Int J Adv Manuf Technol (2010) 51:1121–1138
DOI 10.1007/s00170-010-2679-2

ORIGINAL ARTICLE

Quality assurance model in mechanical assembly

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Received: 20 March 2009 / Accepted: 14 April 2010 / Published online: 6 May 2010

Abstract The uncertainty of mechanical assembly process usually brings great challenge to product quality control and assurance. The systematic approach should be employed in the research to find a comprehensive solution. The quality assurance model for assembly (QAMA), based on the analysis of the major problems in the mechanical assembly process and the factors that affect the quality of products, is established by means of three working models: the assembly process model (APM), the activity control model (ACM), and the quality data model (QDM). The APM formulates the assembly process starting with the analysis of process flow, logical scheme, and key factors. The ACM is built by defining the attributes of control activity, mapping relationship between the control activities and its objects in the multiview space and layers. The ACM presents the control flow with the logical relations among control activities as well as the control rules. Based on the two models mentioned above, the QDM supports the acquisition of quality data through data-collecting carriers along assembly process and defines the data structure to support the system model. All of the three models are grouped into a framework which integrates the technical approaches and solutions for quality assurance in mechanical assembly. Based on modeling studies, a computer-integrated and internet-based system called quality assurance system in mechanical assembly (QAS/MA) has been developed. And the development of QAS/MA proves that APM, ACM, QDM, and QAMA are practical and feasible.

Keywords Mechanical assembly · Quality assurance · Assembly process model (APM) · Activity control model (ACM) · Quality data model (QDM)

1 Introduction

According to statistics [1], the mechanical assembly takes up over 60% of total assembly work of products. It means that the quality of final products highly depends on the quality of assembly operations and processes [2]. However, the mistakes and errors in assembly processes are a high source of defects and erode margins of products. So some valuable theoretical models and technological measures have been brought forward based on the researches in this area recently. Hinckley [3] put forward the concept of assembly complexity factor and quality control performance in electronic equipment assembly. Brent [4] proposed a multiphase approach to managing mixed-model assembly errors in low- to mid-volume assembly environments. Kmenta [2] described “assembly FMEA,” which is a novel technique specifically developed to identify manual assembly errors. Mantripragada [5] presented algorithms to propagate and control variation in mechanical assembly of automobile assembly by the state transition model approach. Siddhartan [6] combined lean manufacturing with six-sigma in aircraft assembly to reduce the nonconformance rate and rework time. Kayani [7] presented a measurement-assisted assembly method for quality assurance in aircraft assembly. In addition, some researches were focused on the automation, lean manufacturing, and just in time (JIT) along with other technology and error-proofing devices.

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However, those of quality control approaches and methods were trying to solve some specific problems and improve some operations in assembly rather than a systematic solution. For meeting more and more demands in flexibility, accuracy, high quality, low cost, and process optimality in mechanical assembly process, a systematic and process-oriented methodology is studied. The operation behaviors, process flow, activity models, and quality data would be studied in detail to improve the operations, and to optimize process, to assure the quality of product and process. The essence of quality assurance of mechanical assembly is to get the process, operation activities, and quality data under control. The approach of systematical modeling would provide theoretical foundation to the process formulation in system development for quality assurance in mechanical assembly. The research results could be obtained from industrial practice by means of modeling assembly process, operation activities, and data flow. Following systematic philosophy, the quality assurance model for assembly (QAMA) is put forward, which is composed of the assembly process model (APM), the activity control model (ACM), and the quality data model (QDM). Figure 1 shows an integrated quality assurance system in mechanical assembly (QAS/MA), which is developed following the QAMA systematic philosophy. QAS/MA is expected to facilitate the quality control in mechanical assembly.

APM divides the assembly process into process, subprocess, and activity and is modeled as "process–subprocess–activity." The APM is modeled under the supervision of the conception of QAMA, the assembly process flow under the control of ACM, and the quality data flow under the control of QDM.

ACM shows the control rules of the assembly activities. And it is the embodiment of APM as well as the design rule of the system control of QAS/MA.

QDM covering data-collecting mode and data structure is the derivative of the ACM. Meanwhile, it is the implementation of APM in the data domain and the foundation of the system data framework. The detailed discussion is as follows.

