Development of a Modular Structure-based Changeable Manufacturing System with High Adaptability

Hong-Seok Park[1,#] and Hung-Won Choi[2]

1 School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2 dong, Ulsan, South Korea, 680-749
2 School of Mechanical and Automotive Engineering, Graduated School, University of Ulsan, San 29, Muger 2 dong, Ulsan, South Korea, 680-749
Corresponding Author / E-mail: phosk@ulsan.ac.kr, TEL: +82-52-259-2294, FAX: +82-52-259-1680

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Today, manufacturers are forced to acknowledge that the life cycles of products are becoming shorter. In the case of the door trim assembly field, the highly frequent introduction of new products and the continuous increase in product varieties leads to the demand for redesigning assembly systems more often. Modular manufacturing systems can be an important issue in helping to overcome these problems. This paper presents the development of a modular assembly system for the door trim, and because it takes the change drives into consideration, this system is highly flexible in adapting to changes in the environment.

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1. Introduction

Today, customers expect products not only with higher quality and competitive prices, but also with personalized features and shorter delivery times Kim et al.,[6] Chryssolouris,[3] Urbani,[13] Abele et al.,[1] Bi et al.[2] Because of these challenges, the dedicated or flexible manufacturing system is no longer suitable. These limitations have led manufacturers to find an alternative manufacturing system that is rapidly changeable and cost-effective. One solution is a reconfigurable manufacturing system (RMS) based on a modular concept Denkena,[4] Wiendahl et al.[14] Because a RMS has several advantages, many researchers have tried to develop and apply reconfigurable manufacturing for commercial systems. Nofen Nofen et al.[8] divided the factory structure into seven levels: network, site, general structure, area, group, workplace, and processes. Factory modules can be designed for all levels except the process level. Even though it has been pointed out Eversheim,[5] Schuh et al.[11] that influencing factors must be considered when forming modules for a manufacturing system, it is still not clear which methods are appropriate and useful in grouping system components into modules. Factors such as reconfigurability, reduction in design time, and utilization of the modules' differences, which help to simplify the redesign work, must be considered.

This paper presents a strategy for developing a reconfigurable assembly system for a door trim. This strategy is based on a library that includes several types of modules having different adaptability. The strategy takes into account the possible changes in the manufacturing environment so that the system is adaptable and remains competitive.

2. Framework for Planning a Modular Manufacturing System

To remain competitive once the production structure has been planned, enterprises must permanently supervise the production structure and examine their functionality in relation to the changed boundary conditions (Zaeh et al., 2006). Because of this practice, a new method is proposed to design a manufacturing system based on the modular concept (Fig. 1).

During the design of a new system, the rules from the knowledge database dictate how the modules of the current assembly system

