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Study on a Layout Design Method for Leisure Ship Production Factories using a Heuristic Location-Allocation Algorithm

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Abstract : *To ensure that the production system of a factory is efficient, the factory layout design should consider the location and material flow plans of facilities, workshops, and storage areas. Highly productive factories need to have an optimized layout planning process, and a customized design methodology of the production system is a necessity for feasible layout planning. This paper presents a method for designing a layout module's size and shape and provides a heuristic location-allocation algorithm for the modules. The method is implemented and validated using a rich internet application-based platform. The layout design method is based on the leisure ship production process; this method can be used for designing the layout of a new factory or remodeling an existing factory and its production system. In contrast to existing layout methods, the inputs required for the proposed method, such as target products, production processes, and human-resource plans, are simple. This layout design method provides a useful solution for the initial stage of factory design.*

Key Words : *Factory layout design, Layout planning, Heuristic location-allocation algorithm, Rich internet application, Leisure ship production process*

1. Introduction

The design of plant layouts means that the facility layout problem (FLP) needs to be solved to determine the physical locations of facilities in factory workshops. In most factories, logistics accounts for 20 - 50 % of the total production costs, which are affected greatly by the placement and layout of equipment in factories(Tompkins et al., 1996). After the factory layout has been determined, the layout becomes a major factor that affects production systems in the long term. Thus, there is a need for a systematic process to design the layouts of factories and plants to ensure effective production. However, most companies that produce leisure ships have insufficient money and time to invest in factory layout design. In reality, companies are limited by the scale of their business.

In general, FLP features are defined logistically by the costs of material so that the equipment can be minimized(Heragu and Kusiak, 1998). The leisure ship manufacturing process is characterized by small-scale, on-demand production. Thus, the leisure ship process is located approximately in the middle of batch-type and job shop-type processes. It is possible to consider the unit space used for work as a single piece of equipment or a facility(Stevenson and Hojati, 2002). In most cases, the final selection of the layout is determined by the stakeholder's decisions, and the stakeholders regard quantitative evaluation criteria such as a distance between equipment and facilities as significant factors in the selection process. The measurement of the distance between the facilities and workshops is based mainly on the distance between the center points of the facilities and workshops during the initial layout evaluation. If the locations of the input and output points of the workshops have been determined, a quantitative evaluation of the layout requires the perpendicular distance of the workshops(Jeong and Seo, 2007). This demands that the detailed flow of the logistics needs to be defined.

Heuristic algorithms are the most common methods used to solve FLPs and other problems related to arrangement. A heuristic algorithm was developed as an early solver for rectangular forms. At present, an algorithm is available that can solve various shapes, which is applicable in various fields(Jeong and Jeon, 2008).

Factories that produce leisure ships usually have a cellular layout production system. The cellular layout production system is a method that arranges the production facilities and workshops to respond appropriately to changes in the production volume. This type of system can improve the efficiency to produce various types of products and it gives the necessary flexibility required to produce bespoke items(Lee and Cho, 1999). Studies of layout

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evaluation are focused on solving the layout problem, which is related to job-shop-type processes and cell-type factories. In these studies, FLP is assumed to be a quadratic assignment problem (QAP) and various optimization techniques have been used to determine an optimal solution. These studies have focused on quantitative solutions to the FLP problem itself rather than developing a new process or methodology for layout problems. This is a problem because of the following reasons.

For many years, FLP studies have applied a basic layout design process and selected patterns specifically for each production type. However, the workshop and facilities used in the layouts were considered to be a fixed variable in these previous studies. Thus, practical studies cannot determine the size and the shape of the facilities and workshops. If the industry is affected by the amount of workers and the product size such as in shipyards and leisure ship manufacturing units, determining the appropriate size of a workshop is very important to ensure productivity and improve cost efficiency. Thus, more studies are required to solve these problems. Recently, a study analyzed the layout to understand the complexity of the production environment in shipyards using a simulation-based feedback process(Song et al., 2008; Shin et al., 2009).