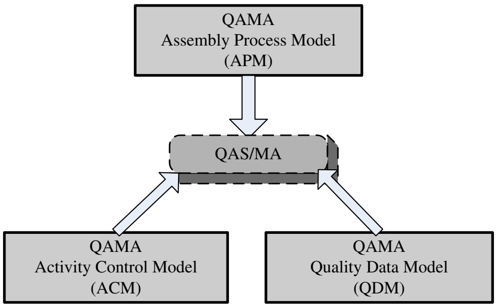


Fig. 1 Systematic solution based on models of QAS/MA, QAMA, APM, ACM, and QDM

2 Quality assurances

Mechanical product is constituted by a number of components (or parts), while each component is also constituted by a number of parts. The final product is assembled according to the assembly process plan [8]. In the process of mechanical assembly, the assembly relationship in orientation, position, geometrical dimensions, and matching between parts and components should be built first, and these relations should be in accordance with the design requirements. The objects of quality control in mechanical assembly can be considered to match the product design in the logical relationship between parts and components, and the precisions of geometric relations. It is shown as Fig. 2.

According to [3, 4], the unstable factors and their variation existing in the assembly process may lead to high risk of serious quality problems [9] and make the objects of assembly quality assurance out of specifications. The quality problems can be categorized as the logical relationship failure, precision failure, and nontechnical failure. Each kind of failure could be caused by the typical errors or factors listed as shown in Fig. 3. For instance, the logical relationship failure may be caused by process omission, omitting parts, wrong arrangement, incorrect installation, and so on. So the essence of quality assurance of mechanical assembly is to get the variation of unstable factors under control in the process.

In machining, the objects in quality control are geometrical dimension and tolerance, surface finish, and relative tolerances on individual part. In mechanical assembly, the quality control is oriented to confirm the correct relations between a group of parts or components and the precisions with multidimensions, shapes, or relative position tolerances. So the relative regulations and methods should be employed in mechanical assembly.

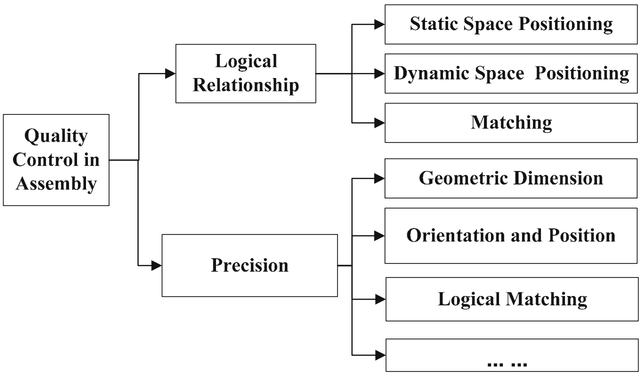


Fig. 2 Quality control in mechanical assembly

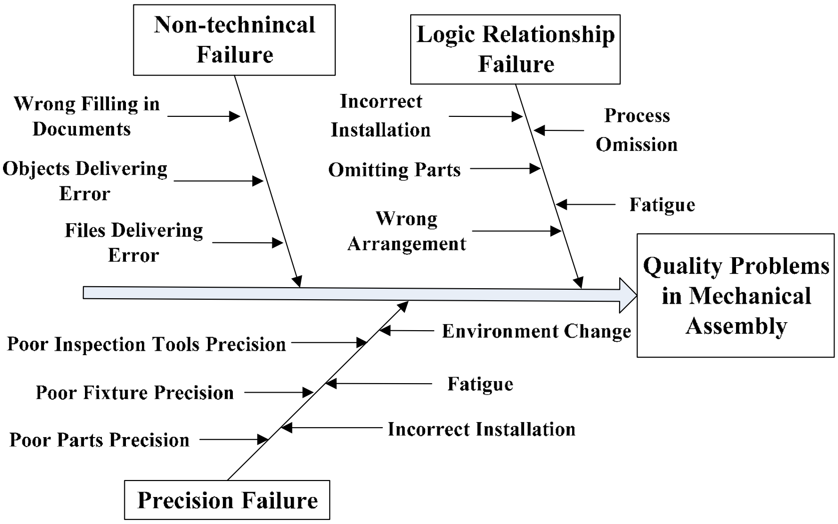


Fig. 3 Influential factors in mechanical assembly

3 Assembly process model

3.1 Process flow

The quality of the final product should not merely rely on the general inspections due to the complexity of unstable factors in mechanical assembly. The errors or variations caused by those factors could be accumulated gradually in the process and thus avoid serious troubles in the following stages. The process model will be quite helpful in the quality control in assembly (as shown in Fig. 4).

The hierarchy of the process flow is shown in a mathematical way as follows.

$$\begin{cases} P = \{S_1, S_2, \cdots, S_i\} \\ S_i = \{Sp_1, Sp_2, \cdots, Sp_j\} \\ Sp_j = \{GA_j, CA_j\} \\ GA_j = \{GA_{j1}, GA_{j2}, \cdots, GA_{jm}\} \\ CA_j = \{CA_{j1}, CA_{j2}, \cdots, CA_{jn}\} \end{cases} \tag{1}$$

Here, P denotes the whole process of mechanical assembly, S_i denotes the stages, Sp_i denotes the subprocesses, GA_i denotes the general activities in Sp_i, CA_i denotes the critical activities in Sp_i.