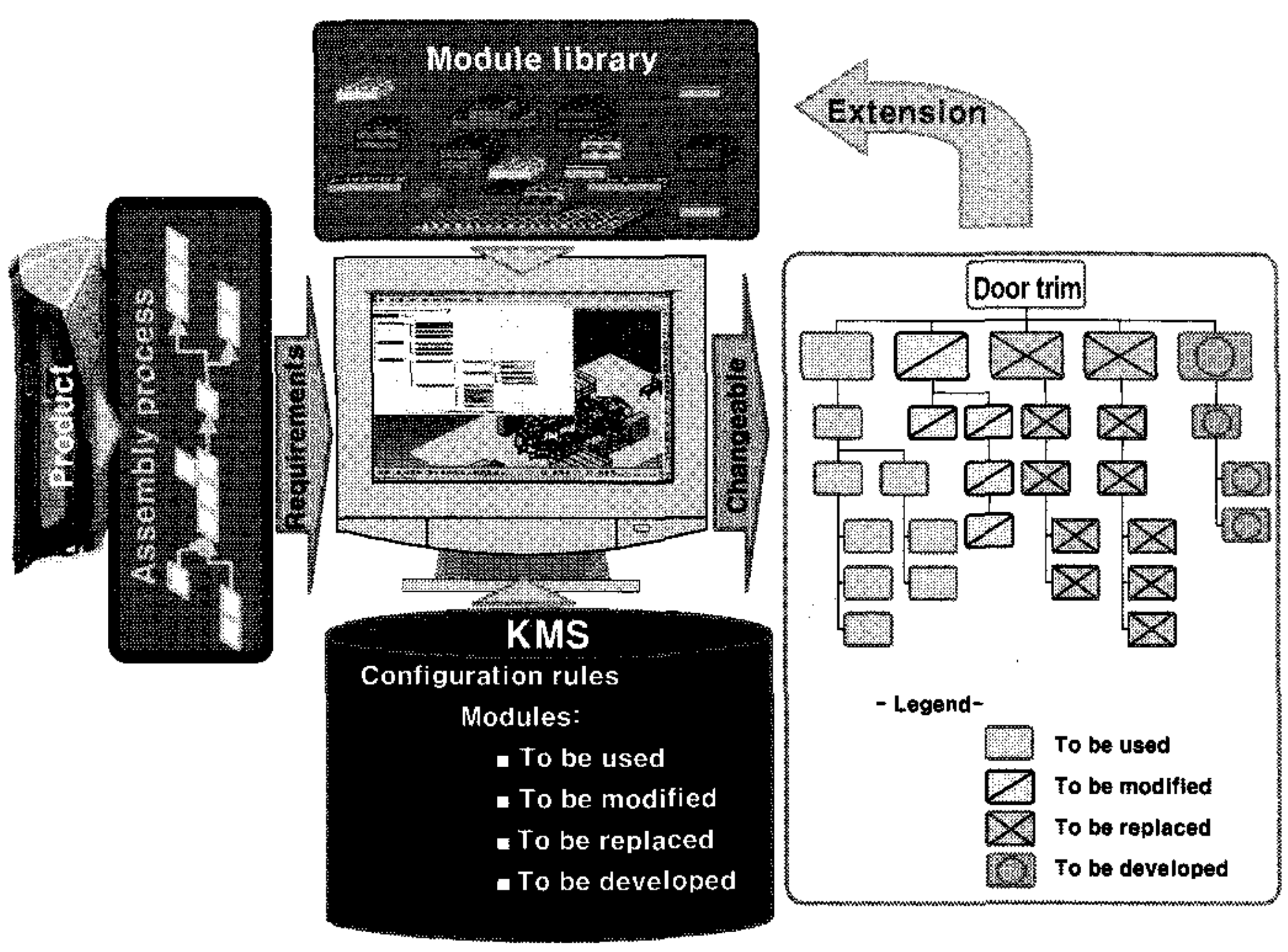

Fig. 1 Architecture for planning a reconfigurable assembly system

should be adjusted, and these rules are based on the new given requirements of the change drives. These requirements are derived from, for example, an analysis of the assembly process, product structure, and production conditions. Based on these parameters, only relevant modules in the existing system are either replaced by modules in the library or modified according to new design specifications. When the appropriate module cannot be found, new modules are developed and placed into the system. The knowledge database and the module library are expanded during the design of the new assembly system.

3. Modular Manufacturing Structure

3.1 Modular approach in the manufacturing system design

When developing a new system, the designers conventionally consider all of the components of the existing system. This method is insufficient in terms of the design cost and time. To resolve this problem, we propose a modular method (Fig. 2).

Based on the analysis of products and production conditions, internal and external influences on a manufacturing system, called change drivers, and all necessary functions are evaluated. Each function that carries out a task in the assembly system is then assigned to one component or a group of components. The assembly system consists of the assigned components that are ranked in a hierarchical structure. Modules of the components are then created by a strategy that is characterized by key terms such as independency, standardization, and the affect; therefore, components or modules should be altered in accordance with the change from a change drive.

To be more competitive in the unpredictable global market, manufacturers try to introduce new products in shorter time intervals. Thus, the system design work must be performed more frequently. Instead of starting from scratch every time they design a new manufacturing system, the designers can now use a modular approach to quickly reconfigure the existing system by replacing or modifying a few modules. Using this method, a changeable manufacturing system can be realized with minimal effort.

3.2 Change drives

Many factors are involved whose changes impact the structure of the manufacturing system. These factors are called change drives. During the analysis of products and production conditions, several change drives were determined to exist: dimension, shape, and surface form of the product. The change drive "surface form of the product" is divided into subchange drives: the position of assembled points, the number of assembled points, and the surfaces on which the assembled points are located.

A specific cycle time is given to each product. Components should perform their tasks in a certain unit of time that is defined as the processing time. The ratio between the processing time and cycle time, which varies for different products, is also considered as a change drive.

To perform the assembly operation effectively, the manufacturers should utilize the latest technologies having more advantageous characteristics than the existing assembly methods. Whenever a decision of changing an assembly method is made, the components of the current assembly system are no longer valid.

These change drives have a great impact on the operation of a manufacturing system. However, because the current global market is characterized by high fluctuations, these drives tend to change more frequently. Thus, the designer must consider these drives as important factors when developing a manufacturing system.

3.3 Function-oriented matrix of system components

To easily identify what kind of equipment is needed, the designer should reduce the complexity of the system. An important criterion for the modular approach is to guarantee the functionality of the assembly system's functions even when the modules are altered due to changes in design demands. Consequently, the assembly system is analyzed and divided into functions. For this study, the IDEF0 (ICAM DEFinition methodology) was chosen to identify the functionalities of the assembly system Park,[9] Park et al.,[10] Lee et al.,[7] Sheen et al.[12] The result is the arrangement of the functions in a hierarchical structure in terms of independence and functional connectivity. The functional independence makes it possible to achieve a modular design in which interactions between modules are minimized. Each module can then be treated independently of each other. Based on this structure, possible components are selected to carry out the functions (Fig. 3).

