Discrete State Change Model of Manufacturing Quality to Aid Assembly Process Design*

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Abstract

This paper proposes a representation model of the quality state change in an assembly process that can be used in a computer-aided process design system. In order to formalize the state change of the manufacturing quality in the assembly process, the functions, operations, and quality changes in the assembly process are represented as a network model that can simulate discrete events. This paper also develops a design method for the assembly process. The design method calculates the space of quality state change and outputs a better assembly process (better operations and better sequences) that can be used to obtain the intended quality state of the final product. A computational redesigning algorithm of the assembly process that considers the manufacturing quality is developed. The proposed method can be used to design an improved manufacturing process by simulating the quality state change. A prototype system for planning an assembly process is implemented and applied to the design of an auto-breaker assembly process. The result of the design example indicates that the proposed assembly process planning method outputs a better manufacturing scenario based on the simulation of the quality state change.

Key words: Assembly System, Process Planning, Production System, Computer Integrated Manufacturing (CIM), Discrete Modeling, Petri-Net

1. Introduction

1.1 Limitations of conventional knowledge management schemes in assembly process

For a designer/planner of the assembly planning process, it is important to understand why defective products are produced. Apart from simply knowing the reasons, it is essential that this manufacturing quality information be recorded. PFMECA (process failure mode, effects, and criticality analysis)(1) or QC (quality control) charts(2) are very effective tools for providing a graphical representation of manufacturing knowledge. However, most of the recorded manufacturing knowledge has not been effectively reused. The most important reason for this, according to the authors, is that the existing process models do not consider the reusability of the recorded information. The differences between existing models—for example, the differences between QC charts and PFMECA—are mainly responsible for lack of reusability. Due to lack of reusability, defects still occur repeatedly in the manufacturing process.

This paper presents a representation model of the quality creation process that is intended for use in the design stage of the manufacturing process. A new modeling method of the assembly process is also presented. Since this modeling method involves the use of a computer-aided planning system, reusability is guaranteed. In the designing stage of the
assembling process, the proposed computer-aided planning system automatically reuses the assembly process knowledge. In order to formalize the assembly process model, the functions, operations, and quality changes are represented as a network model that can simulate discrete events of quality-related issues. The basic premise of this study is that if manufacturing knowledge can be represented as a model that can be used in a computational planning system, this knowledge would not be lost in the future; in other words, reusability would be guaranteed.

1.2 Recent studies on assembly process modeling

Many methodologies have been developed for the purpose of representing, sharing, and utilizing manufacturing knowledge. However, determining the structure of manufacturing knowledge itself is a very difficult problem. In this research, we assume that the structure should be such that the knowledge can be used directly in computational design. Hence, we propose a computational manufacturing knowledge model that is based on the design method considering product quality.

The computational assembly and disassembly model is proposed that uses a joint library (3) and locator-snap systems (4). A method for redesigning the manufacturing system by taking into consideration the manufacturing quality is proposed on the basis of the QFD (Quality function deployment) method (5). For developing the knowledge structure, ontological approaches for representing design errors and unintended product behavior are developed (6–8). As pointed out by Fuse, in order to directly utilize the manufacturing knowledge in the manufacturing planning stage, it is not enough to focus on just the knowledge (9). Therefore, this research focuses on a representation model of the entire assembling process. In order to represent, share, and utilize the manufacturing knowledge in the manufacturing planning stage, a computational representation model of the assembly process that can describe quality-related issues is required. Such a model has hitherto not been proposed.

Mantripragada developed an assembly sequence planning method for obtaining products with the desired functional attributes based on airplane design considering flatness (10). Tamura et al. proposed the SSM (stress-strength model) to represent the failure mode mechanism (11). In this study, we have developed a new integrated model that can represent both the assembly process and its quality. This model is a combination and an extension of Mantripragada’s assembly sequence model and Tamura’s SSM model.

TQD (total quality deployment) and QFD (quality function deployment) are techniques used to map the required qualities and attributes of the products to the design requirements (12)(13). Both these techniques allow designers to determine the importance of operations as per customer requirements. However, both TQD and QFD have a limitation in that they cannot represent the propagations of the quality state changes on assembling process. Hence, in this research, the model of the quality state change is introduced in the assembly processes by using a discrete modeling method based on Gero’s FBS (function-behavior-structure) model (14). The design method adopted in this research is based on an integrated model of the product, assembly processes, and the product quality proposed by the authors (15).

