8283.000)   N: (-0.451, 0.892, 0.000)
Part: _14_SR3S_S2_001
     L:2158.595   B:163.371    T:12.010    W: 2752.376   C: (263479.925, -3049.762, 14073.000)  N: (-0.451, 0.892, 0.000)
Part: _14_SR5S_S4_001
     L:2399.953   B:163.535    T:12.000    W: 3092.772   C: (263362.546, -2716.908, 8283.000)   N: (-0.451, 0.892, 0.000)
Part: _14_LB6Q_B552_002
     L:777.817    B:344.014    T:15.000    W: 1271.041   C: (258557.500, -4542.858, 18822.332)  N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_003001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (260807.500, -4544.313, 2785.744)   N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_004001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (261557.500, -4544.313, 2785.744)   N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_001001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (259307.500, -4544.313, 2785.744)   N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_005001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (262307.500, -4544.313, 2785.744)   N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_006001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (263057.500, -4544.313, 2785.744)   N: (-1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_002001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (260057.500, -4544.313, 2785.744)   N: (1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_007001
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (263807.500, -4544.313, 2785.744)   N: (1.000, 0.000, 0.000)
Part: _14_LB6Q_B551_007002
     L:777.817    B:344.014    T:15.000    W: 1271.046   C: (258557.500, -4544.313, 2785.744)   N: (1.000, 0.000, 0.000)
Part: _14_LB6Q_B552_001001
     L:777.800    B:346.903    T:15.000    W: 1271.049   C: (261557.500, -4552.203, 18782.024)  N: (-1.000, 0.000, 0.000)
```

Figure 7. Geometric data of members: Length (L), breadth (B), thickness (T), centroid (C), and normal vector (**N**).

Table 5. Results of metric calculation for detailed activities (excerpt).

Route Code	Block Code	Joint ID	Part A	Part B	Unit Task	Metric [Seconds]
L1_03	BL61B	N/A	_14_LB6A_BL61B_A_001001	N/A	Alignment	35.91
L1_03	BL61B	N/A	_14_LB6A_BL61B_W1_001001	N/A	Alignment	35.20
L1_03	BL61B	N/A	_14_LB6A_BL61B_A_001001	N/A	Setting	1025.45
L1_03	BL61B	BL61B-1	BL61B-A	BL61B-W1	Tack Welding	165.47
L1_03	BL61B	BL61B-1	BL61B-A	BL61B-W1	Welding	647.60
L1_03	BL61B	BL61B-1	BL61B-A	BL61B-W1	Welding	647.60
L1_03	BL61B	BL61B-1	BL61B-A	BL61B-W1	Grinding	238.26
L1_03	BL61B	BL61B-1	BL61B-A	BL61B-W1	Grinding	238.26
L1_03	BL61Q	N/A	_14_LB6P_BL61Q_A_001001	N/A	Alignment	35.91
L1_03	BL61Q	N/A	_14_LB6P_BL61Q_W1_001001	N/A	Alignment	33.32
L1_03	BL61Q	N/A	_14_LB6P_BL61Q_A_001001	N/A	Setting	1025.45
L1_03	BL61Q	BL61Q-1	BL61Q-A	BL61Q-W1	Tack Welding	165.47
L1_03	BL61Q	BL61Q-1	BL61Q-A	BL61Q-W1	Welding	647.60
L1_03	BL61Q	BL61Q-1	BL61Q-A	BL61Q-W1	Welding	647.60
L1_03	BL61Q	BL61Q-1	BL61Q-A	BL61Q-W1	Grinding	238.26
L1_03	BL61Q	BL61Q-1	BL61Q-A	BL61Q-W1	Grinding	238.26

The calculated metrics for the blocks at the route codes are plotted in Figure 8. The legend L1_XX on the x-axis represents the XX L1-level blocks, whereas L2_YY represents the YY L2-level blocks. The results were compared with the data of a shipyard, and their deviations are summarized in Table 6.