To facilitate the manufacturing system design based on the modular approach, each component should be planned or controlled independently, have a standard interface, and be able to perform several functions, if possible.

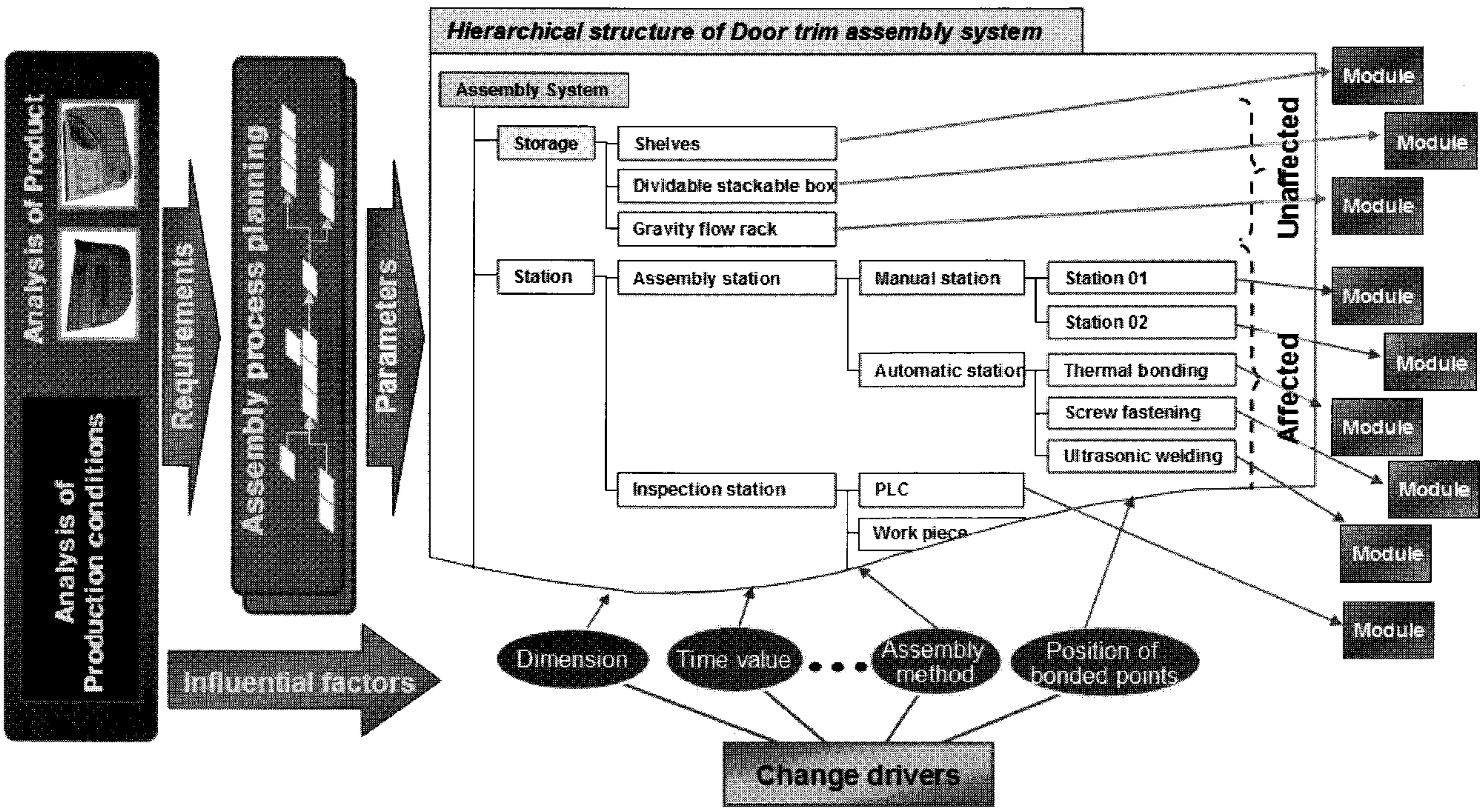

Fig. 2 Procedure of forming modules

Function level					Physical equipment				
Assembly processing	Local controller				PC	PLC	-		
Assembly processing	Assembling	Directly assembly task	Sensor		Torque sensor	Thermal couple	Thermistor sensor	Machine vision	-
			Jointing tool	Automatic tool	Cartridge heater	Single tip ultrasonic welding gun	Multi tip ultrasonic welding gun	Screw driving gun	Tube
				Handheld tool	Screw driving gun	Handheld ultrasonic welding gun	Hammer	-	
			Tool holder		2-jaw gripper	3-jaw gripper	Vacuum cup	Tool change system	-
		Moving of assembly tool	Single performing		Carrier bar (Height : 300mm	Carrier bar (Width : 1000mm	Carrier bar (Length : 1200mm	Polar coordinated robot	Cylindrical rob
			Multi performing		Thermal bonding platform structure	Dual carrier actuator	Multi spindle Ultrasonic welding platform structure	Bending structure	Hot air bon Mach
			Proofing (for accurate working position)		Gauge	Encoder	Optical encoder disk	Limit switch	-
		Tool storage			Tool holding plate	Modular tool stand system	-		
	Positioning		Fixture		Rapidly fixing fixture	Accuracy fixing fixture	-		
			Lifter		Lifting device	-			
			Detector		Proximity sensor	Limit switch	-		
	Feeding		Feeder (continuous)		Large size vibrator bowl	Small size vibrator bowl	Ultrasonic generator	Reciprocating fork hopper	-
			Feeding (intermittent)		Elevating hopper feeder	Bulk supply hopper	Indexing magazine	-	
Transporting			Conveyer		Modular chain conveyer	Belt conveyer	Roller conveyer	Lifting conveyer	-
			Work piece carrier		1 layer pallet	2 layer pallet	-		
			Measuring device		Encoder	Tachometer			

→ The group of components for screw fasten process

Fig. 3 Components of the assembly system assigned to the system functions

When a specific product is given, the system is designed to have a hierarchical structure that includes a transporting system, storage, and stations. Based on the new requirements derived from the analyses of the product and production conditions, the suitable system components will be selected from the function-oriented matrix for each function.

3.4 Modularization based on the similarity of the change drives' effects on system components

The main objective of designing the modular assembly system is achieving the ability to adapt rapidly to the changes. Ideally, only small groups of components (i.e., modules) should be considered in accordance with the changes in the manufacturing environment. For this purpose, we must identify the relationship between the affected

