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DEVELOPMENT OF DIGITAL LASER WELDING SYSTEM FOR AUTOMOBILE SIDE PANELS

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ABSTRACT–Nowadays, the increasing global competition forces manufacturing enterprises to apply new technologies such as laser welding to manufacturing of their products. In case of automotive industries, they interest in assembly system for BIW (Body in White) carrying out laser welding. In this paper, the method of implementation for digital laser welding assembly system is proposed. Based on the requirements of assembly tasks obtained through product analysis, process modeling is executed by using the IDEF0 and UML model. For digital assembly system, the selected components are modeled by using 3D CAD tools. According to the system configuration strategy, lots of the alternative solutions for the assembly system of welding side panels are generated. Finally, the optimal laser welding system is chosen by the evaluation of the alternative solutions with TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method.

KEY WORDS : Digital manufacturing, Laser welding system, Structure planning, TOPSIS method

1. INTRODUCTION

Because of the turbulent market and the increasing demand for product quality and variety, many manufacturing companies try to reduce manufacturing cost and to reduce the product development time. For this reason, many manufacturing companies have used CAx technology at design stage of a new product development for analyzing and modeling static and dynamic behavior of parts and systems (Mak and Wang, 2002; Nomden *et al.*, 2005; Wu *et al.*, 2002). At the same time, they have pursued to cope with instantaneous load and malfunction of manufacturing system through grasping field data in real time by using MES (Manufacturing Execution System). Also, CAPE (Computer Aided Production Engineering) makes possible that manufacturing system is configured in virtual environment before construction of real system and real system uses results acquired through simulation in virtual environment.

By using CAPE, manufacturing companies are able to configure manufacturing system efficiently to reduced cost and time. Furthermore, digital manufacturing is a technology facilitating agile manufacturing with sophisticated computer models representing physical and logical schema and behavior of real manufacturing systems including manufacturing, environments and products. Based on these models, digital manufacturing supports decision making and error checking in the entire manufacturing process (Zhai *et al.*, 2005).

For the design of manufacturing system, the planning procedure follows the structured analysis, so called a process of decomposition, i.e., system-, process- and operation level (Figure 1).

Functional requirements of product and process- and organizational requirements for system operation are grasped in system level. To define functions of system and relationships of system components based on these requirements, IDEF0 diagram and ULM diagram (Martin, 2003; Rosenberg and Scott, 2001) are used in process level. Using these results, system components are determined as well as modeled using 3D CAD tool and the behaviours of them are also modeled in operation level. The selected components are allocated to execute the functionalities of system in correct manner.

Through this procedure, various alternative systems are proposed. The functionalities and behaviours of alternative systems are tested using OLP (Off-Line Programming) in digital environment modeled with DELMIA in process level. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) (Sen and Yang, 1998) method is used to select the optimal manufacturing system among various alternative manufacturing through the evaluation. These configurations – and examing process are carried out in bottom up way from operation- to system

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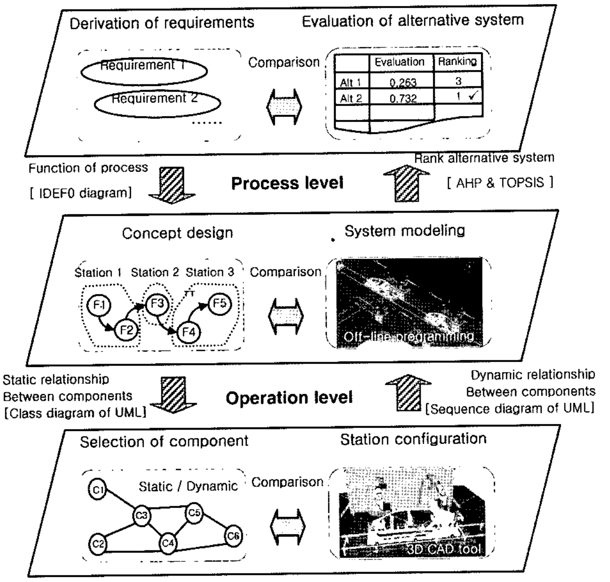


Figure 1. Approach of planning for digital manufacturing system.

level.

This paper was prepared based on the previous paper (Park and Lee, 2006) which described the analysis of laser welding process and the main method of how to implement the digital laser welding cell. The planning tasks related to the operation level was mostly introduced in that paper. So, this paper concentrated on how to design the system for welding automobile side panels with laser and how to evaluate the alternative systems for selecting the optimal. The cycle time is handled as one of the important planning variables considered in the system level due to the production principle of the side panels, i.e. mass production.

For designing the digital welding system, the product analysis is firstly carried out to grasp the requirements for modeling the system and the needed specifications of the equipments.