This study defined a layout design methodology that considered the characteristics of the ship and validated the methodology using actual shipyard cases. In addition to these studies, an environmental impact assessment produced a life cycle assessment (LCA) based on layout information(Lee et al., 2012). However, case studies are rare of the factories used to produce leisure ships and small boats. Leisure ship production is a unique process that combines the characteristics of the production lines used in the automobile industry and the job shops used in the shipbuilding industry. To reflect these characteristics, it is necessary to use a specific and systematic design, as well as analyze the methodology used to produce the layout.

Therefore, this paper proposes a heuristic algorithm that decides the size and shape of workshops using a workshop arrangement method where the algorithm is based on leisure ship building process data. This study includes an algorithm for analyzing the existing factory layout and for designing the new factory layout.

The heuristic algorithm was implemented to verify the approach proposed in this research. This application was also used by a real leisure ship manufacturing company to produce a new factory layout design.

2. Design methodology for the leisure ship factory layout

2.1 Definition of the factory layout module

In this paper, the layout module refers to the unit element used by the layout design, such as the facilities and workshops in the factory. The layout module is an orthogonal polygon in all cases. The types of layout modules are divided into workspaces, storage spaces, and convenience spaces. Fig. 1 shows the reference structure of the layout modules. The workspace-type layout module can be subdivided into the hull manufacturing space, component manufacturing space, and outfitting/interior space. This reference structure was defined by analyzing the fiber reinforced plastic (FRP) boat production process, which was used as the basis for analyzing the factory or generating a new layout module.

Fiberglass and aluminum are the main materials used in the construction of leisure ships, although carbon fiber is used in some cases. The leisure ship production processes are similar with fiberglass and carbon fiber. Therefore, the reference structure applies to factories that produce fiberglass and carbon fiber leisure ships. However, the detailed processes used during aluminum and fiberglass leisure ship production are different, so the reference structure defined in this paper cannot be applied directly to aluminum leisure ship factories. Thus, the scope of this paper is limited to fiberglass and carbon fiber leisure ship production factories.

The size of the layout modules for the FRP and carbon fiber reinforced plastics (CFRP) production factories are determined by the production output, the size of the facility, and the number of workers engaged in each production process simultaneously. Thus, the size of the layout module is determined by the production process characteristics. Depending on the automation ratio in the manufacturing process, the manufacturing processes can be divided into manual, semi-automatic, and automatic processes. If the automation ratio in the manufacturing process is greater than 70 %, the process is defined as an automatic process. If the ratio is 30 – 70 %, the process is defined as a semi-automatic process. Other cases are defined as manual processes (Fig. 2).

All the layout modules are created to match the form of a square grid. The horizontal and vertical lengths of the square grid are based on the space that one worker needs to work, i.e., 1.9 m^2. According to Tompkins et al.(1996), the minimum space requirement for one worker can be calculated by considering the width of the shoulder and the length of the arm of worker. Thus,

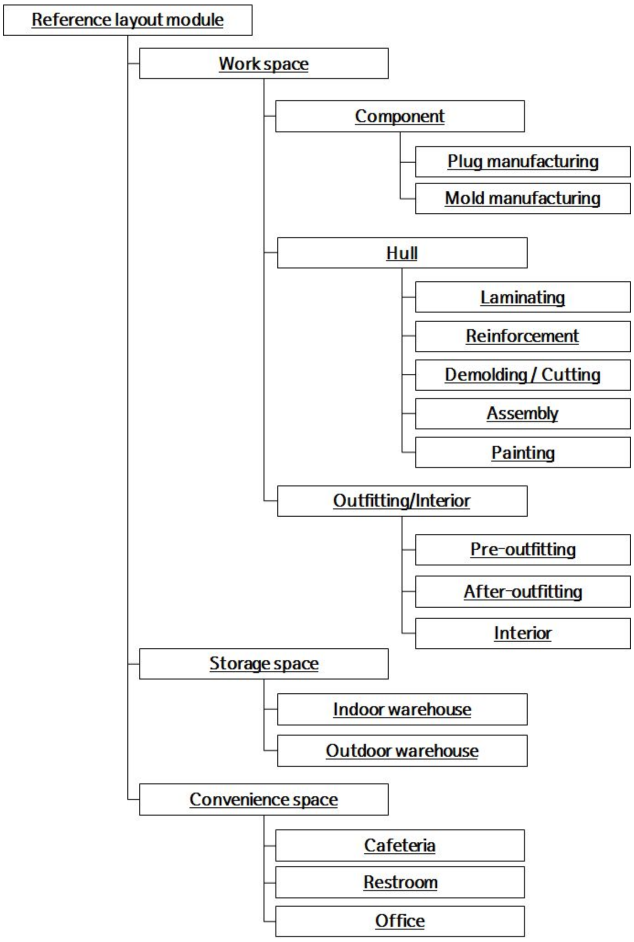

Fig. 1. Reference structure of layout modules.