The main elements in the process flow is described as follows:

Stage (S_i*)* The process flow of mechanical assembly includes three stages $\{S_1,S_2,S_3\}$, i.e., the preassembly S_1, assembly S_2, and postassembly stage S_3. The assembly S_2 is the core stage in the process flow.

Subprocess (Sp_i*)* Several subprocesses are involved in each stage. For instance, the preassembly S_1 is composed of the subprocesses of preparation Sp_i and evaluation Sp_2.

Activity (GA_i *or* CA_i*)* The subprocess is constituted by some activities (GA_i or CA_i). The activities can be categorized as general (GA_i) or critical (CA_i), depending on the assembly process plan. And GA_i or CA_i is the fundamental and undivided cell in process, as well as the operation unit in quality control plan.

The measuring activities in the whole process are described as follows:

Grouping and checking All parts should be grouped and individually checked before they enter the assembly line. The failure in logical relationship such as omitting parts or precision failure such as nonconformance of some parts or components could partially be prevented by measuring. This activity involves grouping the parts or components and assuring that all of these parts or components are assembled together in a product and that nothing is left on the assembly desk when the work finished.

Reviewing and validating All instructions, operations, operators, tools, etc. should be reviewed by experts before the assembly operation starts. The object is to judge whether the conditions and preparations have met the assembly requirements or not. If some problems are found in reviewing, the assembly work should not be started until the problems are solved.

Data collection Quality data should be collected and managed effectively during assembly and postassembly. They are generated in each assembly or inspection operations and could be used to monitor the quality and reflect the problems in time in the assembly process.

Nonconformance control This is to ensure that all errors and failures could be corrected and solved effectively. The

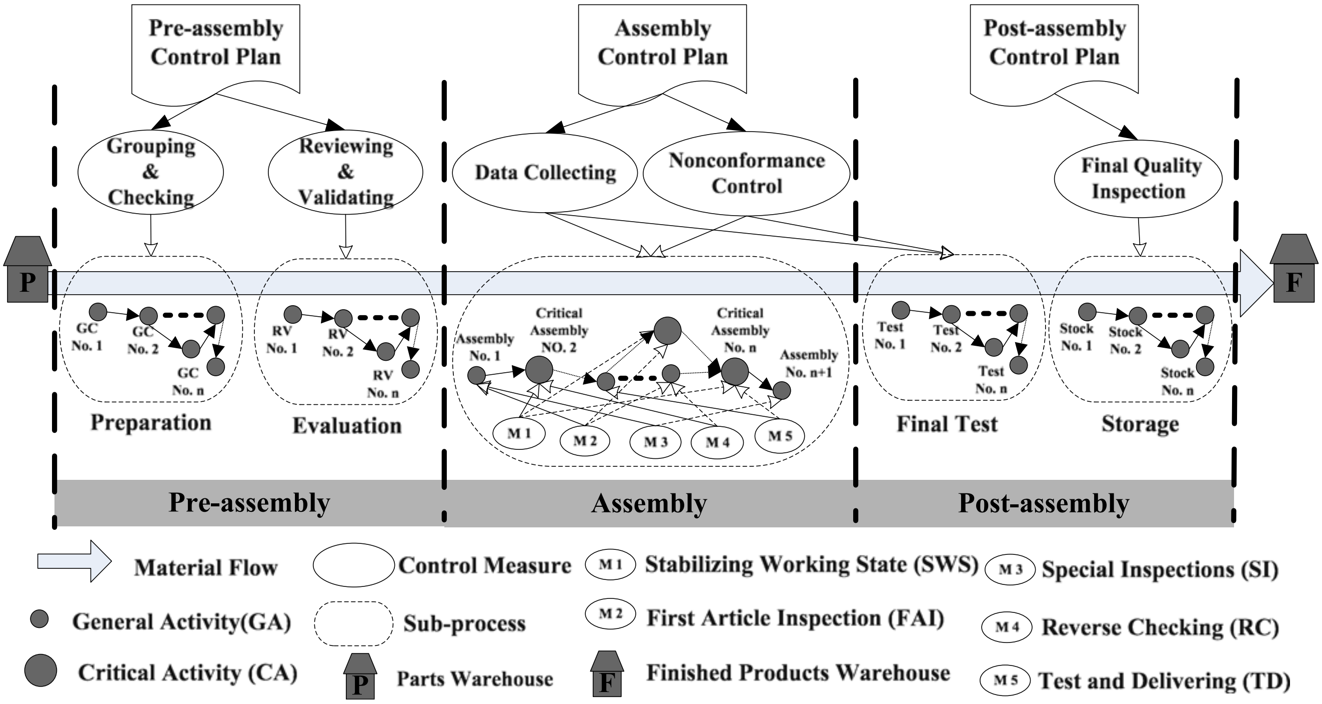


Fig. 4 Process flow chart in mechanical assembly

problems of nonconformance in the stages of assembly and postassembly such as logical relationship failure, precision failure, etc. should be analyzed by failure model effectiveness analysis (FMEA) or failure tree analysis (FTA) firstly. Then, the failure reason and grade of the nonconformance should be assessed, and the control measures, such as rework and scrap, should be taken.

