PROCESS PLANNING SUPPORT SYSTEM CONSIDERING PRODUCT QUALITY

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ABSTRACT

This paper proposes a new process planning method to achieve intended product quality. The design for the product quality is achieved by total designing and planning of production process considering both good factors and bad factors that affect product quality in the production process. The representation model of quality related production knowledge that is directly used in the computational design method is proposed. The discrete quality related behavior of product in process is modeled. Input information of the proposed design method consists following information: 1) a product structure; 2) feasible operations of the production process; 3) possible quality related causalities in the production process. The design method calculates the space of quality state automatically by this method. Final output information from this method is a good production process (good operations and good sequence) that achieves the intended quality state of final product.

In order to develop this production process planning method for keeping the intended quality, this paper proposes a computational representation model of the quality related information in production process. Based on the production process model, a computational recommendation algorithm of production process that can achieve the intended product quality state is developed. The representation, sharing and re-use of production knowledge and know-how are realized based on the proposed production process model. A prototype system for planning a production process without failures of final product is implemented for the purpose of examination and validation for proposed method. A practical design example of a production process planning for one component of an auto-circuit breaker is demonstrated. The methodology proposed in this research addresses: (1) how the product quality in production process should be modeled; (2) how to design good operations and a good process in production that can achieve the intended product quality; and (3) how to apply the proposed method to a practical planning problem of an actual production process.

Keywords: Quality Design, Process Planning, Production Knowledge Model, Petri-Net

1. INTRODUCTION

In these years, the loss of money and reliability of manufacturing industry, caused by product quality related issues, is increasing. The product failures and quality issues in a production process are very serious problems because of their high proportion (45%, [LITM 2002]). This research aims at a computational production process planning method that can achieve the intended product quality state and avoid fatal errors or failures of the product.

In order to reduce failures, errors and defects of final product, a process planner has to plan a good production process considering quality related issues. However, it is generally difficult because factors in an upstream production stage could cause quality issues in a downstream production stage. Because of the causal chain in production process, some change in the production process to prevent a quality issue might derive other kinds of quality issues of final product.

The computational representation model of production knowledge and know-how is highly desired to solve such difficulty in the prevention of quality issues. It is pointed out that the product failures and product quality related issues in the production process are very difficult to represent and...
visualize. Various factors of failures, errors, faults and defects of final product in production process must be modeled and represented in a computer. Under existing methodologies in engineering design and manufacturing field, there is no unified and general method for representing and sharing failures or the quality related issues in the production process. This is one of the reasons for the existing documents of production knowledge (ex. PFMEA (Production Failure Modes and Effects Analysis) sheets, QC (Quality Control) Process Chart, etc.) are not effectively used in the process planning stage. Hence, it is desired that the product quality related issues in the production process are represented in a computer comprehensive way. This representation realizes a computational method to store, share, manage and utilize a huge number of production know-how and knowledge in the process planning stage. So, this is the reason the representation for production quality is required.

The product quality issue in the production process means a product state that cannot fulfill a product function that is intended in the product design stage. Hence, the product quality issues consist of product failures and defects caused by the production process. This research recognizes the production process planning as a design of operations and processes, and proposes a planning method of operations and processes that satisfy an intended product quality of the final product.

2. RECENT WORKS ON PRODUCTION KNOWLEDGE REPRESENTATION AND SHARING

Many methodologies have been developed for the purpose of representing, sharing and utilizing production knowledge. The problem of “what the structure of production knowledge should be” is a very difficult problem by itself. This research assumes that the knowledge structure should be the structure that is used directly in the computational design method. Hence, this research proposes the computational production knowledge model based on the design method considering product quality.

For a purpose of the development of the knowledge structure, ontological approaches for a representation of design errors and unintended product behavior are developed [Vegte 2004] [Iino 2003] [Iino 2005]. Fuse pointed out that only focusing on the knowledge itself is not enough for direct utilization of production knowledge in the production planning stage [Fuse 2002]. For this reason, this research focuses on a representation model of the production process itself. In order to represent, share and utilize the production knowledge in the production planning stage, the computational representation model of the production process that describes quality related issues is required. Such model is not proposed in the existing methodologies. Hence, the new model of the production process and its quality is necessary.