2. PRODUCT ANALYSIS FOR GRASPING THE REQUIREMENT OF IMPLEMENTING THE SYSTEM

In order to fulfill customer's demand expecting something more than price and basic performance, the application of a new technology such as laser welding is a critical factor in competition of manufacturing enterprises (Suh *et al.*, 2006; Park and Lee, 2006).

The existing spot welding is not anymore appropriate for new structure such as hydro forming and materials. To cope with these problems, the application of laser welding instead of spot welding is examined for car body welding. Because laser welding has so many advantages such as good accessibility, fast welding speed and good welding quality, the automotive companies try to put this technology into practice.

The conventional assembly method of side panels is spot welding, which is formed by about 233 spot points. For the application of laser welding, the side panels which require welding- and sealing processes have to be analyzed exactly for the welding conditions. There are some areas where the application of laser welding is not easy because the existing car body is oriented to spot welding. This leads to the fact that it is difficult or impossible to use only laser welding for side panel assembly. Also laser welding results in more jigs than the existing spot welding due to keeping the gap between panels at welding area ($t = 0.2$ mm).

The side panel has some structures where laser welding is not acceptable such as 4 layers, high reflexibility and so on. For solving these problems, spot welding is

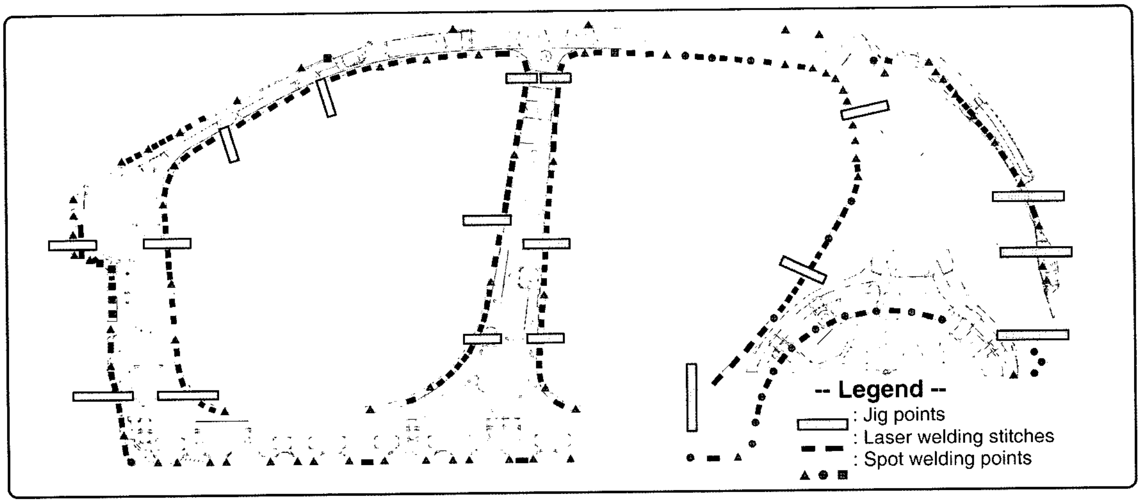


Figure 2. Generation of laser welding stitches, spot welding points and jig points.

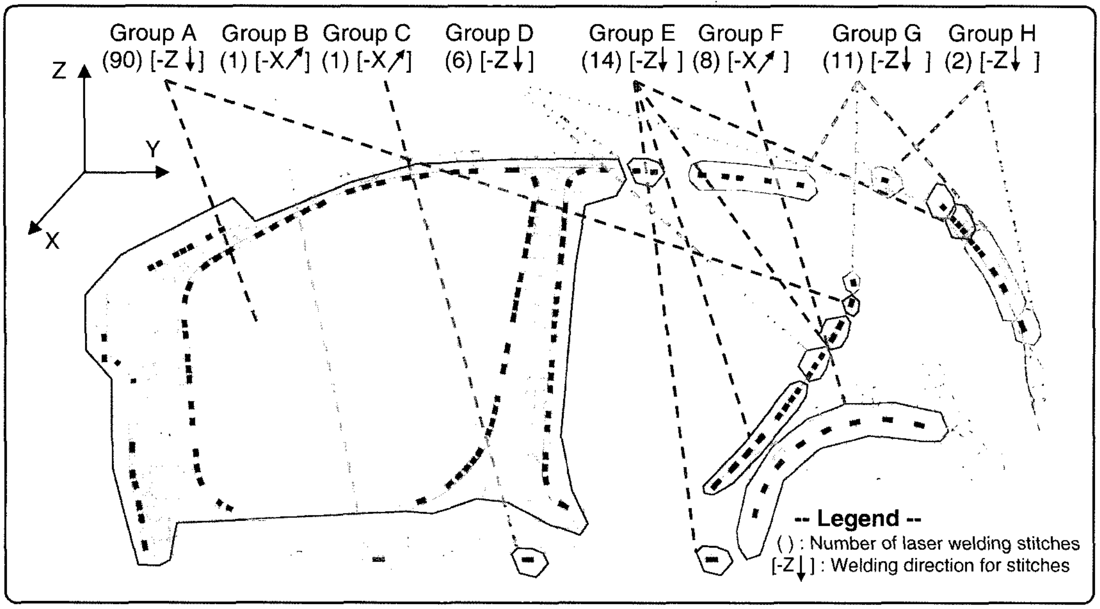


Figure 3. Grouping of laser welding stitches based on process parameters.