Stabilizing working state The conditions of operators, equipment, and processes of critical activities should be kept in a proper state before the operations start to ensure that the key factors affecting the assembly quality are stable. Then, the problems of poor precision failure such as environment change, poor fixture precision, etc. could be prevented.

First article inspection To judge whether the process meets the requirement for assembly process plan or not, the self-inspection, interinspection, and inspection by inspector for the first piece of the product should be done. The assembly work could not go on unless the first piece of the product conforms to the specifications. So FAI can make SWS effectively.

Specialized inspections SI means that the inspection is done by a professional inspector. In the assembly process, every product should be inspected by inspectors to make sure that the technical targets are in accordance with the requirements of assembly process plan. Otherwise, the assembly work should be stopped for checking. All failures or problems could be found and prevented by this measure. So this measure is important for preventing the variation from being cumulated and transferred.

Reverse checking If there is something wrong in the progress of assembly process, the reverse work should be started according to the reverse operation instruction to locate the trouble points and to validate the product. This measure could detect the causes of the failures and help in making a decision for improvement.

Test and delivery This includes testing and delivering the final products. The analysis and confirmation of products and quality data should be checked before delivery. Then, this measure could catch the nontechnical failures in the assembly process.

Final quality inspection The final products should be entirely inspected before the storage subprocess. The documents should be signed by the related departments or individuals for the products certificated.

3.2 Process model

From the above discussions, the assembly process could be decompounded into stages. The stages could be decompounded into subprocesses. The subprocess could be decompounded into activities. This makes it convenient to analyze the product quality control tactics. The characteristics of every activity can be monitored, and then the whole process can be monitored [10, 11]. A process model of quality assurance in mechanical assembly is structured as shown in Fig. 5.

The process model can be expressed by formula 2:

$$P = \langle O, A, C, \mathrm{In}, \mathrm{Out}, \delta \rangle \tag{2}$$

In Eq. 2, O is a set of activities including the assembly relations, assembly precision, and nontechnical factor, respectively. And the set of O can be divided into three subsets, i.e., O_r, O_p, and O_n. It could be expressed as $O=\{O_r, O_p, O_n\}$.

A is the set of activities, including all of the business activities in assembly.

C is the conditions of process in running, which can be expressed as:

$$C = \{c \rightarrow p | c \in C, p \in P\} \tag{3}$$

In presents the inputs of each activity, being expressed as functions of

$$O \times A \rightarrow \{0,1\} | O \cap A = \phi, O \cup A \neq \phi,$$

$$\begin{aligned} &\forall o_i \in O, \quad \forall a_j \in A \\ &\mathrm{In}(o_i, a_j) = \begin{cases} 1 & \text{when } o_i \text{ is the input of } a_j \\ 0 & \text{other conditions} \end{cases} \end{aligned} \tag{4}$$

Out presents the outputs of each activity, being expressed as functions of

$$A \times O \rightarrow \{0,1\} | A \cap O = \phi, A \cup O \neq \phi,$$

$$\begin{aligned} &\forall o_p \in O, \quad \forall a_q \in A \\ &\mathrm{Out}(o_p, a_q) = \begin{cases} 1 & \text{when } o_p \text{ is the output of } a_q \\ 0 & \text{other conditions} \end{cases} \end{aligned} \tag{5}$$

δ defines the sequence of activities, which can constitute the affiliated input function f_{pre} and the affiliated output function f_{post}. They are expressed as follows, respectively:

$$\begin{aligned} &\forall a_i, a_j \in A \\ &f_{pre}(a_i, a_j) = \begin{cases} 1 & \text{when } a_i \text{ is before } a_j \\ 0 & \text{other conditions} \end{cases} \end{aligned} \tag{6}$$

$$\begin{aligned} &\forall a_p, a_q \in A \\ &f_{post}(a_p, a_q) = \begin{cases} 1 & \text{when } a_p \text{ is after } a_q \\ 0 & \text{other conditions} \end{cases} \end{aligned} \tag{7}$$