1.3 Aim of this research

In order to realize a process design aid considering the quality of the manufacturing process (it determines quality of the manufactured product), representation and sharing of manufacturing knowledge is highly essential. For effective representation and sharing of manufacturing knowledge, it is necessary to develop an assembly process model. The product quality must be described explicitly in this assembly process model. Thus, a computational design method for an assembly process that can achieve the required quality
and prevent manufacturing failure must be realized. To achieve this goal, the following steps must be implemented:
1. Development of an information model of the assembly process that can represent both the assembly process and the manufacturing quality
2. Development of a method for a process design aid that takes into consideration the manufacturing quality
3. Development of a prototype system for validating the proposed model and the proposed method

2. Process model considering manufacturing quality

2.1. Manufacturing process model

In this research, we assume the following process: materials → parts → product. During the manufacturing process, the raw material is made to undergo various transformations with regard to its form, shape, and quality and individual parts are produced; these parts are then assembled into the final product. Basically, this research models the manufacturing process as a set of operations performed by workers and machines in order to change the state of the product from a material to the final product. This modeling decomposes the manufacturing process into several sequential operations. An operation is decomposed into its translation function (main task) and translation target (product in process). The product quality implies the shape and the attributes of the product in the manufacturing process.

This modeling process is a two-step process that can be summarized as follows:
1) The manufacturing process is first defined as a set of operations. The sequence of operations and the product to be manufactured in that process are both defined.
2) The relationship between the product and the operation is defined.

Fig. 1 shows a simple model of the manufacturing process adopted in this research. This model consists of two individual models [A] and [B], and [R(A,B)] denotes the relationship between the two models.

[A]. Product in process (Fig. 1 [A])
[B]. Sequence of operations (Fig. 1 [B])
[C]. Relationship between product and operation

The product quality state is changed by the operation object. The sequence of operations transforms the quality state of the product in the process from a material to a final product. In this study, we have used Petri net to represent the changes in the product quality state in the manufacturing process.

A Petri net (PN) is a well-known mathematical, graphical, and computational language for describing a dynamical, concurrent, and discrete system\(^{(16)}\). The manufacturing process model is described on the basis of the PN. A PN models a system as a bipartite
graph that consists of places and transitions. Detailed definitions of PN elements of the manufacturing process model are given in Table 1. An operation in the manufacturing process is given by a transition node and its translation function (transition object). The operation requires an equipment (worker, machine, and equipment). A condition of the operation in the manufacturing process is represented by means of an operation node, and it represents the equipment attributes that are required for the function of translation of quality states. This operation node is represented as a transition node in the PN model.

The product in process (Fig. 1 [A]) models the incomplete product components and parts. It consists of the structure and quality of the product. The product structure is defined as the elements of product (Product Entity object in Process: PEP) and as its interfaces between PEP (Product Interface object in Process: PIP). Based on the product definition using PEP and PIP. The quality of product is represented by quality of the product. The product structure defines the quality state of PEP and PIP. Both PEP and PIP have a network of quality states. The PEP and PIP object are modeled as a bipartite graph of the Quality State object (place object) and the quality state change object (transition object), respectively.

An attribute object defined in the PEP and PIP represents the attribute of the product supposed to be/being manufactured. A token object represents a current state of the manufacturing process. A quality token describes the quality state of the product at some point in time. A manufacturing token describes the progress of the manufacturing process at some point in time.

The manufacturing process model can be categorized by two kinds of operation flows:

1. Assembly operation flow
2. Processing operation flow

The processing operation flow represents the process of manufacturing the parts from the material. The operation in the processing operation flow mainly acts on the PEP, and changes quality state of PEP. The assembly operation flow represents the process of manufacturing an assembled component (ASSY) from the parts. The operation in assembling system mainly acts on the PIP, and changes its quality state.

2.2. Causality model of the manufacturing quality

A product quality model is proposed on the basis of the manufacturing process model. Failure of the manufacturing process is defined as the generation of the failure quality state of the product. The failure quality state is defined as a quality state of the final product that derives loss of product function. Fig. 2 shows the model of the manufacturing quality implemented for the manufacture of a hood panel (an iron plate for a car bonnet). The failure quality state is defined as the product failure state, and it is indicated by the red circle ("Wrinkled") in Fig. 2.

Production failure can be categorized into two types:

[A]. Production failure caused by product

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="PEP" /></td>
<td>Product Entity Object in Process (PEP)</td>
<td>Components and Parts that are not finished yet</td>
</tr>
<tr>
<td><img src="image" alt="PIP" /></td>
<td>Product Interface Object in Process (PIP)</td>
<td>Assembling Connection between PEP</td>
</tr>
<tr>
<td><img src="image" alt="At" /></td>
<td>Attribute in Process</td>
<td>Attribute of Entities and Interfaces generated by Production Process</td>
</tr>
<tr>
<td><img src="image" alt="QS" /></td>
<td>Quality State in Process</td>
<td>Quality State of Entities and Interfaces (Place object)</td>
</tr>
<tr>
<td><img src="image" alt="QSC" /></td>
<td>Quality State Change</td>
<td>Change of Quality State (Transition object)</td>
</tr>
<tr>
<td><img src="image" alt="Op" /></td>
<td>Operation</td>
<td>Work of worker and machine that can operate product (Transition object)</td>
</tr>
<tr>
<td><img src="image" alt="Cond" /></td>
<td>Condition</td>
<td>Attribute of worker and machine on operation</td>
</tr>
<tr>
<td><img src="image" alt="IP" /></td>
<td>Intermediate Part</td>
<td>Intermediate Part or Assembly (Place object)</td>
</tr>
<tr>
<td><img src="image" alt="QTok" /></td>
<td>Quality Token</td>
<td>Qualitative state of product at a given moment (Token object)</td>
</tr>
<tr>
<td><img src="image" alt="PTok" /></td>
<td>Production Token</td>
<td>Progression of Production Process (Token object)</td>
</tr>
</tbody>
</table>
Production failure caused by an operation