applied to the inapplicable points such as 4 layers and the inappropriate points for the reduction of the number of jig. This contributes to assure quality and reduce whole assembly time by decreasing set-up time. After determination of jig points and spot welding points, laser welding stitches are generated in consideration of jig points and spot welding points.

Contrary to spot welding, laser welding has various lengths of welding lines called stitch i.e. the unit length of laser welding path. The path of stitches is intended to have straight line to teach robot easily. The stitch length 20~30 mm is found on the basis of the experiment results and references.

The interval of stitches is set more than 10 mm regarding strength and thermal stress. As a result, 18 jig points, 102 spot welding points and 133 laser welding stitches are generated on the side panel (Figure 2). In order to ensure the quality in carrying out laser welding for the generated stitches, process parameters should be chosen. For this purpose, process parameters are determined according to the data acquired by various welding experiments. After the investigation of all 133 stitches, stitches having same process parameters were grouped and 8 groups were generated. When the group A shown figure 3 is welded in vertical direction (-z) and welding speed of 0.04 m/sec at Nd:YAG laser 4 kW, the best quality is obtained.

3. PROCESS MODELING FOR THE CONCEPT OF LASER WELDING SYSTEM

For the configuration of manufacturing system, product, process and resource are needed as basic planning objects. Based on the product analysis, the process modeling is carried out to define the process sequence, the required system components and the information flow between components. In this work, an object oriented model is applied for the process modeling. From lots of object oriented ideas, the UML (Unified Modeling Language) and IDEF0 (ICAM DEFinition methodology) model are chosen to describe dynamic and static relationships of the assembly system of car side panel.

The IDEF0 as a descriptive tool is used to identify the static functionality of the system. Following the structured analysis and design technique, at the top of the tree there is a very high-level description of the entire system and the further down the tree one goes, so the descriptions of the individual parts of the system become more detailed. This concept for the assembly system of automobile side panel with laser welding technique is illustrated in Figure 4.

The highest diagram describes a whole assembly system as an activity which converts the inner side panel and the outer side panel into the finished side panel by using engineering experience, e.g. jointing methods and the previous experience of system design. All boxes in the middle diagram represent the functions of each station which will be generated in the consideration of the functionalities of system, the cycle time and the constraint of system configuration such as forced process sequence due to product geometry. The lowest diagram details the processes carrying out in the station by identifying the major information involved in each process, i.e. process requirements and constraints, practical welding know-

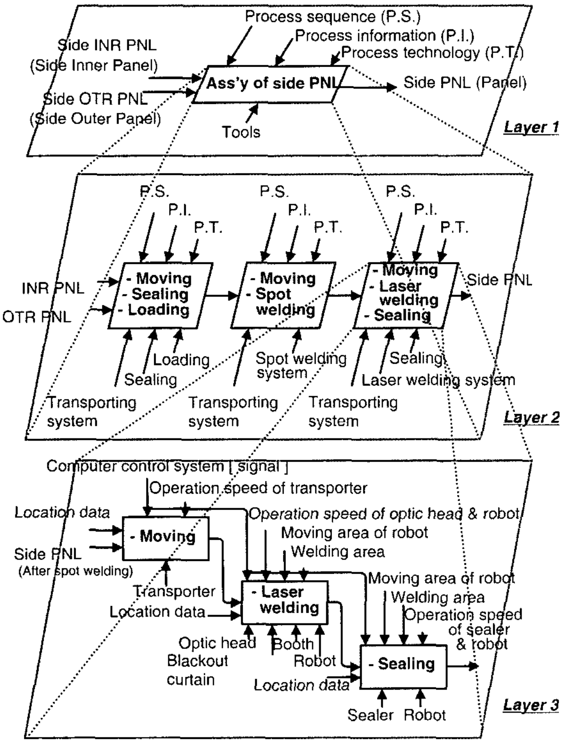


Figure 4. IDEF0 model of the assembly system for automobile side panels.