the size of the layout module is determined by the number of workers required by the process. There may be many differences depending on the process but the size of the layout module is generally proportional to the number of workers engaged in the process. The number of workers engaged in a process is closely related to the production output, which is also used as a criterion for determining the process capacity.

The size of a manual-type layout module is determined by the number of workers needed for the process. For example, an assembly process layout module that requires 12 workers is designed with an area of 43.32 m^2, which is 12 times the grid cell unit. The layout module is created in the form of a square, provided the number of workers assigned to the process is a perfect square number. Otherwise, the layout module is generated in the form of a rectangular concave polygon. For example, the layout module assigned to 14 workers is generated in the form of a rectangular concave polygon where two columns at the bottom right are excluded from the form of a square.

Process Type	Automation ratio(%)
Manual	0~30
Semi-auto	30~70
Automatic	70~100

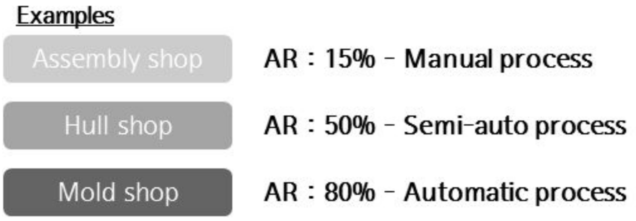

Fig. 2. Process characterization criteria.

An automatic process-type layout module is generated in the shape of a rectangle. In addition, the area of the module is determined by the number of workers assigned and the maximum length of the facility used by the process, which considers the space occupancy of the facilities. The width of the layout module should be larger than the width of the facility used in the process. Therefore, the width of the layout module must be greater than either the vertical or the horizontal length of the facility. However, the layout module is created based on a grid. Thus, when the length of the facility is L, the width of the layout module must occupy the smallest integer value n, which is larger than L. For example, let us consider an automatic process that requires four facilities with widths of 5 m. The width of the layout module in this process is three rows of the grid included in the facility. The length of this module occupies four columns of the grid that constitutes the facilities. Therefore, the width of the module is 5.7 m, which is 1.9 m × 3 rows, and the length of this module is 7.6 m, which is 1.9 m × 4 columns. The characteristics of the manual- and automatic-type layout modules are used to make semi-automatic-type layout modules. The semi-automatic-type layout module generation method is similar to the automatic type. However, the grid cell unit is added to consider the number of workers assigned to the process. To make a regular shape, the length of the layout module is determined within a range that does not exceed the length of the facility.

In the previous paragraph, the attributes of the layout module were determined based on the number of workers and the process type. These methods are suitable for the initial layout design step, which only needs to know the production volume and target product. Therefore, this method uses only the minimum information to determine the attributes of the layout module. Defining the unit

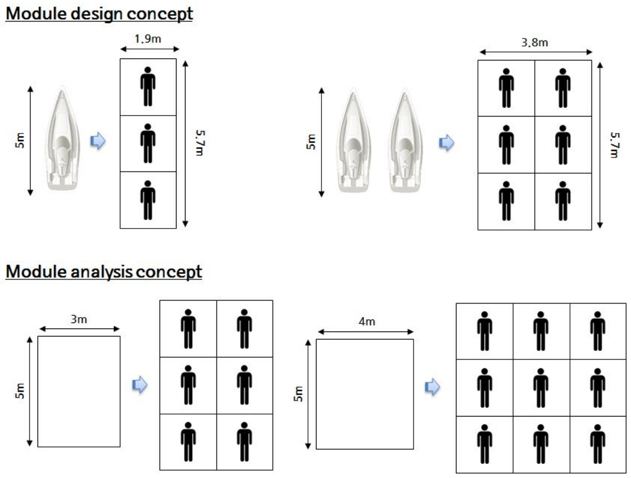

Fig. 3. Systematic layout module design.