Type [A] represents the failure due to the product itself. This type of failure could arise due to a number of reasons including inadequacy of the material and defects of additives or a causal chain inside a product structure. Type [B] is the failure that is caused by an operation, e.g., worker errors or machine errors.

3. Design method of assembly process considering manufacturing quality

3.1. Overview of planning method of assembly process

This section discusses the algorithm for assembly planning to reduce product quality issues. The designer has to define the operations and the sequence of operations to prevent failure quality states. In this research, designing the assembly process involves the determination of the operations and their processes. In order to reduce the product failure quality states, the product quality related issues must be considered in the planning stage of operations and its processes.

Fig. 3 provides an overview of the design method of the assembly process. This Fig. shows the entire model of the assembly process and the product quality. In the design process, the following method are implemented:

1. Integrated model of product-process-quality (Fig. 3 [1])
2. Space of quality state (Fig. 3 [2])
3. Sequence of Operations (Fig. 3 [3])

The Z axis in Fig. 3 represents the hierarchical relationships between an assembled product layer and a parts layer. “Pump ASSY” in Fig. 3 consists of two sub-components—“Valve” and “Pump.” The quality state of Pump ASSY is represented by a combination of the quality states of the sub-components Valve and Pump. Since the assembling process can be rather complex, hierarchical representation is introduced to enable multistage decomposition of the quality design of the assembly process.

3.2. Steps in design of assembly process

The design of the assembly process considering the product quality is carried out according to the following steps:

**STEP1 [a] Definition of product to be manufactured**

The Entity object defined on the component level is decomposed into some entity objects on the parts level. The product structure is defined by the design of interfaces. Fig. 3 shows that Pump ASSY is decomposed into two components—Valve and Pump.

**STEP1 [b] Listing feasible operations**

The designer lists the feasible operations that can be carried out by an organization or a factory. The example in Fig. 3 indicates that there are three feasible operations—fill oil,
remove air, and close. The changes in the product quality state according to the feasible operations are described in the product quality information. The example in Fig. 3 indicates that there are three state changes—“influx” by fill oil, “boil” by remove air, and “close” by close operation.

**STEP1** (c) **Listing possible failures**

The designer lists the possible failures related to the applied operations. The example in Fig. 3 indicates that there are one failure—“Air Containing” by influx, since “boil” requires that valve is opened.

**STEP2** **Calculation of integrated model of product-process-quality**

The design system generates an integrated model of product-process-quality by integrating the results of steps 1 [a], [b], and [c].

**STEP3** **Generating space of quality state**

The design system calculates the space of quality state of the assembling process from the integrated model of product-process-quality. The integrated model is defined on the basis of the PN model. A reachable tree calculated from the PN model of the integrated model represents the space of product quality state in the assembly process. The algorithm for generating a reachable tree is shown in Fig. 4:

The reachable tree is represented as a bipartite graph that consists of markings and firing sequences. The markings represent the placement of tokens. “Marking1” indicates
that places “P1” and “P2” have a token. The firing sequence represents the transitions that are enabled to fire from each marking. The condition of firing of each transition is described by an arc. Fig. 4 [3] shows the different types of arcs used in this research. Basically, transitions can fire when all start places of the input arcs have a token. In this research, a
original Petri net (weight of arcs = 1, capacity of places = 1) is used.

**STEP 4 Selecting final quality and production scenario**

The designer selects a final product quality state (Fig. 3 [A]) and production scenario (Fig. 3 [B]) from the calculated space of product quality state. The example in Fig. 3 shows that the designer selected the quality state “Closed, Filled, and No Air” as the final intended quality state.

**STEP 5 Output assembly process**

The selected scenario of quality state change includes the operations and its processes. The design system proposes the assembly process from the operations.

4. Auto-breaker design example and discussion

4.1. Prototype system and design example of auto-breaker

On the basis of the proposed model and algorithm, a prototype system for planning an assembly process has been developed. The effectiveness of the proposed design method has been confirmed by a design example of a manufacturing system of contact ASSY, one of the components of the auto-breaker. Fig. 5 shows the structure, shape, and arrangement of the contact ASSY.