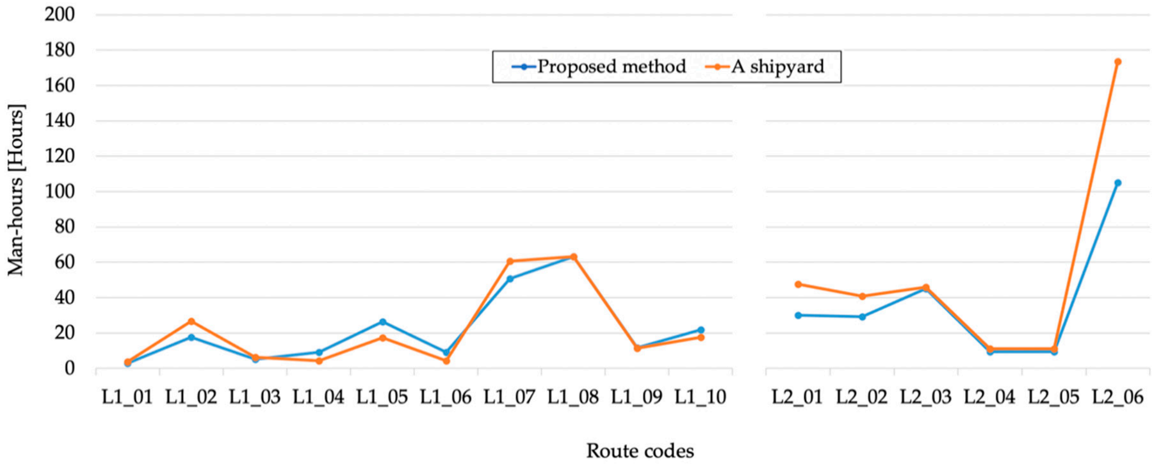

Figure 8. Comparison between production metrics obtained via the proposed method (blue) and shipyard data (orange): L1-level (**left**) and L2-level (**right**) blocks.

Table 6. Deviation of production metrics obtained via the proposed method from shipyard data.

Route Code	A. Metrics via Proposed Method [Hours]	B. Metrics from Shipyard Data [Hours]	Deviation: $\frac{B-A}{B}$ [%]
L1_01	3.067	3.67	−16%
L1_02	17.775	26.68	−33%
L1_03	5.158	6.38	−19%
L1_04	9.243	4.38	111%
L1_05	26.449	17.35	52%
L1_06	9.243	4.38	111%
L1_07	50.755	60.69	−16%
L1_08	63.289	63.32	0%
L1_09	11.667	11.42	2%
L1_10	21.868	17.56	25%
L2_01	29.957	47.73	−37%
L2_02	29.262	40.86	−28%
L2_03	45.051	45.87	−2%
L2_04	9.373	11.21	−16%
L2_05	9.373	11.21	−16%
L2_06	104.958	173.69	−40%

4.1. Discussion

Based on a comparison of the two results, it is evident that the trend of the production metrics calculated via the developed method is somewhat consistent with that of the metrics used in an actual shipyard. However, in some blocks at the route codes, the two results are different, which can be explained by various factors such as the equipment, layout, and expertise of the worker.

As the developed method aims to sequentially define the working procedures involved in the assembly process and calculate the metrics based on geometric and production information, a certain amount of variation between the actual man-hours of a shipyard and the metrics obtained using the developed method is expected.

A dominant cause of the difference between the two results is believed to be the allowance time. The value calculated for the actual shipyard reflects both the normal time and the allowance time, whereas the results of the proposed method do not fully account for the allowance time. The allowance time is normally shorter than the normal time, but it is difficult to quantify. Therefore, in most shipyards, allowance time is included in the normal time at a certain ratio. At present, we have not been able to determine a reasonable ratio that can be applied for this purpose. Therefore, the differences caused by the exclusion of a short but non-negligible allowance time must be acknowledged.

Next, it is necessary to understand that the results derived from this study do not necessarily coincide with those of an actual shipyard. The working methods employed at a shipyard, especially at the assembly workshops, are significantly influenced by the human and material constraints reflected over the past decades. In contrast, the proposed method is developed by theoretically analyzing the assembly process. These two approaches are inevitably different, which, in turn, results in a discrepancy in the results. However, if the allowance time is considered in the proposed method and the practices of a specific shipyard are customized, the gap between the two results is expected to be reduced considerably.

4.2. Use of Correction Factors

For the abovementioned reasons, it is meaningless to directly compare our results with those of a shipyard. To compare the two methods in detail, it is necessary to determine precise values for the lowest level of activities; however, such data cannot be obtained from shipyards.

The trends of the two results shown in Figure 8 appear similar, but the deviation is still significant. Therefore, it is difficult to directly use the developed method in the current state. To apply the developed method to current ships or ships to be built in the future at a specific shipyard, an alternative method capable of calibrating the difference between the two results must be developed. To this end, we propose a simple correction method using workplace factors.