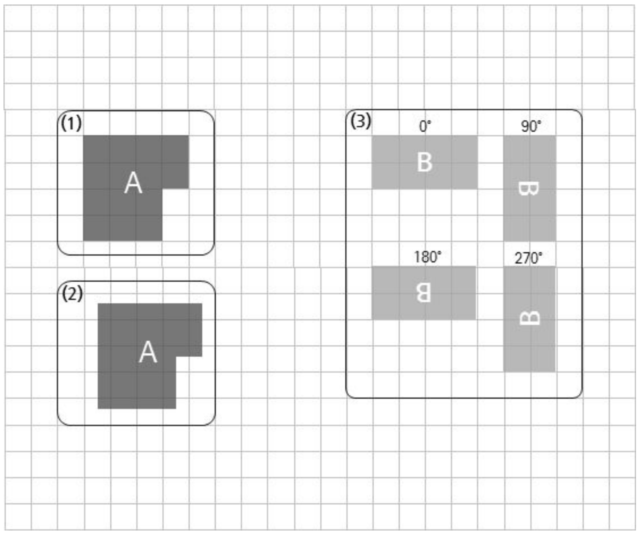

Fig. 4. Location arrangement rule for modules.

space required for one worker facilitates the analysis of the factory layout, which is currently considered in terms of the number of workers. Most existing layout design methodologies are based on the experience of the layout designer. However, the method proposed in this paper allows a more systematic approach to the layout design process. This process can be carried out on a consistent basis for repetitive layout design and it can allow automated layout design using a formulaic layout design algorithm.

Fig. 3 shows the process used to define an automatic-type layout module and to generate a layout module in an existing workshop. When analyzing the layout of an existing factory, the number of workers that correspond to the layout module is calculated using the method defined earlier. Thus, the space required for the new layout design is calculated based on the production capacity. Of course, this method has the disadvantage of not considering the size of the facilities that are actually available. Furthermore, there is no specific information during the initial stage of the layout design. Thus, the layout design process proposed in this paper has the advantage that it produces various drafts of the layout design.

2.2 Heuristic algorithm for arranging the positions of the layout modules

The heuristic layout module location arrangement algorithm aims to derive a layout design plan that minimizes the total area in the new factory. In this paper, we define a heuristic algorithm that maximizes the concentration of the modules in the minimum layout area. This concept is similar to nesting during the cutting of steel plates or textiles, which is used to organize the arrangement of shipyard building blocks. The module arrangement heuristic algorithm has four prerequisites, which are shown in Fig. 4. First, the module location arrangement is designed on a virtual grid, which is constructed with unit-lattice-size intervals. Second, the modules can have orthogonal polygonal shapes, as shown in Fig. 4 (1). Third, the vertices of the module must coincide with the vertices of the unit-lattice on the grid. Fig. 4 (2) shows some impossible arrangements. Finally, the module has four rotational axes: 0°, 90°, 180°, and 270° (Fig. 4 (3)).

The basic module arrangement process is as follows.

a. Arrange a current module on the layout grid.
b. Calculate the length of contact sides between the current module and the next module.
c. Save possible arrangement candidates and determine the maximum length of the contact side between the modules.
(If the possible arrangement candidates exceed three, proceed as follows.)
c.a. Calculate the number of contact sides between the current module and the next module.
c.b. Save possible arrangement candidates and determine the maximum number of contact side between the modules.
(If the possible arrangement candidates exceed three in 3.2, proceed as follows.)
c.b.a. Calculate the length of the centroid between the current module and the next module.
c.b.b. Save possible arrangement candidates and determine the minimum length of the centroid between the modules.
d. Determine the next module on the layout grid (a single possible answer).
e. Merge the current module and the next module.