Mantripragada developed the planning method of assembling sequence for a purpose of satisfying product functional attributes based on airplane design considering flatness [Mantripragada 1998]. Tamura et al. proposed a model of mechanism of the failure mode [Tamura 2002] as SSM (Stress-Strength Model). Based on these methodologies, this research proposes a new integrated model that can represent both the production process and its quality, by a combination and extension of the Mantripragada's assembling sequence model and Tamura's SSM model.

TQD (Total Quality Deployment) and QFD (Quality Function Deployment) are mainly focused on the mapping of the required qualities, product attributes and operations [Clausing 1994] [Chao 2004]. For the purpose of the production process planning considering the product quality related attributes, both methods can help the planners to know and determine the importance of operations from customer requirements. The weak point of TQD and QFD is the lack of the representation of propagations of product and causal chains on production process. Hence, this research introduces the behavior of product in the production processes using discrete modeling method proposed by the Gero's FBS (Function – Behavior - Structure) model [Gero 1996]. The design method in this research is based on an integrated model of product, production processes and product quality proposed by authors [Koga 2005].

3. AIM OF THIS RESEARCH

In order to realize the production planning method for keeping the product quality, the representation and sharing of the production knowledge is highly desired. For this purpose, the modeling of the production process itself is necessary. The product quality must be described explicitly on this production process model. Based on the production process and quality model, the computational design method of production process that can achieve required quality and prevent the production failure must be realized.

The aim of this research is the development of the quality design method of the production process based on the representation model of production knowledge. To achieve this goal, this research addresses following three objectives 1) – 3):

1) Proposition of an information model of the production process that describes product quality related issues
2) Development of the production process planning method to achieve the intended product quality
3) Verification of the proposed model and method by an actual design example

4. MODEL OF PRODUCTION PROCESS AND PRODUCT QUALITY

4.1. Production Process Model

In order to propose the model of production process, we have to answer the following questions, “How do we manufacture a product? / Why can we manufacture a
product?". In this research, we assume that a product is manufactured by several transformations of its form, shape and quality state from material to parts and parts to a final product (assembled product). Basically, this research models the production process as a set of operations, those are done by workers and machines in order to change the product state from material to final product. This modeling decomposes the production process into several operations with its sequences. The operation is decomposed into its translation function (main task) and translation target (product in process). The product quality is defined as the quality state of the shape and attributes of the product in the production process.

This modeling mentioned above is summarized as;
1) the production process is defined as a set of operations with its sequence and a product in process, as well as
2) their relationships are defined.

Fig. 1 shows a simple model for the production process in this research. This model consists of two types of models [A] [B] and relationships between the two models [R(A,B)];
[A] Product in Process (Fig. 1 [A])
[B] Sequence of Operations (Fig. 1 [B])
[C] Relationship between Product and Operation

The function of an operation object defined in the model [B] represents a transformation of a product quality state. The sequences of the operations transform the quality state of the product in process from material to a final product. In this paper, we introduce the Petri-Net to represent the changes of the product quality state in the production process.

The Petri-Net (PN) is well-known mathematical, graphical and computational language for dynamical, concurrent and discrete system [Petri 1962] [Murata 1989]. The production process model is described based on the PN. PN models a system as a bipartite graph that consists of places and transitions. Detailed definition of PN’s elements of the production process model is shown in Table 1. An operation in a production is defined as the transition node and its function of translation (transition object). This node has the main body of its action (worker, machine and equipment). Condition in a production is defined with the operation node, and represents the attribute of equipments that is required for function of translation of quality states. The operation object is identified by the input of a product in process and output of a product in process. This operation is represented as a place object in PN model.