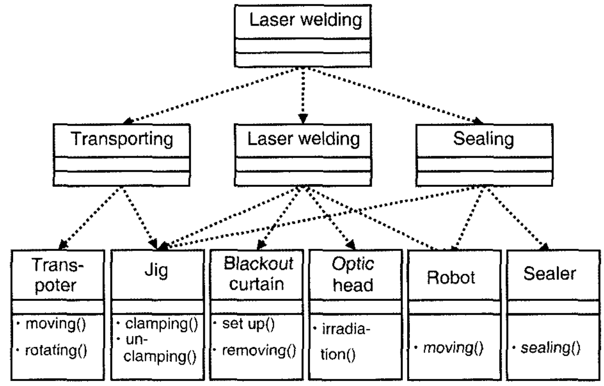


Figure 5. Class diagram for the static relationship between components.

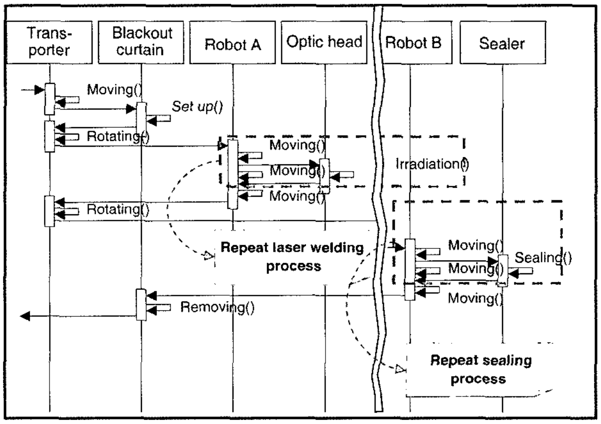


Figure 6. Sequence diagram for the dynamic relationship between components.

how, existing system components and so on.

In order to execute the defined process of the stations, the components of the assembly system for side panels are grasped by using UML class diagram. Activities of the components in the laser welding and sealing station in Figure 4 are expressed with the activity functions (Figure 5).

As shown in the bottom layer, the components, i.e. transporter for side panels, jig to fix them, blackout curtain to protect worker from laser beam, optic head and robot to carry out laser welding and sealer for sealing panels are required for the laser welding and sealing station presented in the above IDEF0 model. The MOVING (start point: end point) function is used to identify the movement of robot. With these components and their activity functions acquired from the class diagram, we can model the interaction, consisting of a set of components and their relationships by using sequence diagram (Figure 6).

As Figure 6 shows, the relationships among the components can be built up in two ways by emphasizing the activities of the components and by emphasizing the messages ordered in increasing time from the top of the diagram to the bottom that may be dispatched among them. Graphically, the arrow returning to itself having MOVING function at the 'Transport' component means that the transporter is moved from initial to new coordination during the given time. The other arrow connected with another component gives the flow of the message for control. It says that a component sends a message for completion of its task to system controller and another component receives a message for starting the assigned task from system controller. This sequence diagram is directly applied to simulate the processes of the assembly system by using GSL (Graphic Simulation Language).

As the result of process modeling using IDEF0 and UML, the task and sequence of process for assembling the side panels were decided. After that, the time required for executing the task of each process was collected from experiment and field data. Based on these, the time table for the whole assembly system was generated under consideration of the 90 sec cycle time given from production data and the actually available working time of each station (Figure 7). The maximal available working time of each station except transport time 11 sec was 79 sec. With this data, the fixed process sequence and the available space of working station, the required number