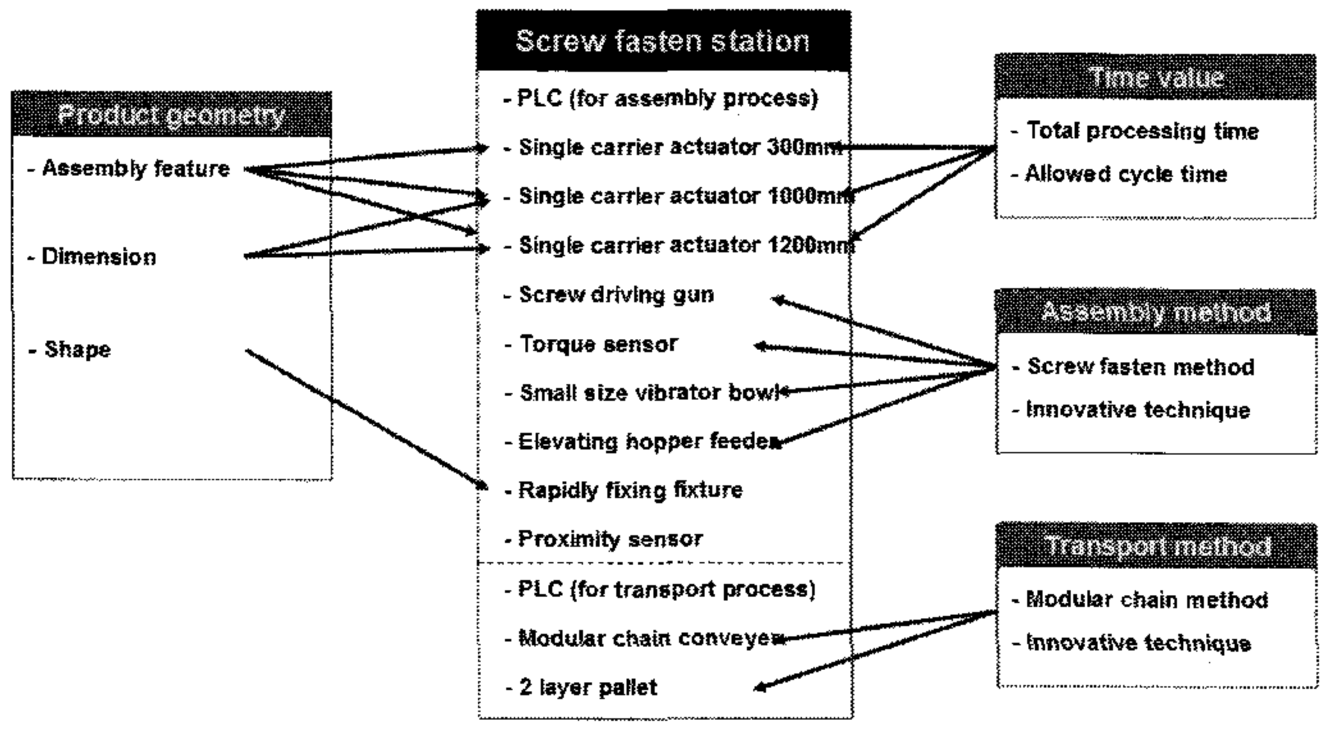

Fig. 4 Related components to change drives in a screw fasten statio

		Changeable drives							
		Product geometry					Time value	Assembly method	Transport method
	Component	Dimension	Shap e	Surface form				Screw fasten	Modular chain conveyer
				Are assembly points on horizontal surface?	Position of assembly points	Number of assembly points			
1	PLC(for assembly process)	-	-	-	-	-	-	-	-
2	Carriage bar (Height): 300 mm	-	-	+	+	+	+	-	-
3	Carriage bar (Width): 1000 mm	+	-	+	+	+	+	-	-
4	Carriage bar (Length): 1200 mm	+	-	+	+	+	+	-	-
5	Screw-fastening guns	-	-	-	-	-	-	+	-
6	Torque sensor	-	-	-	-	-	-	+	-
7	Small size vibrator bowl	-	-	-	-	-	-	+	-
8	Elevating hopper feeder	-	-	-	-	-	-	+	-
9	Rapidly fixing fixture	-	+	-	-	-	-	-	-
10	Proximity sensor	-	-	-	-	-	-	-	-
11	PLC(for transport process)	-	-	-	-	-	-	-	-
12	Modular chain conveyer	+	-	-	-	-	-	-	+
13	2-layer pallet	+	-	-	-	-	-	-	+

Fig. 5 Change drive-component matrix for the screw fasten station

components and the related change drives. When any change in a change drive occurs, the structure of some components is altered, along with the ability to carry out the required functions (Fig. 4). Due to this effect, an approach is proposed to group components into modules based on the dissimilarity coefficient. A change drive-component matrix is used to illustrate the relationship between the change drives and the affected components with a "+" entry (Fig. 5).

The matrix is then transferred to a component–component matrix to aid the grouping of components into modules (Fig. 6).