The key points of the process model is that, no matter how complex the product structure and the assembly technologies are, the assembly can be deployed into operation cells, and some key control points can be determined in the process plan. Some proper quality control measures can be taken for every control point to ensure every operation under control. For different batch size or production mode,

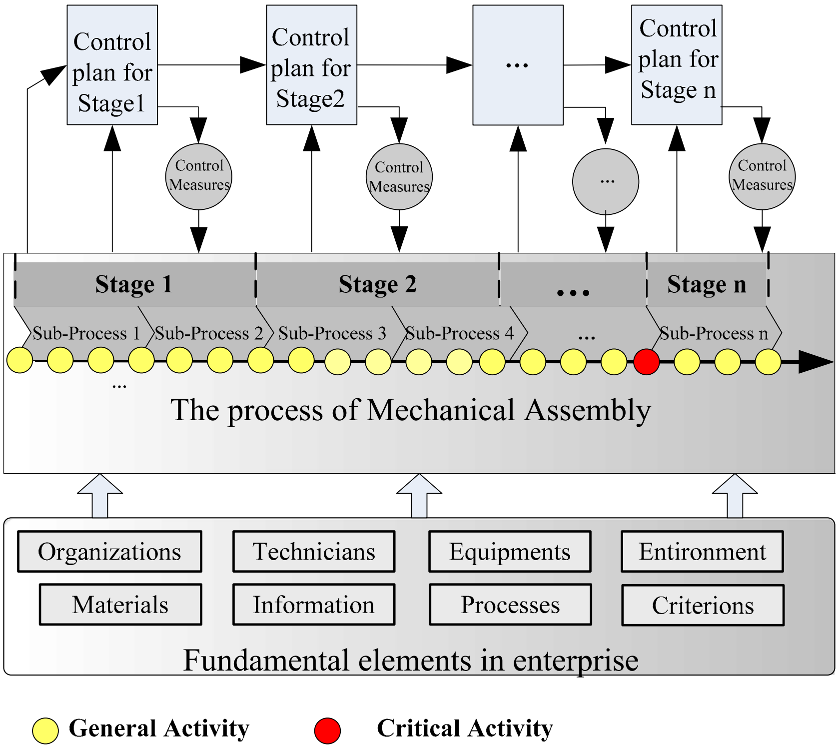


Fig. 5 APM for quality in mechanical assembly

corresponding flows of assembly quality control can be built, and these flows can work together and meet the need of the mixed batch size or multimode production perfectly.

4 Activity control model

The quality in the whole assembly process relies on the effective control constitution, policy, and actions, which depend on whether the APM is effective. The control policy stresses on the critical assembly activities since these activities are crucial for the assembly quality characteristics of products in the process.

4.1 Attributes of control activity

The attribute sets of control activities in quality control of mechanical assembly include object attribute, function attribute, process attribute, state attribute, resource attribute, and so on. Every attribute has some attribute values for expression of its meaning.

The object attribute has two attribute values, i.e., the control objects *CO* and the specification of the control activities *S*. The function attribute has two attribute values of control tactic *CT* and control plan *CP*, with the positive restriction R_1 from object attribute. The process attribute has two attribute values of the activity state *AS* and the restriction condition *RC* in the whole process restricted by the positive restriction R_2 of function attribute and the positive restriction R_3 of state attribute. The state attribute also has two attribute values of the control state *CS* and effect of the control activities *CE*. And the resource attribute has two attribute values as well, i.e., the necessary equipment *E* and operator ability *O* for the quality control activities. The restriction relationship among these attributes is very important for the characteristics of control activity as shown in Fig. 6.

Based on Fig. 6, the conditions of a finite set of $\mathrm{Attr} = \{A, R\}$ which could be the activity's attributes are:

Condition 1:

$$A = \{A_i | A_i =< i^n, V_i > \wedge i^n \in I^n \wedge V_i \subseteq V^n\}$$

Condition 2:

$$R = \left\{R_i | R_i =< i_p^n, i_q^n, x > \wedge i_p^n \in I^n \wedge i_q^n \in I^n \wedge x \in N\right\}$$

Where A stands for an activity attribute set; R stands for a restriction relationship set among the activity attributes, while the symbol I^n is a unique set representing the attribute objects. As mentioned above, the attribute sets of control activities include object attribute $\mathrm{Attr_o}(A_1)$, function attribute $\mathrm{Attr_f}(A_2)$, process attribute $\mathrm{Attr_p}(A_3)$, state attribute $\mathrm{Attr_s}(A_4)$, and resource attribute $\mathrm{Attr_r}(A_5)$. And $i^n \in I^n$ represents the identity code of the attribute object $n|_{i^n}$. The symbol V_i represents a finite attribute value set which expresses the characteristics of attribute object $n|_{i^n}$. The restriction relationship set R, the foundation for control flow, is defined as $\left\langle i_p^n, i_q^n, x \right\rangle$, representing the restriction relationship among activity attributes. The symbols i_p^n and i_q^n are the tags of attribute objects $n|_{i_p^n}$ and $n|_{i_q^n}$, respectively. The symbol x is called restriction value. If x=1, −1, or 0, the relationship between the attribute objects $n|_{i_p^n}$ and $n|_{i_q^n}$ can be positive, be negative, or have no restriction relationship, respectively.