Assuming that the complexity of a block affects the fabrication time, the number of joints in the block is used as the criterion for complexity. The number of joints of each route code is divided by the corresponding metric, and the resulting value is adopted as a correction factor for that particular route code. After normalizing the metrics of all the route codes, the normalized value is multiplied with the metric calculated using the proposed method to obtain the corrected metric. Results of the correction are shown in Figure 9 and compared with the results before correction, shown in Table 7.

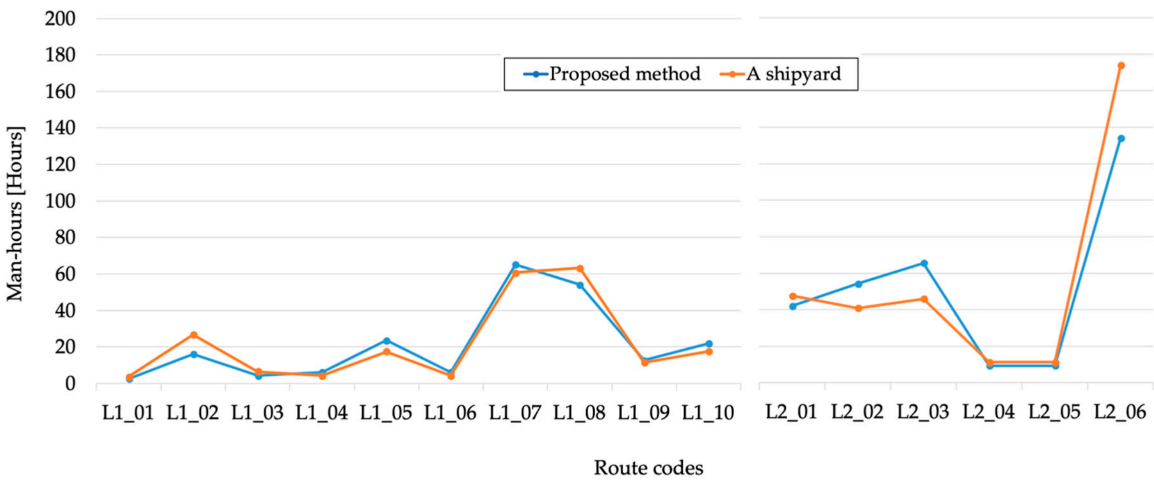

Figure 9. Comparison between production metrics obtained via the proposed method after applying the correction factor (blue) and shipyard data (orange): L1-level (**left**) and L2-level (**right**) blocks.

Table 7. Comparison of production metrics before and after correction process.

Route Code	A. Metrics from Shipyard Data [Hours]	Before Correction		After Correction	
		B. Metrics via Proposed Method [Hours]	Deviation: (A − B)/A [%]	C. Metrics via Proposed Method with Correction [Hours]	Deviation: (A − C)/A [%]
L1_01	3.67	3.067	−16%	2.611	−29%
L1_02	26.68	17.775	−33%	16.001	−40%
L1_03	6.38	5.158	−19%	4.378	−31%
L1_04	4.38	9.243	111%	6.159	41%
L1_05	17.35	26.449	52%	23.509	35%
L1_06	4.38	9.243	111%	6.159	41%
L1_07	60.69	50.755	−16%	65.159	7%
L1_08	63.32	63.289	0%	54.039	−15%
L1_09	11.42	11.667	2%	12.634	11%
L1_10	17.56	21.868	25%	21.868	25%
Sum of L1	215.83	218.51	1%	212.52	−2%
L2_01	47.73	29.957	−37%	41.971	−12%
L2_02	40.86	29.262	−28%	54.265	33%
L2_03	45.87	45.051	−2%	65.502	43%
L2_04	11.21	9.373	−16%	9.373	−16%
L2_05	11.21	9.373	−16%	9.373	−16%
L2_06	173.69	104.958	−40%	134.011	−23%
Sum of L2	330.57	227.97	−31%	314.49	−5%
Sum of L1 + L2	546.40	446.49	−18%	527.01	−4%

For L1-level blocks, which feature less complicated shapes, there was no noticeable improvement or deterioration; however, for L2-level blocks, which feature more complex shapes, a significant improvement was noted in the sum of all route codes. However, this correction method is limited because the number of joints cannot fully represent the complexity of a block; hence, the correction results should not be overestimated.

Another correction approach involves using a curve fitting technique. Here, the relationship of the differences between the two results and the number of joints is formulated as a correction function to be fitted. Our initial trial showed that the correction performance was similar to that of the method using workplace factors.