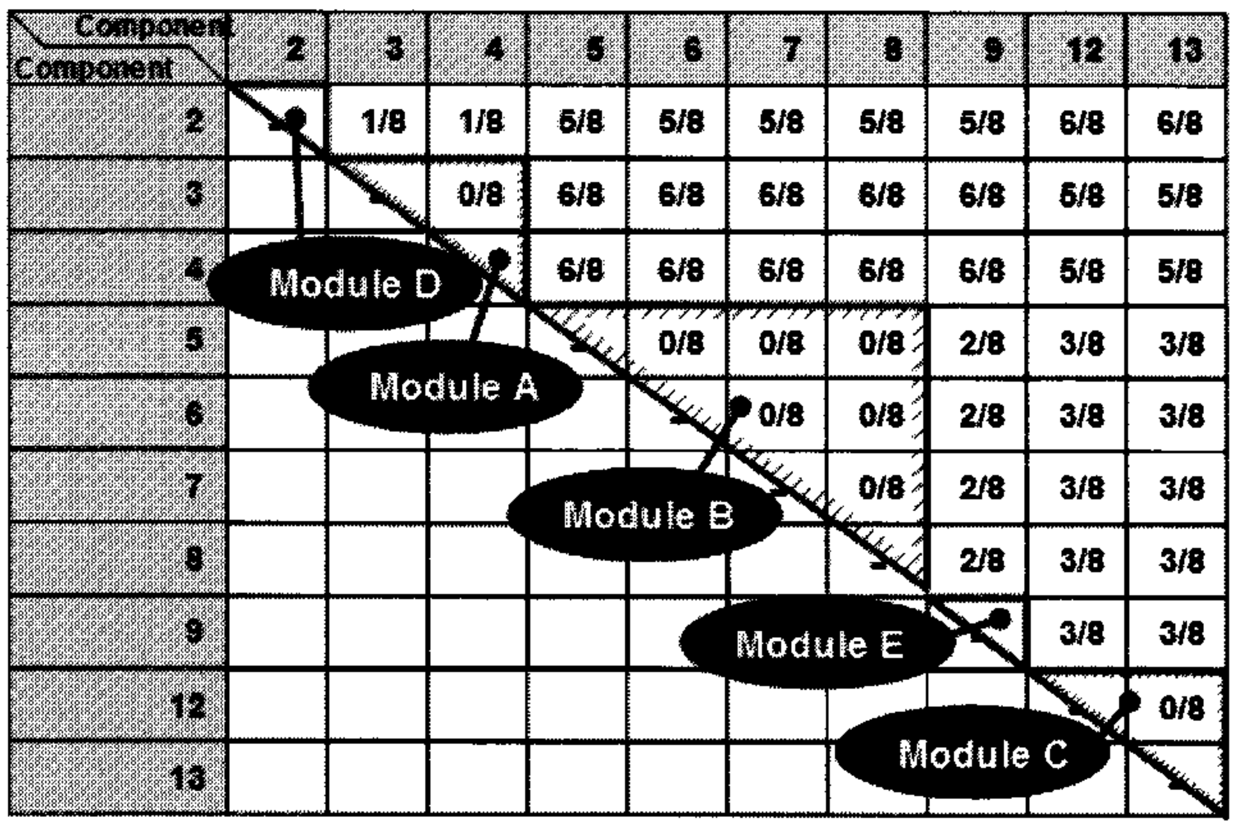

Fig. 6 Component–component matrix for the screw fasten station

Components 1, 10, and 11, which do not have relationships with the change drives, are not taken into account. Each cell in this matrix presents the value of the dissimilarity coefficient of the two corresponding components: the smaller the value of the dissimilarity coefficient, the more similar the two components are. The dissimilarity coefficient of the two components can be measured as follows:

$$DS_{ij} = \frac{q_{ij} + r_{ij}}{p_{ij} + q_{ij} + r_{ij} + s_{ij}} \quad (1)$$

p_{ij}: number of variables that are positive for both objects i, j

q_{ij}: number of variables that are positive for the i^{th} object and negative for the j^{th} object

r_{ij}: number of variables that are negative for the i^{th} object and positive for the j^{th} object

s_{ij}: number of variables that are negative for both objects

This method investigates all values in the component–component matrix and helps to group components whose dissimilarity coefficients are smaller or equal to a specific value, called the "threshold" of a single module. The threshold is first assigned to the lowest value of the dissimilarity coefficient in the matrix. After completion of the module formation in this step, the threshold is assigned to the next lowest dissimilarity coefficient and so on in the next steps. Two regulations should be considered. First, each component belongs to only one module. Second, the coefficient value of each pair of components within a module must be smaller or equal to the threshold value. As this process continues, the threshold value increases until all components are grouped into modules.

To begin the process of module forming, the threshold is assigned the value of zero. The pair of components having a dissimilarity coefficient equal to this value is clustered into a single group. Several initial groups are generated in this step. To satisfy the second regulation for this step, two modules are generated as follows: module A (3, 4), module B (5, 6, 7, 8), and module C (12, 13). The rest of the ungrouped components are 2 and 9.

With the next threshold of 1/8, component 2 should be considered as a module (module D). Component 9 is the final one to consider. However, all components have already been grouped into modules with lower dissimilarity. Thus, component 9 forms a single module (module E).

Some components cannot be grouped into modules in terms of change drives. They are 1, 10, and 11. These components remain constant with their own functions and are not affected by any change drives. Thus, each of them is regarded as one module.

4. Classification of Modules for Designing Manufacturing Systems

4.1 Strategy for module classification