![Fig. 1 Production Process Model](image)

Table 1 Definition of Elements in the Production Process Model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="symbol" /></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="symbol" /></td>
<td>Product Interface Object in Process (PIP)</td>
<td>Assembling Connection between PEP</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Attribute in Process</td>
<td>Attribute of Entities and Interfaces generated by Production Process</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Quality State in Process</td>
<td>Quality State of Entities and Interfaces (Place object)</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Quality State Change</td>
<td>Change of Quality State (Transition object)</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Operation</td>
<td>Work of worker and machine that can operate product (Transition object)</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Condition</td>
<td>Attribute of worker and machine on operation</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Intermediate Part</td>
<td>Intermediate Part or Assembly (Place object)</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Quality Token</td>
<td>Qualitical state of product at a given moment (Token object)</td>
</tr>
<tr>
<td><img src="image" alt="symbol" /></td>
<td>Production Token</td>
<td>Progression of Production Process (Token object)</td>
</tr>
</tbody>
</table>
The product in process (Fig. 1 [A]) models product components and parts that are not finished yet. The product in process consists of its structure and quality. 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). The product quality is defined as its quality state. Both of Product Entity object and Product Interface object have a network of quality states and they changes in production process. They are modeled as the bipartite graph of Quality State object (place object) and Quality State Change object (transition object) respectively.

An attribute object is defined in the PEP and PIP, and represents the product attribute supposed to be / being manufactured. A token object describes an active concept on the time-axis, and represents a current state of the production process. A quality token describes the quality state of product at some point in time axis. A production token describes the progress of production process at some point in time axis.

The model mentioned above indicates that the production process model can be categorized by two kinds of operation flow:
(1) Assembling operation flow
(2) Processing operation flow

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

4.2. Product Failure Model in Production

A failure model of product in process is proposed based on the production process model. The failure of production process is defined as the generation of failure quality state of product. The failure quality state is defined as a quality state of final product that derives loss of product function. Fig. 2 shows the model of the production failure by a manufacturing example of Hood Panel (An iron plate of car bonnet). The failure quality state is defined as a product failure state, shown as the red circular quality state “Wrinkled” in the Fig. 2.

Main factors of this failure are categorized as two types:
[A] A product failure in a production caused by a product (Fig. 2 [A])
[B] A product failure in a production caused by an operation (Fig. 2 [B])

The type [A] is the failure that is derived from product itself, e.g. an inadequate material, defect of additives or a causal chain inside a product structure. An example of model description in Fig. 2 [A] represents the following process:

If a sheet (stuff of the hood panel) has uneven material (Fig.2 a1), operation of form pressing (Fig. 2 a2) could derive a wrinkled state (Fig. 2 a3).

The type [B] is the failure that is derived from an operation, e.g. worker’s or machine’s errors. An example of model description shown in Fig. 2 [B] represents the following process:

Even if the material of sheet is normal, wrinkled state could be derived by the operation error (in this case, the setting of height of press machine (4mm) is not adequate).

The expression of ‘Good’ or ‘Bad’ of an operation in Fig. 2 cannot be defined locally. ‘Bad’ can be only defined as the final quality state of product. Whether bad quality is generated or not depends on the whole production process. This is the reason that the total quality design system considering both quality related good factors and bad factors is required.

5. DESIGN METHOD OF PRODUCTION QUALITY

5.1. Overview of Design Method

This section discusses the algorithm for production planning to reduce the product quality issues. The designer has to define the information of operations and its sequences to avoid and prevent failure quality states. The computational product quality design method of production process is shown in Fig. 1 and Fig. 2.

This research recognizes the design of the production process as the determination procedures of operations and its 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.

The overview of the design method of the product quality in the production process is shown in Fig. 3. This figure shows the whole model of the production process and the product quality in the method. The design method operates following three models:

[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 quality design algorithm (Fig. 4) is defined as the information processing procedure between models [1], [2] and [3].
Fig. 2 Production Failure Model
Fig. 3 Design Method of Production Quality

Z axis in Fig. 3 means 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 space of product quality state of ‘Pump ASSY’ is represented by a combination of quality states of sub-components, ‘Valve’ and ‘Pump’. The production process can be so complex that the hierarchical representation is introduced to enable a multistage decomposition approach of the quality design of the production process.

5.2. Design Flow Chart

Detailed flow-chart of information processing procedures in the design method for the product quality in the production process is shown in Fig. 4. It consists of following four steps, from STEP1 to STEP4:

STEP1 [a] Decomposing product structure

The Entity object defined on a component level is decomposed into some entity objects on the parts level. The product structure is defined by the design of interfaces. The example in Fig. 3 indicates that ‘Pump ASSY’ is decomposed into two components, ‘Valve’ and ‘Pump’.