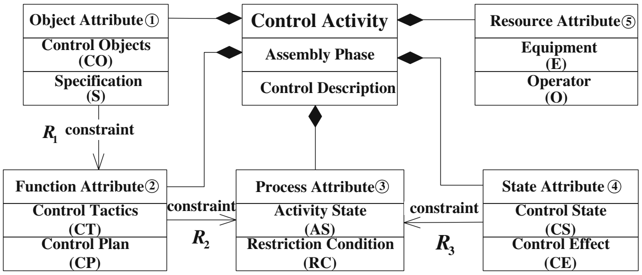


Fig. 6 Constitution of control attributes

Based on the definitions and some industrial experience, the practical expression of control activity attribute can be given as follows:

$$\mathrm{Attr_{CA}} = \{A[5], R[10]\} \tag{8}$$

$$\begin{cases} A[5] = \{A_1, A_2, A_3, A_4, A_5,\} \\ A_1 = \langle 1, \{CO, S\}\rangle \\ A_2 = \langle 2, \{CT, CP\}\rangle \\ A_3 = \langle 3, \{AS, RC\}\rangle \\ A_4 = \langle 4, \{CS, CE\}\rangle \\ A_5 = \langle 5, \{E, O\}\rangle \end{cases} \tag{9}$$

$$\begin{cases} R[10] = \{R_1, R_2, \cdots, R_{10},\} \\ R_1 = \langle 1, , 2, 1\rangle \\ R_2 = \langle 2, , 3, 1\rangle \\ R_3 = \langle 3, , 4, -1\rangle \\ R_4 = \langle 4, , 5, 0\rangle \\ \vdots \\ R_{10} = \langle 4, , 5, 0\rangle \end{cases} \tag{10}$$

4.2 Multiview control layer

Product quality in assembly is often unstable, and the quality assurance is a complex process including process state monitoring and resource deployment derived from different logical views. And these views can be obtained from different attributes of the control activities. The multiview control layer composed of different logical views is the basis of the tactic of data collecting, data structure design, and quality data analysis. And this control layer can help the monitor actions in different situations in an enterprise and acquire different quality data from a uniform quality assurance system.

The manager and the operator are the two major roles in a mechanical assembly enterprise. So the control layer can be divided into two sublayers, the management control layer and the execution control layer. The multiple views include the basic views, i.e., object view and tactic view; the intermediate view named state view; and the advanced views, i.e., resource view and process view. The different logical views are connected by the work flow, material flow, and data flow in the assembly process. The structure of the multiview control layer is shown in Fig. 7.

Managers' control layer Managers usually pay more attention to the conditions of work, resources, and product state. So the management control layer usually includes the state, resource, and process view. According to these three views, the managers can monitor the state of product quality, the resources, and the progress of assembly work flow and then make adjustment and changes in time.

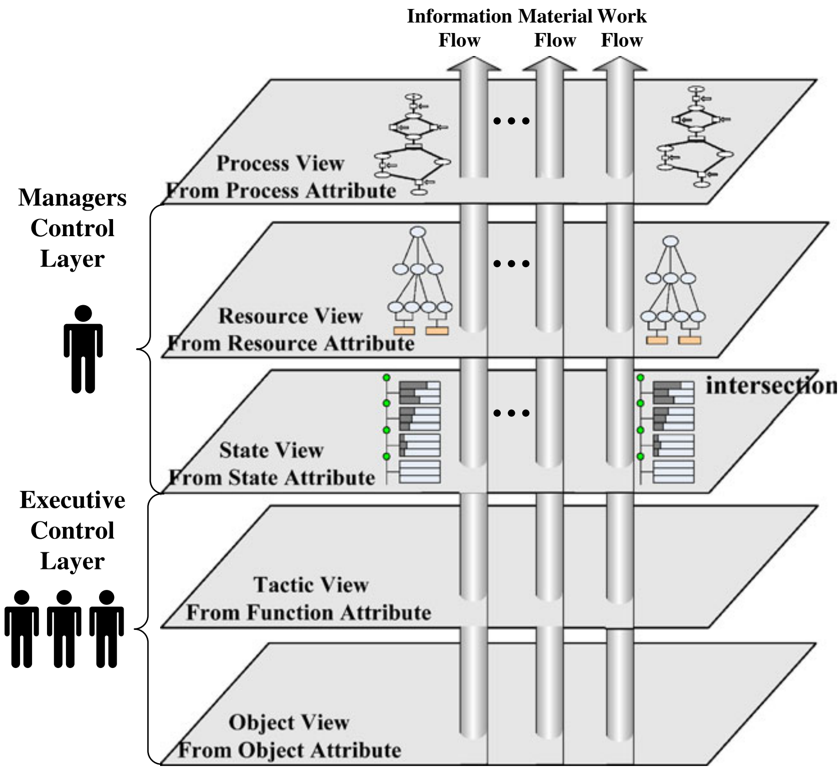
Executive control layer "What to do" and "how to do" are important for operators. The executive control layer usually focuses on the object, tactic, and state view. According to the object view, the operators can know how many jobs they should do and how they could control them by the tactic view. And the operators can also monitor the state of product quality and make adjustment for control activities in time from the state view.