To design a new manufacturing system quickly that accommodates the new requirements of the change drives, we must develop a strategy for efficiently using the generated modules. Based on an analysis of the functions and the assessment of their relationship with the change drives, the applicability and the interface of the modules within a manufacturing system are classified into four categories: "to be used" module, "to be modified" module, "to be replaced" module, and "to be developed" module.

"To be used" modules are not impacted by any change drives. They therefore can be carried over from an existing system to a later one. Modules that are likely to undergo modifications as a result of changes in change drives are regarded as "to be modified" modules.

"To be replaced" modules are those that need frequent replacement due to new change drives. Without any changes in terms of, for example, shape and dimension, these modules are simply replaced with the modules that existed in a previous system.

"To be developed" modules do not exist in the library and are built whenever a demand arises for applying novel techniques to the design of an assembly system. After developing them, they are saved in the library for future use.

4.2 Rules for classifying modules

The relationships between modules and change drives are analyzed to evaluate how the structure or the operational ability of a module is affected by the change drives. Based on the analysis, each module in the library will be assigned to a suitable category.

"To be used" modules include all modules in the library that are not affected by the change drives. They have the highest degree of flexibility, which implies a long lifetime despite any changes in the manufacturing environment. By reusing them for designing a new system, the planner can not only reduce the investment cost but also reduce the design time.

Module "modular chain conveyer" is affected by two change drives: transport method and the product dimensions. The dimensions are not the same in different products. The structure of this module can be partly redesigned according to the specifications of the new product dimensions and reused in the new assembly system. From the definitions of the four types of modules mentioned above, this module is classified as a "to be modified" module.

An evaluation process is performed to find the appropriate module properties for a handheld screw-fastening gun and the small-size vibratory bowl in the manual station. This module is dependent on the "screw-fastening method" change drive because the screw-fastening method is needed for assembling the current door trim product. When a new product is assembled and an improved method is required, this module will be eliminated and replaced with a new module. Therefore, this module is considered as a "to be replaced" module.