STEP1 [b] Listing feasible operations

The designer lists the feasible operations that an organization or a factory has. The example in Fig. 3 indicates that there are three feasible operations, ‘fill oil’, ‘remove air’ and ‘close’. The product quality state changes corresponding to 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.

STEP1 [c] Listing possible failures

The designer lists the possible failures related to the applied operations. The example in Fig. 3 indicates that there two failures, ‘Air Containing’ by influx and ‘boil’ required that valve is opened.
**STEP2 Generating integrated model of product-process-quality**

By integration of three models (obtained by STEP1 [a] [b] [c]), an integrated model of product-process-quality is generated by design system.

**STEP3 Generating space of quality state**

The design system calculates the space of quality state of the production process from the integrated model of product-process-quality. The integrated model is defined based on the PN model. A reachable tree calculated from the PN model of the integrated model means the space of product quality state in a production process. The algorithm for generating reachable tree is shown in Fig. 5:

The reachable tree (Fig. 5 [2]) generated from PN model (Fig. 5 [1]) is represented as a bipartite graph that consists of markings and firing sequences. The marking means the placement of tokens. ‘Marking1’ describes the place ‘P1’ and ‘P2’ have a token. The firing sequence means the transitions that are enabled to fire from each marking. The condition of fire of each transition is described by arcs. Fig. 5 [3] shows the types of the arc that used in this research. Basically, transitions can fire when all start places of input arcs have token. PN of this research is a normal Petri-Net (Weight of arcs = 1, Capacity of places = 1).

**STEP4 Selecting final quality and scenario**

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

**STEP5 Output production process**

The selected scenario of quality state change includes the operations and its processes. The design system proposes the production process from the operations.
6. DESIGN EXAMPLE AND DISCUSSION

6.1. Prototype System

Based on the proposed model and algorithm, a prototype system for planning of production process has been developed. Main window of this system is shown in Fig. 6 [A]. The designer can define the production process on the Model View (Fig. 6 [1]) by adding, removing, evaluation and selection of the model of product, quality and operation sequence. The hierarchical information of the product and production process is managed from the conceptual design stage to the detailed design stage in the Model View. The designer can refer the related knowledge from the Knowledge View (Fig. 6 [2]). The production knowledge is supplied from the Knowledge Registration System (Fig. 6 [B]). The production knowledge in the Knowledge Registration System is described by the model of production system proposed by this research. The Attribute View (Fig. 6 [3]) displays the 3D shape of the product and arrangement of product elements. The Design Process View (Fig. 6 [4]) manages the design process and helps the separation and roll-back of the design plans.

6.2. Design Example of Auto-Breaker

The effectiveness of proposed design method is confirmed by the design example of a production system of Contact ASSY, one of component of Auto-Breaker. Fig. 7 shows the structure, shape and arrangement of the Contact ASSY.

The behavior and function of the Contact ASSY is as follows:

The Contact ASSY is an important component of the Auto-Breaker, and its function is 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 production process of the Contact ASSY on the prototype system is shown in Fig. 7 – Fig. 11. Fig. 12 shows the best design result obtained by this design method.

**STEP1 [a] Decomposing Contact ASSY**

First step of design method is 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. 8 (1) – (3):

1. **Braze**
   The Contact Plate and the Contact can be connected by brazing operation.

2. **Caulk**
   The Arc Hone and the Contact Plate can be assembled by calking operation.

3. **Form press**
   The Contact Plate can be shaped by form press operation.

**STEP1 [c] Listing Possible Failures**

The designer lists three possible failures based on listed operations (Fig. 9 (4) – (6)):

1. **Curve by braze**
   The Contact Plate is curved by the heat of brazing.

2. **Misalign by form pressing**
   The mounting angle of the Arc-Hone is changed in wrong range due to the impact of form pressing of the Contact Plate.