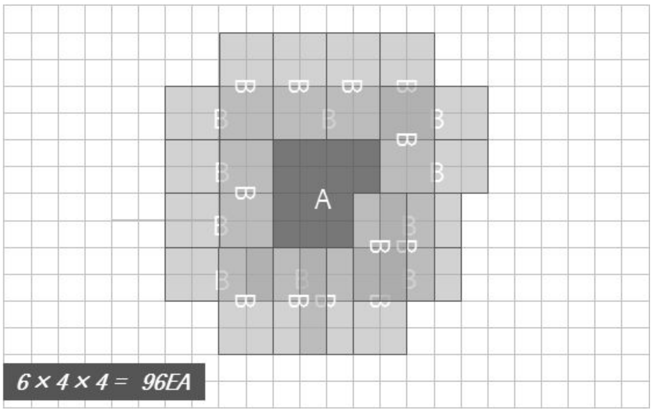

Fig. 5. Arrangement candidate for two modules.

The heuristic algorithm makes it possible to consider all possible arrangement candidates. The number of possible arrangement candidates is determined using the following formula: the number of current module vertices x the number of vertices on the next module × 4 (the number of rotational axes for the orthogonal polygonal module). Fig. 5 shows the process used to determine the number of arrangement candidates based on an example arrangement with two modules. The final selection arrangement for these candidates is based on the variable features, i.e., the length, the number of contact sides between the arranged modules, and the length of centroid between the arranged modules. The layout designer can select options that reflect the application order of the variables. The factory layout result can have various alternatives, depending on the layout designer's aims and the purpose. For example, if a layout designer considers all the variables in order, process c.b.b. will be the final arrangement result. However, if the layout designer only considers the length and the number of contact sides between the arranged modules, process c.b. will be the final arrangement result.

Fig. 6 shows why the length and the number of contact sides between the arranged modules are important variables. Case 1 and case 2 illustrate a situation where the designer is attempting to arrange another 1 × 3-size module when a 1 × 3-size module has already been arranged. In the cases shown in Fig. 6, the number of contact sides between the modules is a one-length unit-lattice grid and a three-length unit-lattice grid. This result shows that case 1 has a higher degree of concentration than case 2.

Case 3 and case 4 in Fig. 6 also illustrate a situation where

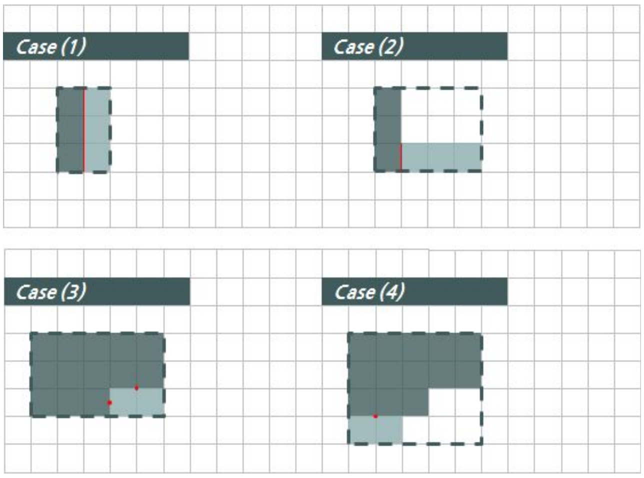

Fig. 6. Examples of arrangement candidates.

the current module is a merged concave orthogonal polygon while the next module is a 1 × 2-size orthogonal polygon. Case 3 has a higher degree of concentration than case 4. In general, the concentration of the module size increases with the length of the contact side and the number of contact sides is higher with orthogonal polygon layout problems. However, the length and the number of contact sides between modules often yield more than one arrangement solution, so we developed a feature that can select freely based on various criteria.

The heuristic algorithm used for arrangement candidates is a three-step process. First, a numerical set is created that contains the arrangement candidates. The numerical set is a binary matrix. The matrix has the same size as the entire layout grid. A cell in the matrix has a numeric value "0" when the module is not arranged and "1" when the module is arranged. These numbers identify the module arrangement status. Second, the set of candidates is filtered based on three arrangement criteria: length, number of contact sides, and length of the centroid. During the filtering process, the algorithm calculates the vertices of the modules and the coincident points between vertices in the unit-lattice grid and the module boundary lines. Finally, two modules are merged into one module when the entire arrangement process is complete. Next, the merged module becomes the new current module, which is ready for the next module arrangement. Fig. 7 shows the process used by the heuristic algorithm for the location arrangement of the layout modules.