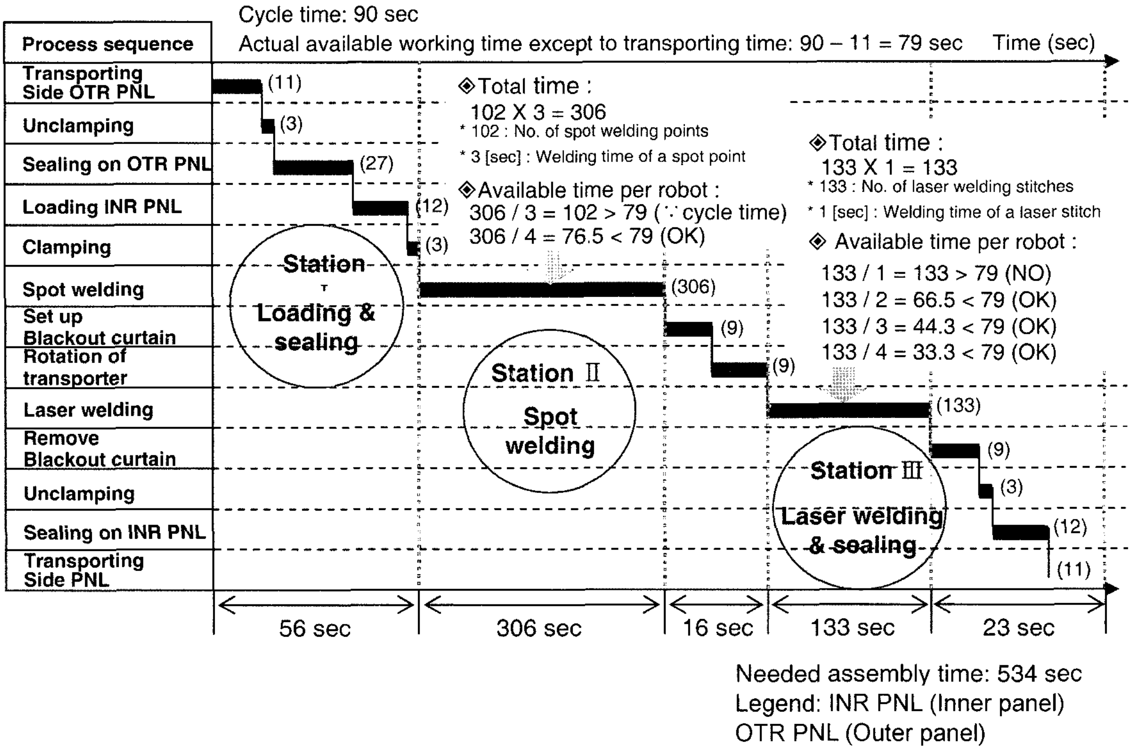


Figure 7. Time table for assembling automobile side panels.

of stations and robots was calculated. The results were shown in Figure 7, i.e. 3 stations and maximal 10 robots. The planning structure for the assembly system was begun with the above decided data and manufacturing principle, i.e. continuous flow manufacturing. It covers the allocation planning of production means, the transport planning and the surface planning.

Under consideration of the manufacturing process, the characteristics of production means, e.g. robot, spot gun, optic head and jig/fixture etc., the material flow and the available surface, the concept layout of the system was generated (Figure 8). The first station consists of two robots for loading the inner side panel and sealing to protect the leakage of water between inner and outer panel. To ensure the gap between two side panels for laser welding, spot welding with four robots in the second station preceded laser welding. The third station required the rotatable transporter due to the different welding direction.

The mechanism of the robots used in the third station was not suitable for laser welding in the –X direction shown in Figure 3. So, the three robots for laser welding were located in one side because the accessibility to laser welding stitches was impossible through the rotation of side panels. Also, the enlargement of the station happened from the short distance between robot and side panel which was caused by it.

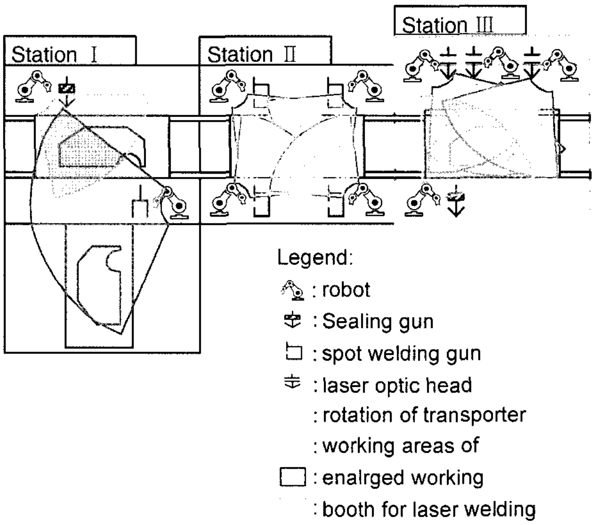
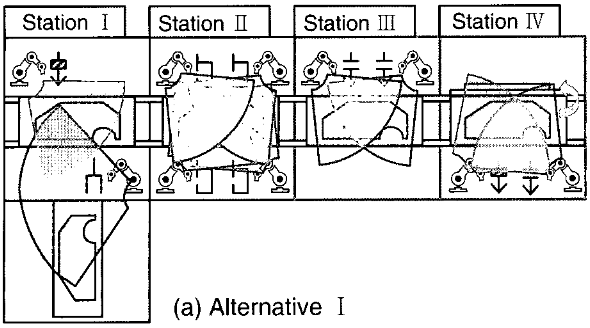


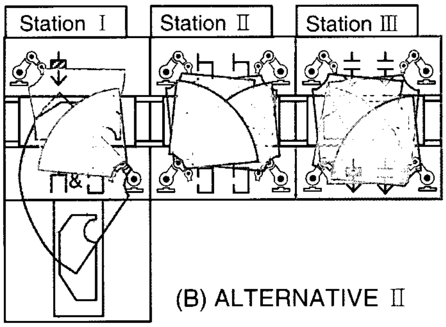
Figure 8. Initial concept layout of the assembly system.