Although the tentative corrections achieved using workplace factors and curve fitting yield satisfactory results, the use of the proposed correction methods still remains limited. We believe that the customization process, which is required at a shipyard when the proposed method is applied, will serve as the optimal correction method. The simple correction approaches proposed herein can be used for pure estimation until complete customization is achieved.

5. Conclusions

A method for calculating the production metrics for ship blocks by primarily using a three-dimensional CAD model was proposed. To extract meaningful data from the CAD model, an open-source geometry processing library was used. Additional information required for the metrics was automatically processed via geometry processing algorithms. By supplementing the shipyard's resource information, the production metrics of the assembly process that can be used in a shipyard were calculated.

In this study, we developed a method that mainly utilizes the three-dimensional geometric model and some production information, without relying on empirical data or past experiences in a shipyard. The developed method served as the basis for easily predicting the production metrics during the design stage. The significance of this study lies in the fact that the proposed method enables the estimation of production metrics for new ships, even when construction data are unavailable.

However, the proposed method currently involves a few limitations. First, to use the developed method effectively, a computerized block model, including structural drawings, must exist. Nevertheless, to predict the required material quantities and man-hours in advance or to estimate the schedule for building a new ship, the abovementioned limitation can be overcome simply by using the model of a similar ship. Second, because the proposed method only considers normal time, its results cannot be compared with the actual production metrics of a shipyard. Therefore, a follow-up study in which the allowance time is included needs to be conducted. Lastly, to apply the developed method to a new shipyard, it is necessary to determine factors that reflect the environmental characteristics and practices of workshops in the shipyard. This emphasizes the need for customization. Customization is an indispensable process for the application of this method and can be regarded as an essential requirement as well as a constraint.

Because the developed production metric calculation system is a method for theoretically calculating man-hour-related metrics in sequence by separating detailed tasks, its results may differ from the man-hours currently used in shipyards. The results inevitably differ from the values used at a shipyard that has been in operation for a long period of time, where characteristics of the yard reflect past experiences. Given that one of the goals of the developed method is predicting the production metrics in the earliest possible design stage, it would be unfair to expect agreement between results of the developed method and the metrics used at actual shipyards, at least until further developments in this method. Nevertheless, continuously applying the proposed method and customizing it in accordance with the characteristics of a shipyard can result in a method suitable for use in actual shipyards. Furthermore, machine learning techniques, which have emerged as a powerful tool in recent years, are expected to be of significant help in terms of customization, and the authors are conducting follow-up studies to assess the potential of applying these techniques.

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Appendix A

Welding volume is usually calculated based on complex factors such as the root gap, root face, and shell thickness, but it is difficult to directly derive such information from a block model. In this study, an indirect method [16] was used to calculate the welding volume using only the joint type, bevel shape, leg length, and welding length.

Figure A1 shows the welding section area, $A_{section}$, expressed in terms of the welding leg length, t_{leg}. The welding volume is obtained by multiplying the welding section area with the welding length.

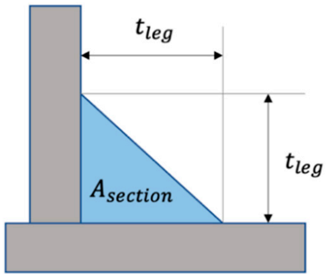

Figure A1. Welding section area expressed by leg length.

The welding leg length was calculated using the formula specified in DNV-GL [17], as shown in Equation (A1):

$$t_{leg} = f_c\ f_1\ f_2\ t_w \tag{A1}$$

where f_c is the factor related to the environment of the block, f_1 is the factor depending on whether the welding is continuous or spaced for each welding line, f_2 is the coefficient depending on edge preparation, and t_w is the thickness of the member. In addition, f_c is 1.2 when the block is a liquid cargo tank, ballast tank, dry cargo, or bilge well; otherwise, its value is 1.0. Because all filet welding covered in this study is continuous, f_1 is 0.3 and f_2 is 1.0. Thus, Equation (A1) becomes Equation (A2):

$$t_{leg} = 0.3\ t_w \tag{A2}$$

Note that the minimum leg length tabulated in Table A1 should be used instead of Equation (A2) to ensure the appropriate calculation of the welding volume.

Table A1. Minimum leg length for plate thickness.

Plate Thickness, t_w, in mm	Minimum Leg Length
$t_w \leq 4.0$	3.0
$4.0 \leq t_w \leq 6.5$	3.5
$6.5 < t_w \leq 9.0$	4.0
$t_w \geq 9.0$	4.5

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