Application of the latest advancements in technology is important to the development of new, more efficient, and highly adaptable manufacturing systems. To accomplish this task, a new component should be developed to meet the requirements of the new technology. In the future, the system should be equipped with such components that cannot be found in the module library. Those are called "to be developed" modules. The rules for classifying modules are based on these reasons (Fig. 7).

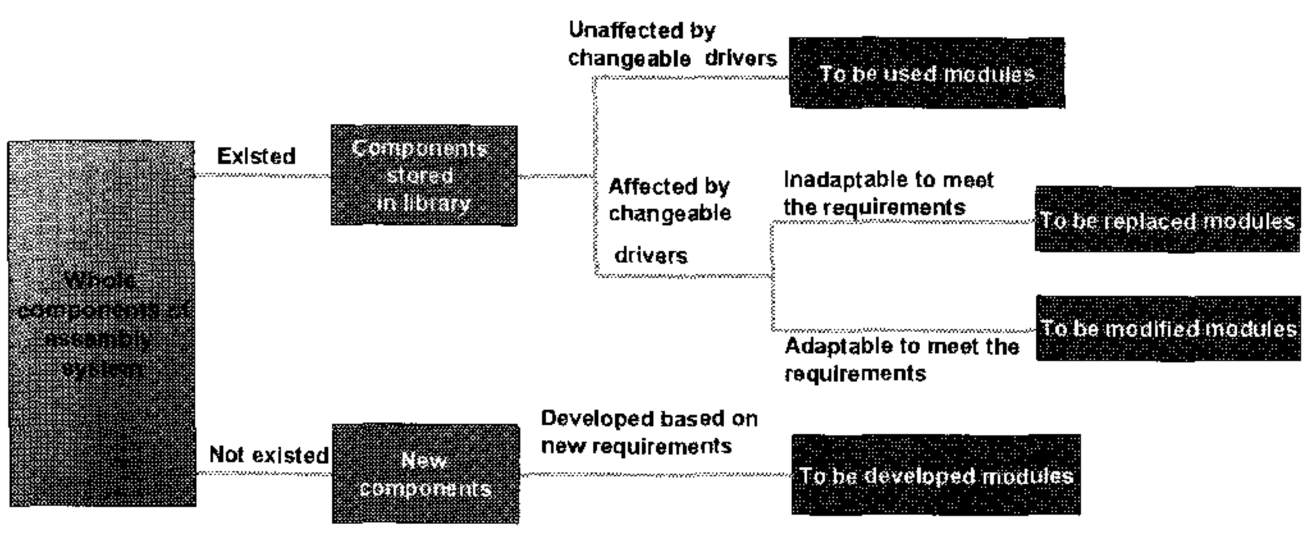

Fig. 7 The rules for the classification of modules

All modules in the library are divided into four types: "to be used" modules, "to be modified" modules, "to be replaced" modules, and "to be developed" modules. The adaptation potential in dealing with the change drives variation was determined for each module.

After designing a new system, the module library can be extended continuously with the newly developed components. New modules also need to be assigned to one of the four types according to their adaptation possibilities.

5. Implementation of the Modular Manufacturing System

To prevent any risks in commercial systems, the developed system was implemented on the commercial tool, DELMIA. All modules were modeled using a 3D CAD tool and stored in the library.

To efficiently support the redesign work, it is essential to develop implementation rules that describe how the modules of the current manufacturing system are adjusted according to change drives. The following is an example for module A (Fig. 8).

IF *the positions of assembled points are on horizontal surface* AND
IF *the ratio between processing time and cycle time >1* AND
IF *the ratio between processing time and cycle time <2* AND
IF *product's width >650 mm*

Then *module C is replaced with module consisting of cantilever type-dual XYZ robot*