Object view and tactic view The object view from object attribute provides an object set for the operators. The tactic view from function attribute provides a tactic set for the corresponding objects. These two views constitute the primary control layer and provide the basis of the advanced views. The operators can obtain some basic control information from these two views and then control the product quality.

State view The fluctuation state of quality characteristics obtained from state attribute and execution results of control activities is recorded, monitored, verified, and evaluated. The qualitative and quantitative results of control activities are compared with the corresponding expected results. According to the executive effect of control activities, the current and later control activities can be adjusted to make the output effect meet the specification. With dynamic feedback and monitoring in control process, the assembly quality is assured consistently.

Resource view The resources, such as equipment, gauges, and so on, are allocated to the activities. The resource view

Fig. 7 Multiview control layer



from resource attribute describes the resources and their dynamic loading in the process of mechanical assembly. Thus, the efficiency of all kinds of resources can be supervised.

Process view The process view can be acquired from process attributes. The quality control plan establishes the activities on each quality control point and quality control measures which are presented in terms of process documents and operation guide. Accordingly, the quality control points are the key links to assure the quality characteristics and can be inspected in the process. On the control points in the trial production phase, the process are reviewed and evaluated before trial production. On the control points in the formal production phase, the special process, documentation, equipments, and so on would be identified and traced, validated, monitored, and measured.

4.3 Mapping between activities and objects

In mapping between control activities and objects, one object may be controlled by several control activities simultaneously, and of course single control activity can affect several control objects simultaneously too [12]. Moreover, the influence could be negative correlation or positive correlation to a certain control object. Accordingly, the mapping relationship between control activities and control objects is classified into three categories as shown in Fig. 8.

"One-to-one" In terms of the existent experience and knowledge, a certain object can only be actualized by a certain control activity, and the correlation between them may be positive or negative, which can be expressed as follows:

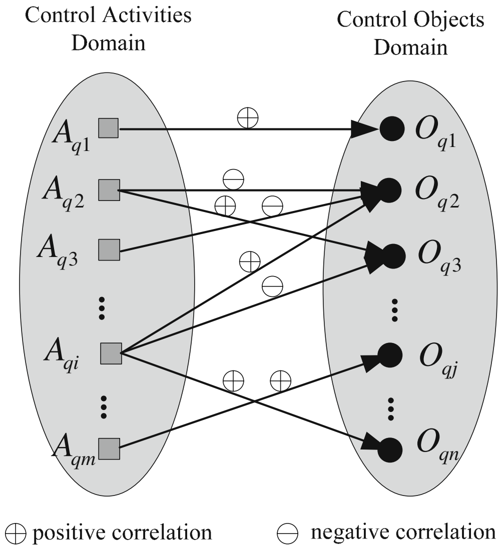


Fig. 8 Mapping between activities and objects

$$\begin{cases} A_{qi} \xrightarrow{1 \quad \oplus \quad 1} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{plus} \\ A_{qi} \xrightarrow{1 \quad \Theta \quad 1} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{minus} \end{cases} \tag{11}$$

For instance, the airproof state of the assembly product can only be controlled by the activity of airtight check. There is a positive correlation between them.

"One-to-many" A certain activity can control a series of control objects, and the correlation between them may also be positive or negative, which can be expressed as follows:

$$\begin{cases} A_{qi} \xrightarrow{1 \quad \oplus \quad n} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{plus} \\ A_{qi} \xrightarrow{1 \quad \Theta \quad n} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{minus} \end{cases} \tag{12}$$

For instance, the interactive inspection activity can control a series of objects such as the integration of parts, the value of inspection characteristic, and so on. The property of the control object demands positive or negative correlations.