4. GENERATION OF THE ALTERNATIVE SYSTEMS FOR WELDING SIDE PANELS

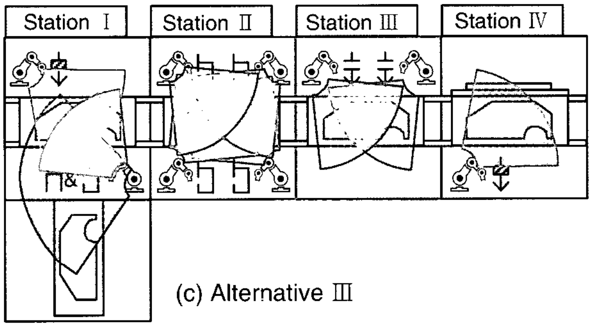
For the configuration of the assembly system for side panels, initial concept layout was proposed through the previous process modeling. Even if an experienced expert design manufacturing system based on the existing know-



(a) Alternative I



(B) ALTERNATIVE II



(c) Alternative III

Figure 9. Alternative layouts for the assembly system.

how of company, most of concept layouts have lots of problems in applying to practice because the actual behavior of system is estimated by the experience of system designer. From this reason, it is needed to generate all possible alternative systems from the initial concept layout. To carry out this work more rapidly and effectively, digital manufacturing technology with which the structure and simulation of manufacturing environment is possible in close realistic description is recently used. The advantage of it is the simple and early alternative planning and the optimization in the planning phase. Changes are examined in applicability and effect before they are implemented in real manufacturing system. By reason of these, Digital manufacturing is one of the noteworthy manufacturing technologies to reduce cost and time for the design of new system. The basic steps for applying digital manufacturing technology were introduced in Figure 9 in the previous paper (Park and Lee, 2006).

The planning procedure of implementing digital laser welding cell was detail described in that. With this fundamental principle of digital manufacturing, the process of the initial concept layout was simulated in digital environment to test the applicapability of it and to generate various alternative layouts. The laser welding stitches of the group B, C and F in Figure 3 can't be welded in direction of –X due to the mechanism of the used robots. So, the side panels on the transporter have to be rotated 90° in clockwise for welding these groups in direction of gravity –Z, i.e. easy accessibility of optic head to the welding stitches. Because of that, the three robots for laser welding in the third station of the initial layout were located out of the working area of the other two stations. Also, these robots might have the collision problem at welding. In order to solve these problems, the three alternative systems were proposed in Figure 9 in consideration of the fulfillment of the design specifications such as cycle time and satisfaction of welding quality and so on.

In alternative I, the third station of the initial concept layout in which 133 stitches were welded with laser was divided into two stations to solve the enlargement of the station. In the first station of two, 123 stitches having the same welding direction were welded with two robots. The welding of 10 stitches belonging to group B, C and F was performed in the other station in which the side panels on the transporter had also to be turned to the vertical position for increasing the accessibility. The robot for welding them was located in opposite side compared to the initial layout to prevent the collision.

A new strategy that 10 laser welding stitches with a bad accessibility were replaced with spot welding points was applied to alternative II and III. With this method, the enlargement of the station was removed and the rotatable transporters were not needed. It was examined that the newly generated 10 spot points might be welded in the second station for spot welding. However, it is impossible due to the constraints of cycle time and free collision. So, the welding of the new spot welding points was carried out through the change of grip by the robot itself for loading inner side panel in the first station because the loading process is short so that the robot can take another task.

In alternative II, the laser welding process and the sealing process can't be performed simultaneously from the forced assembly sequence. Therefore, the three robots are needed for the compensation of the shortened welding time which means the reduction of the utilization of the expensive laser equipments. To save one robot and to increase the utilization of them, alternative III was proposed. This configuration has a disadvantage in line balancing. The total process time of the fourth station

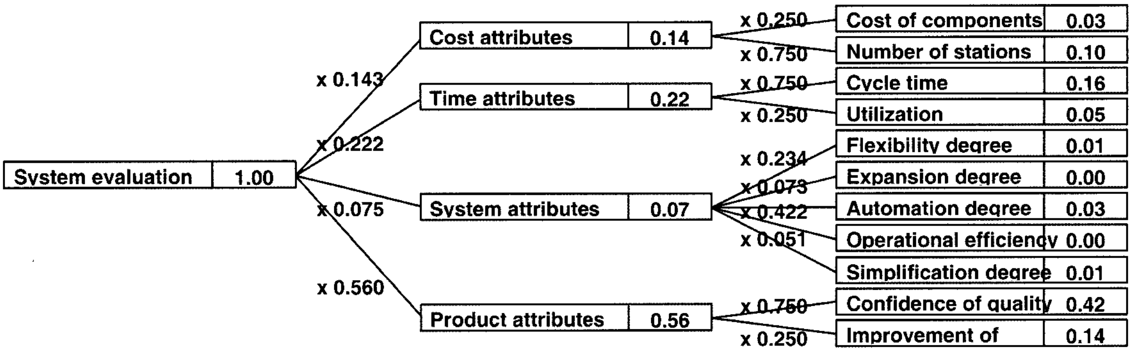


Figure 10. Weight values of the criteria.

was only 32 sec.