3. **Remedy by form press**
   The curved state of the Contact Plate is remedied by plastic deformation of the form pressing operation.
Burr by cutting dust
Spread burr

Manufacturing Item: Front Fender
Operation: Forming Operation by press

Failure Mode
Spread Burr
Occurrence Condition: R<30
Physical Phenomena
brittle-crack branching
Causes
Sharp shape or small R
Cut dust
Impacts
Defective appearance
Measures
Spot Air, Design Change of
Shape Attribute

Register

Knowledge Registration Sheet

Forming Operation
Plate
Formed
Front Fender
Pressed burr

Press Machine
Operator

Forming Operation

Pressing Fender

Pressing Fender

Front Fender

Pressed burr

Attached

Burr

Fig. 6 Overview of Prototype System
Contact ASSY

Fig. 7 Decomposition of Product Structure (STEP1 [a])

(1) Brazing

Disconnected

Brazed

(2) Calk

Disconnected

Caulked

(3) Form press

Cut

Shape Formed

bend by form press

Symbol Definition of Symbols

Normal Arc

Test Arc

Directed Sync. Arc

Fig. 8 List feasible Operations (STEP1 [b])
STEP2 Calculating Integrated Model of Product-Process-Quality

The design system calculates the integrated model of product-process-quality by combination of the result of STEP1 [1] – [6]. The calculation result is shown in Fig. 10.

STEP3 Calculating Space of Quality State

The design system calculates the space of quality state by reachable tree analysis (Fig. 11). The top marking node of calculated tree means the start state of the production process. The bottom marking node of the calculated tree means the end state of the production process. The red markings mean the failure quality of product.

STEP4 Selecting Final Product Quality and Scenario

The designer selects the final quality (Fig. 10 [A]) and its scenario (Fig. 10 [B]). The end marking that has no failure quality of the product means that the final product is good / available. The scenario from top marking to the final good product means the good production scenario.

STEP5 Outputting Production Process without Product Failure State

The design system proposes a production process to the designer from selected production scenario. The production process recommended by the design system is shown in Fig. 12 (a). The production process shown in Fig. 12 (a) is as follows:

The Contact ASSY is manufactured by brazing the Contact Plate and Contact (Fig. 12 [2]), form pressing (Fig. 12 [3]) and caulking with the Arc Hone (Fig. 12 [4]).

Fig. 9 Listing of Possible Failures (STEP1 [c])
6.3. Discussion

The production process shown in Fig. 12 (a) means the production process proposed by the design system that does not include failure quality state of final product. Without this design method, the designer has to select only one good production scenario from 6 candidates by try and error. Hence, the design method of this research surely can assist the designer to design the quality of the production process.

A possible design result without the design method of this research is shown in Fig. 12 (b). The production process shown in Fig. 12 (b) means following production scenario:

The Contact ASSY is manufactured by form pressing of the Contact Plate (Fig. 12 (2)), brazing with the...
Contact (Fig. 12 [3]) and caulking with the Arc Hone (Fig. 12 [4]).

The difference between the production process (a) and (b) is only the order of two operations, ‘brazing’ (Fig. 12 [A]) and ‘form press’ (Fig. 12 [B]). One of them is the production process that produce failure quality, and the other one is good quality. From this difference, the designer can know why the brazing must be upstream operation than the form pressing operation. This knowledge is one of important production know-how and can be represented by the production process model in this research. Generally, an impact of the design change of the production process is very difficult to estimate and predict. Hence, the design method of this research can assist the designer to change the production process by listing all conceivable quality issues automatically.

**Space of Quality State**

![Diagram showing the space of quality state with good and bad production scenarios.](image)

**Fig. 11 Calculation and Selection of Space of Quality State (STEP3,4)**
7. CLOSING REMARKS

7.1. Conclusions

The computational representation model of the production process that represents its quality related issues is proposed. Based on the production process model, the design method of the production process that can achieve required product quality state is developed. This design method enables to plan the production process as one system considering both quality related good factors and bad factors. The effectiveness of this proposed method is confirmed by applying the actual design problem of the production process of one component of Auto-Circuit Breaker.

In these years, large number of product failures in production stage caused by the design change of the production process for the reason of cost-down has been reported. The representation method of production knowledge of sequence of operations or important quality state is highly desired. The proposed production process model and quality design method in this research will contribute to reduce the final product failures in production stage caused by the design change of the production process.
7.2. Future Works

Future studies are needed to investigate the following issues:

1) Integration with the existing PDM (Product Data Management) system and ERP (Enterprise Resource Management) system
2) Development of the global database based on the representation of the production knowledge
3) Integration with the product design system

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