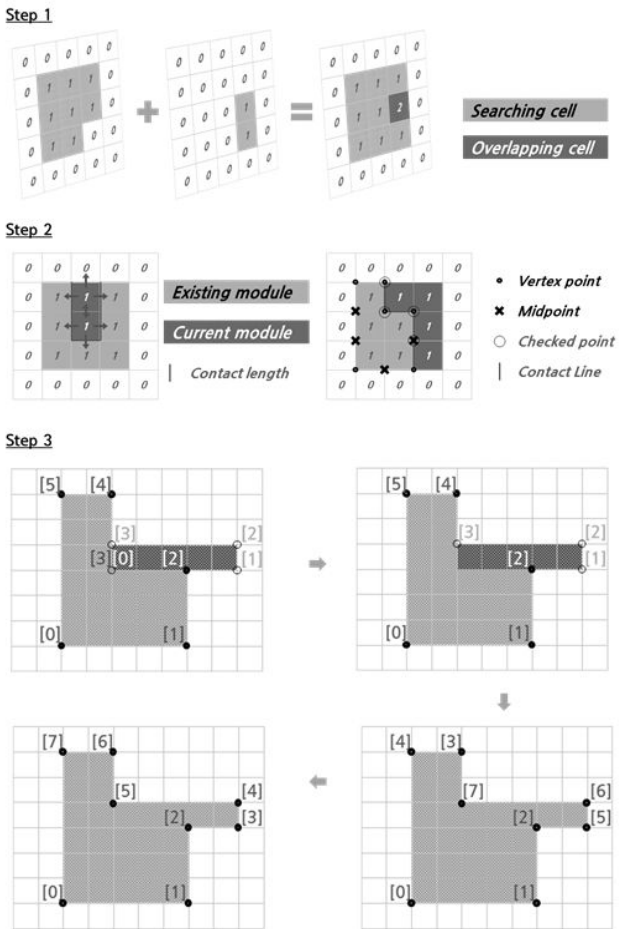

Fig. 7. Location arrangement process using the heuristic algorithm.

3. Layout design example in a leisure ship factory

To validate the results of this study, a layout design was produced using a virtual scenario for a real leisure ship factory. The target factory was located in Gyeonggi-do, South Korea, where it produced hydroplane boats, sailing yachts, fishing boats, and small cruise ships. The company owned two factories, which were located far apart so the company had a problem with internal logistics. Therefore, the layout design aimed to solve the problem of logistics and its target was integrating one factory.

Figs. 8 and 9 show the actual size and location of the target factory layout based on a satellite map. Fig. 8 shows the No. 1 factory, which had indoor mold shops, computer numerical control (CNC) machine mold shops, etc., and outdoor shops such as FRP material storage, and painting shops. The No. 2 factory contained the final product, outdoor mold storage, an office, and outdoor deck shops. According to the layout analysis, the two factories had no similar workshops. Thus, the production process was different in both factories, although some storage facilities were located in both factories.

The module layout of an integrated factory is based on the spaces available for work in the current factories, as shown in Table 1. The work space of a new integrated factory is defined by the space analysis results for factories No. 1 and No. 2, which are categorized as A (automated process), SA (semi-automated process), and M (manual process), depending on the automation ratio of the process. The total number of workers assigned for the layout module analysis was 93. However, it was assumed that all work was conducted at the same time. Indeed, if the company needed to produce small- and medium-sized leisure ships, the interior and exterior assembly processes would actually require 18 workers. Thus, the workers in small- and medium-sized companies must have multiple jobs. However, the total worker count in the actual company was 14, so the error was 20 %. This is an allowable level error because the sample dataset for the factory was small and the study reported in this paper is the initial step of the layout design.