The contact ASSY is an important component of the auto-breaker, and its function is

Fig. 5. Decomposition of product structure (example of STEP 1 [a])

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**Fig. 6. Listing feasible operations (example of STEP 1 [b])**
conduction and insulation of electric current. Usual path of the electric current is from the contact plate to the contact. Because high current derives arcs from the contact, the arc hone is required to avoid the arcs from the contact, and to realize quick insulation.

The planning result of the assembling process of the Contact ASSY on the prototype system is shown in following steps.

**STEP1 [a] Decomposing contact ASSY**

The first step of the design method is the decomposition of the contact ASSY. The contact ASSY consists of three parts: contact, contact plate, and arc hone.

**STEP1 [b] Listing feasible operations**

The designer defines three feasible operations as shown in Fig. 6 (1)–(3):

1. **Brazing**
   - The contact plate and the contact can be connected by brazing.
2. **Caulking**
   - The arc hone and the contact plate can be assembled by caulking.
3. **Form pressing**
   - The contact plate can be shaped by form pressing.

**STEP1 [c] Listing possible quality-related causalities**

The designer lists three possible failures based on listed operations (Fig. 7 (4)–(6)):

1. **Curve by braze**
   - The contact plate is curved due to the brazing heat.
2. **Misalign by form pressing**
   - The mounting angle of the arc hone changes due to form pressing.
3. **Remedy by form pressing**
   - The curvature of the contact plate can be removed by form pressing.

**STEP2 Calculating integrated model of product-process-quality**

The design system calculates the integrated model of product-process-quality by combining the results of steps [1]–[6]. The calculation result is shown in Fig. 8.
STEP3 Calculating space of quality state

The design system calculates the space of quality state by reachable tree analysis (Fig. 9). The top marking node of the calculated tree represents the start state of the assembly process. The bottom marking node of the calculated tree represents the end state of the assembly process. The red markings denote the failure quality state.

STEP4 Selecting final product quality and scenario

The designer selects the final quality (Fig. 8 [A]) and its scenario (Fig. 8 [B]). When the end marking has no failure quality state, it means that the final product is good/available. This scenario means a manufacturing process in which there is no product failure.

STEP5 Outputting assembly process without product failure state

The design system proposes an assembly process to the designer from the selected manufacturing scenario. The assembly process recommended by the design system is shown in Fig. 10 (a). The process is as follows:

The contact ASSY is manufactured by brazing the contact plate and the contact (Fig. 10 [2]), form pressing (Fig. 10 [3]), and caulking with the arc hone (Fig. 10 [4]).
4.3. Discussion

Fig. 10 (a) shows an assembly process proposed by the design system that does not include the failure quality state of the final product. Without the design method proposed in this study, the designer has to select one good manufacturing scenario from 6 candidates by trial and error. Hence, the proposed design method can help a designer to design an assembly process considering the product quality.

A possible design result without the proposed design method is shown in Fig. 10 (b). The assembly process shown in Fig. 10 (b) can be described as "the contact ASSY is manufactured by form pressing the contact plate (Fig. 10 [2]), brazing the contact plate with the contact (Fig. 10 [3]), and caulking the contact plate with the arc hone (Fig. 10 [4])."

The difference between processes (a) and (b) lies only in the order in which the brazing (Fig. 10 [A]) and form pressing operations are carried out (Fig. 10 [B]). From this difference, the designer can know why the brazing must be upstream operation than the form pressing operation. This knowledge is an important manufacturing know-how and can be represented by the assembling process model proposed in this study. Generally, it is very difficult to predict the effect of the design change of the assembling process. The proposed design method is advantageous since it automatically lists all possible quality issues, thereby allowing a designer to easily change the assembly process.

5. Conclusions

We have proposed a representation model of the quality state change in an assembly process that can be used in a computer-aided process design system. We have also developed a design method for the assembly process. The design method calculates the space of quality state change and outputs a better assembly process (better operations and
better sequences) that can be used to obtain the intended quality state of the final product. A computational redesigning algorithm of the assembly process that considers the manufacturing quality is developed. The proposed method can be used to design an improved manufacturing process by simulating the quality state change.

A prototype system for planning an assembly process is implemented and applied to the design of an auto-breaker assembly process. The result of the design example indicates that the proposed assembly process planning method outputs a better manufacturing scenario based on the simulation of the quality state change. This result supports our assumption that the design method of the assembly process can be used to discuss quality-related issues and to manufacture products with better quality. Hence, we can conclude that the proposed model and design method are effective.

Recently, because the product development is getting more and more complex, the model-driven product development is getting more and more important. We are hoping that the proposed computer-aided process design system will contribute to achieve the model-driven manufacturing system design in the near future.

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