5. EVALUATION OF THE ALTERNATIVE SYSTEMS

Generally, manufacturing systems should have the characteristic that they can produce products having good quality by using simple equipments with low expense and short lead time. Under consideration of this, evaluation criteria were derived and divided into four attribute groups such as cost, time, system and product. The cost attribute consists of the investment for equipments and area and their operating cost. It is considered in the time attribute to minimize the cycle time and to increase the utilization through line balancing. The system attribute deals with the flexibility, the expansion ability according to the change of manufacturing environment, the automation degree, the operational efficiency of equipments and the simplification of system structure and so on. The reliability and improvement of quality belong to the product attribute.

In order to evaluate alternative systems with selected criteria, MADM (Multiple Attribute Decision Making) method (Sen and Yang, 1998) was applied as a collection of attributes that relate to choice in the context of competing technical or functional requirements. The relative weight of the criteria have to be determined because alternative solutions must be evaluated based on the criteria. For this purpose, AHP (Analytic Hierarchy Process) and eigenvector method were used. The AHP method is the hierarchical decomposition methodology (Figure 10).

The evaluation goal is expressed at the top level. Following the structured analysis, the descriptions of the individual criteria become more detail. Thus the criteria described in the higher level are detailed by the bottom level. To determine the relative weight of the criteria, the eigenvector method which enables the pairwise comparison between the criteria was applied. The relative weight of the criteria in each level was obtained from the

Table 1. The calculated and weighed normalized value of the criteria in the alternative systems.

Criteria \ Alternative	Alt 1	Alt 2	Alt 3
✱ Cost of components [x106$]	2.413 (0.022)	2.407 (0.022)	1.867 (0.017)
✱ Number of stations [No.]	4 (0.067)	3 (0.050)	4 (0.067)
✱ Cycle time [sec]	89 (0.096)	89 (0.096)	89 (0.096)
✱ Utilization [%]	83.7 (0.030)	98.5 (0.036)	83.7 (0.030)
◈ Flexibility degree [–]	6 (0.012)	4 (0.008)	6 (0.012)
◈ Expansion degree [–]	8 (0.003)	6 (0.002)	8 (0.003)
✱ Automation degree [%]	100 (0.018)	100 (0.018)	100 (0.018)
✱ Operational efficiency [%]	56.3 (0.002)	57.3 (0.002)	64.2 (0.002)
◈ Simplification degree [–]	6 (0.007)	8 (0.010)	8 (0.010)
◈ Confidence of quality [–]	6 (0.197)	8 (0.262)	8 (0.262)
◈ Improvement of quality [–]	8 (0.096)	6 (0.072)	6 (0.072)

Legend:
✱ : Quantitative value
◈ : Qualitative value (Nondimension value: 1~10)

$$UT=\frac{1}{k}\left(\sum_{i=1}^{k}\frac{O.T.}{C.T.}\right) \qquad OE=\frac{1}{n}\left(\sum_{i=1}^{n}\frac{W.T.}{C.T.}\right)$$

UT: Utilization OE : Operational Efficiency
k: number of stations n: number of robots
O.T. : Operational time of each station
C.T. : Cycle time of the system
W.T. : Working time of each robot
xx : Values belonging to the Ideal solution.

Table 2. Ranking of the alternative systems.

	S+	S–	C	Ranking
Alt I	0.068	0.024	0.263	3
Alt II	0.025	0.068	0.732	1
Alt III	0.030	0.066	0.689	2

influence of them on the object to which the assembly system was going to be oriented (Figure 10).

After finding out the weight of the criteria, Hwang and Yoon introduced TOPSIS method, based on the concept that the chosen alternative i.e. the best solution should have the shortest distance to the ideal point and the furthest distance from the negative ideal point. The ideal point is the oriented point of the ideal solution which consists of the highest value of each criterion among alternative solutions. On the contrary, the negative ideal point is derived from the lowest value. The input data of the TOPSIS were the criteria values estimated from the characteristic of each alternative system.

They were presented in Table 1. To get the ideal and negative ideal point, it is necessary to calculate the weighed normalized value of each criterion. It was shown in the parentheses of Table 1.