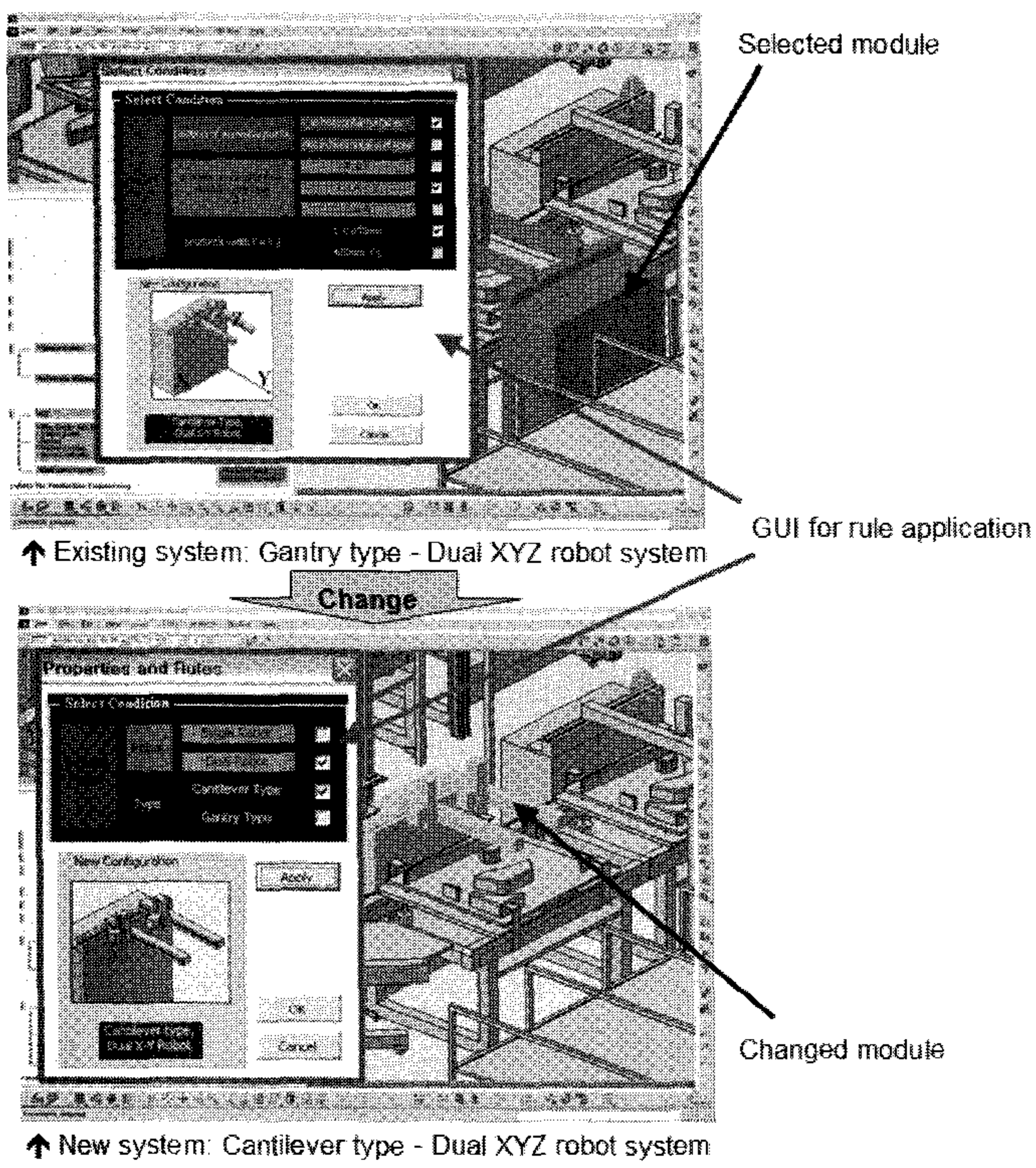

Fig. 8 Implementation of the screw fasten system based on a modular strategy (replaced module)

Based on these rules, a software application was programmed to supply an easy-to-use tool for the design work. The new requirements of the change drives derived from the product and production conditions analyses are input through the windows. With the combination of the new state of the change drives, the most appropriate module in the library will be found by the defined relationship rules and replaced with the appropriate "to be replaced" module in the current system. If a "to be modified" module is needed, the planner can redesign its structure in a 3D CAD tool such as CATIA after consulting the implementing rules and the new design specifications. After redesigning, the exchange process is automatically executed by the information of the existing module in the current system. Any modifications will be automatically updated in the current models. When new demands arise, the module library can also be extended by importing the "to be developed" modules. The redesign work is processed without interfering with the remaining "to be used" system modules. Therefore, the design time decreases and the investments for the reconfiguration of the manufacturing system significantly decreases.

6. Conclusions

To be more competitive in the turbulent global market, enterprises must shorten the interval for new product introduction and diversify their products. To address this trend, we present a strategy to reconfigure the assembly system of a door trim in an efficient and effective way; to adapt to changes in the environment, this strategy takes change drives into account. The components are selected based on the hierarchical structure of the functions of the designed system. To reduce the effect of a turbulent environment, components of the system are grouped into four modules based on the dissimilarity coefficient concept. To utilize the adaptabilities, modules are classified into four categories: "to be used" modules, "to be modified" modules, "to be replaced" modules, and "to be developed" modules. The implementation rules based on this classification are then used as the knowledge database by the software application. Using this software helps to simplify the system redesign work so that the design time and cost can be significantly reduced. The risks that can occur when using this system should be predicted. For this reason, the developed system was implemented in the digital environment with the commercial tool, DELMIA.

The modular strategy proposed in this study will contribute to the efficient improvement of the manufacturing system design method. Due to its generalized property, this strategy can also be applied to designing manufacturing systems for other kinds of products.

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