The size of the space required for storage is calculated relative to the size of the associated workspace and the ratio of the

Table 1. Work space data required to determine the future layout of the factory

Module	Size (L × B)	Area (m^2)	Type	Labor
#1 Hull mold shop	5 × 13	65	A	5
#1 Deck mold shop	4 × 13	52	A	4
#1 BHD & structure mold shop	6 × 2.5	15	A	1
#1 CNC shop	4 × 8	32	A	2
#2 Hull shop	15 × 5	75	SA	4
#2 Deck shop	12 × 5	60	SA	3
#1 Dust-free shop	7 × 12	84	SA	5
#1 Paint shop	7 × 13	91	SA	5
#2 Outfitting shop	15 × 4	60	M	17
#2 Exterior assembly shop	4 × 16	64	M	18
#2 Interior assembly shop	4 × 16	64	M	18
#1 Assembly shop	4 × 11	44	M	12

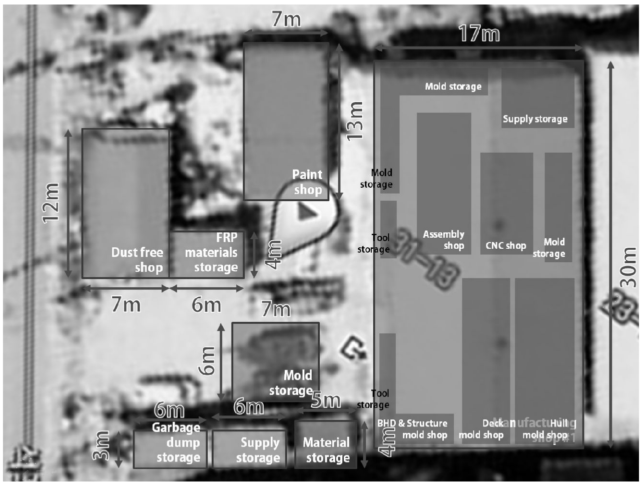

Fig. 8. The layout of factory #1.

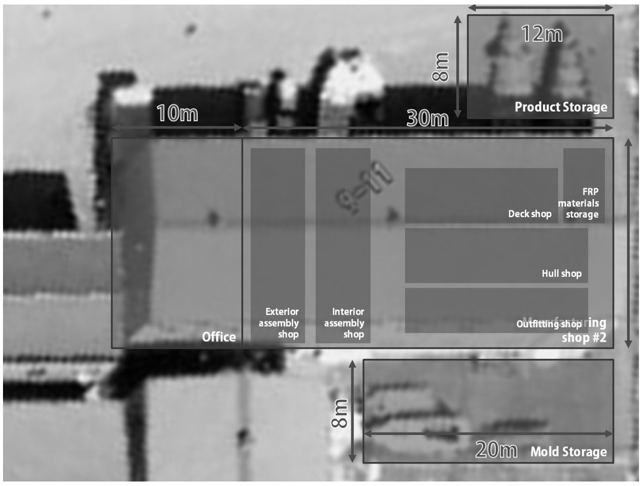

Fig. 9. The layout of factory #2.

Index	Process Name	Area(m²)	Category
1	Hull mold shop	65.0	Automatic
2	Deck mold shop	52.0	Automatic
3	BHD & Structure mold shop	15.0	Automatic
4	CNC shop	32.0	Automatic
5	Hull shop	75.0	Semi-auto
6	Deck shop	60.0	Semi-auto
7	Dust free shop	84.0	Semi-auto
8	Paint shop	91.0	Semi-auto
9	Outfitting shop	60.0	Manual
10	Exterior assembly shop	64.0	Manual
11	Interior assembly shop	64.0	Manual
12	Assembly shop	44.0	Manual
13	FRP materials storage	48.0	Storage
14	Material storage	20.0	Storage
15	Mold storage	259.0	Storage
16	Product storage	96.0	Storage
17	Garbage dump storage	18.0	Storage
18	Supply storage	48.0	Storage
19	Tool storage	10.5	Storage
20	Cafeteria	62.4	Convenience
21	Office	170.0	Convenience
22	Restroom	50.0	Convenience

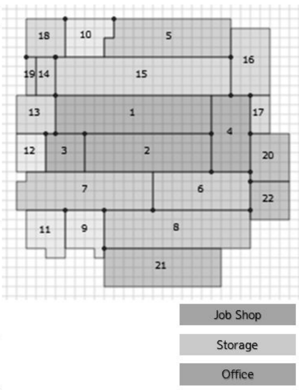

Fig. 10. Layout result for the factory future design.