It came from the multiplication of the normalized value with respect to the square root of the sum resulting from the square of the criterion's value by the weight taken in Figure 10. Using these weighed normalized values, the distance (S+) of each alternative system from the ideal point and the distance (S–) from the negative ideal point were calculated (Sen and Yang, 1998). With these, the closeness (C) between the ideal solution, i.e. the assembly system having the highest value of each criterion, and each alternative system was decided by the equation (1)

$$C = \frac{S^-}{S^- - S^+} \tag{1}$$

S^+ : the distance of the alternative system from the ideal solution

S^- : the distance of the alternative system from the negative ideal solution

The results of the distance S+ and S– as well as the closeness were presented in Table 2.

From Table 2, the alternative II was selected as optimal due to the high score in load balancing, the simplification of system and the improvement of product quality.

6. SYSTEM IMPLEMENTATION

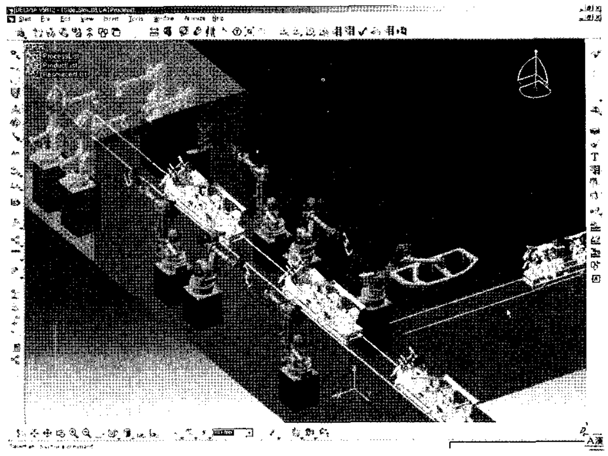


Figure 11. Implementation of the digital assembly system for automobile side panels.

The problems to be occurred when applying the selected alternative system II to practice should be grasped. For that, assembly system II was implemented in the digital environment with the commercial tool, DELMIA (Figure 11).

To implement the digital laser welding system, the optimal components which were selected from comparing the requirements for building the system with the capability of equipments were modeled based on object-oriented modeling method by using 3D CAD tool. For modeling the main, e.g. side panels, robots and jigs components such as fiber, laser generator and booth and so on, the geometry and kinematics data for these components were collected from the field of the participated automobile company. Through that, the reliability of the digital system was increased. These 3D models of the components are stored in library and used for new configuration of cells by calling back through a search (Kim and Choi, 2000).

The digital assembly system for automobile side which consists of 10 robots, 4 transports and 1 booth for laser welding was configured as 3 stations. In order to test the satisfaction of cycle time, insurance of welding quality and minimization of transfer time for material flow, the simulation for operating the assembly system was performed with the OLP (Off-Line Programming) technique. This is also used to verify the executing capability of the processes. When programming, the accessibility of optic head to all stitches, the collisions with equipments such as jig etc., the welding parameters for the secure of quality, the applicability of sensor to tracing welding path and the operation sequence for preventing from distortion of parts were fully examined to execute the events offered from the sequence diagram.

One of the principle problems in the design and operation of assembly system is the balancing the work load among the stations along the line. As the result of line balancing enough the simulation, the cycle time at the given stations ranged between 86 sec and 89 sec according to the allowed cycle time in 90 sec.

7. CONCLUSION

Increasing competition due to globalization requires the introduction of innovative processing technologies. In particular, laser welding has gained increasing importance for economical manufacturing of BIW (Body in White) due to lots of advantages compared to conventional spot welding. In order to exploit the potential of this technology, it is needed to develop an effective manufacturing system to carry out welding processes optimally.

In this paper, a concept of method for planning the digital laser welding system was developed.

The product was firstly analyzed to grasp the requirements for planning the digital welding system. This was achieved by examing the characteristics of welding processes. The investigation showed that rationalization of welding side panels requires not only laser welding but also spot welding because the current structures of side panels are oriented to spot welding.

For the configuration of the welding system based on the investigation, the static- and dynamic behaviors it were modeled by using IDEF0 and UML technique. With this model, the process sequence and the given constraints such as the cycle time and the accessibility to welding points and so on, the welding system was designed in a conceptional approach. To apply the designed system to the conventional welding line at the factory. The alternative systems were generated from it to carry out the welding processes effectively and efficiently.

To select the optimal one among them, the 11 evaluation criteria which have different weight given by AHP method were derived out in terms of cost, time, quality and time. The TOPSIS method used in economical field were applied to evaluate the three systems. As result, the alternative II was chosen as the best. The prototypical implementation realized by digital manufacturing technique has shown the practical applicability.

This paper presents one important step for a rationalization of welding automobile panels. Another step is a great contribution to extend the application area of laser welding technique.

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