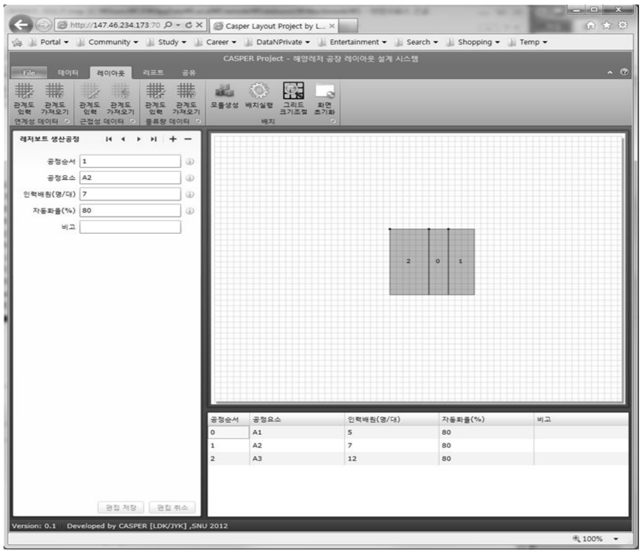

Fig. 11. Web application implementation results.

overall existing factory area. The storage spaces contain FRP material storage, miscellaneous material storage, mold storage, final product storage, waste temporary storage, sub-resource storage, etc. The storage arrangement is designed after the workspace arrangement is complete, so the storage arrangement can use the remaining area of the overall layout space. In particular, the mold and final product storage area have high priority in the storage layout process because the sizes of the storage objects are related to the target product size.

The remaining space, including the cafeteria and restroom, are controlled by government guidelines depending on the number of employees. According to the guidelines, an 18-employee factory would require two toilets and three washstands. Thus, the restroom size needed to be approximately 33 m^2. A cafeteria does not have to be installed in companies with < 100 employees. If a cafeteria is installed, however, it requires a dining space of 1.1 m^2 per person based on the maximum number of people present simultaneously.

Fig. 10 shows the final integrated factory layout design. No. 1 – No. 12 in Fig. 10 represent the workspaces, No. 13 – No. 19 represent storage spaces, and No. 20 – No. 22 represent the remaining space. These results were generated by a web-based application that included the heuristic algorithm. This application was developed using Microsoft Silverlight and the C# programming language. At present, the application is deployed on a website (http://147.46.234.173:7001/), as shown in Fig. 11. The design and detailed contents of the application are described in our previous study(Lee et al., 2013).

4. Conclusion

This study proposed a heuristic algorithm based the FLP for designing the layout of small- and medium-sized leisure ship factories. Through an application using the algorithm, leisure ship builders can evaluate their layout scenarios without an additional expense for purchase of layout solutions. The layout reference structure was defined by the leisure ship building process, where the layout modules were designated as automated, semi-automated, and manual modules, depending on the ratio of automation in each process. The modules in this paper provided a master unit for analyzing the existing factory layout and for designing the new factory layout. Thus, systematic and consistent layout design can be achieved based on these modules.

The production capacity of leisure ship factories is closely related to the factory area size and the number of workers. Thus, the layout module design process proposed in this paper was based on the area and types of spaces that workers needed, i.e., this study used a worker-centric approach.

The heuristic algorithm used to determine the location arrangements of the modules can consider all cases when there are two possible module arrangements. After arranging the two modules, the modules are merged into one module and algorithm can solve the problem again. In general, the heuristic algorithm had disadvantages when considering all cases because the calculations took a long time. However, these disadvantages can be ignored because the target of this study was a small- or medium-sized layout. This method was validated by implementing the application for a real-life layout design. This method had limitations because it did not consider aisles, doors, or the detailed logistics inside the factory.

However, the main advantage of this approach is that it is a simple and systematic layout design process, which determines the necessary space and the directional arrangement of modules during an initial step without any specific information. In future work, the heuristic algorithm will be improved to consider material flow and miscellaneous spaces such as aisles, paths, and customized prohibited spaces, which will include practical options such as factory layout boundary setting, and obstacle recognition.

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