"Many-to-many" A series of objects can only be actualized by a series of control activities, and the correlation between them might also be positive or negative, which can be expressed as follows:

$$\begin{cases} A_{qi} \xrightarrow{n \quad \oplus \quad n} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{plus} \\ A_{qi} \xrightarrow{n \quad \Theta \quad n} O_{qi} \quad i,j = 1,2,\cdots,n \quad \text{minus} \end{cases} \tag{13}$$

For instance, the error-proofing activity could affect a series of objects such as wrong arrangement, incorrect installation, and so on. Furthermore, the control object of incorrect installation cannot only be controlled by the error-proofing action but also by the interactive inspection , performance test, and so on. These activities and objects have "many-to-many" mapping relations.

4.4 Control model of quality activity [5]

The assembly process can be described as a multistage linear discrete-time activity chain to keep the state of the system close to its origin, as shown in Fig. 9.

$X(1), X(2), \cdots, X(n)$ denotes the input of quality characteristics matrix of each activity obtained from the corresponding state attributes of control activities.

$V(1), V(2), \cdots, V(n)$ denote the variation matrix contributed by each activity.

$U(1), U(2), \cdots, U(n)$denote the control vector of each activity obtained from the corresponding function attributes of control activities. The number of the elements may be one or more in accordance with the mapping relations between control activities and control objects.

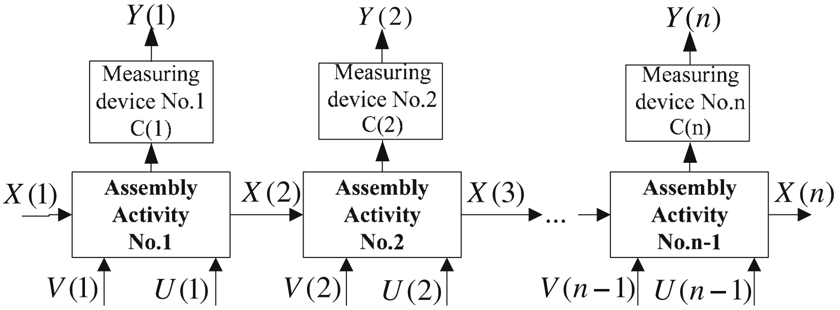


Fig. 9 A multistage linear discrete-time activity chain

As shown in Fig. 9, the outputs of every assembly activity are the inputs of its next assembly activity except the last one. Thus, the influence of the former one should be considered when controlling the current assembly activity except the first one. Then, the results of the former control activity could be known from the state attribute of the former one before the current assembly activity starts.

The control model for individual activity based on the above discrete multistage linear discrete-time activity chain can be described as shown in Fig. 10.

According to Fig. 10, the control model is stated:

$$\begin{cases} X'(n) = A(n-1)X(n-1) + E(n)V(n) \\ X(n) = X'(n) + B(n)U(n) \\ Y(n) = C(n)X(n) \end{cases} \tag{14}$$

Here, $X(n-1)$ denotes the output of quality characteristics matrix of the activity $n-1$ which is also the input of quality characteristics matrix of the activity n. The value of $X(n-1)$ can be obtained from the state attribute of $n-1$ control activity.

$X'(n)$ denotes the sum of the input of quality characteristic matrix of the activity n and the variation matrix of quality characteristic matrix of the activity n.

$X(n)$ denotes the output of quality characteristic matrix of the activity n.

$Y(n)$ denotes the output of quality characteristic matrix of the activity n according to measurement. The value of $Y(n)$ should be fed back with the state and process attribute of the control activity n.

$V(n)$ denotes the variation matrix contributed by the activity n.

$U(n)$ denotes the control vector of the activity n. The value of $U(n)$ can be obtained from the function attribute of the control activity n.

$A(n-1)$ denotes the system matrix of the activity $n-1$.

$E(n)$ denotes the variation associating matrix of the activity n.

$B(n)$ denotes the control associating matrix of the activity n.

$C(n)$ denotes the observation matrix of the activity n.

The model describes the control process of assembly activity n. In formula 14, $A(n-1)X(n-1)$ is the variation of the activity $n-1$; $E(n)V(n)$ is the variation of the activity n; $B(n)U(n)$ is the measure of the control activities which reduces the variation of the output of quality characteristics. So the ACM is a two-stage process: in variation forming stage, $X(n-1)$ is converted to $X'(n)$, and in variation control stage, $X'(n)$ is converted to $X(n)$. The result of $Y(n)$ measured by some equipment is the feedback of the control vector $B(n)U(n)$. If $Y(n)$ cannot achieve the expected results, the control vector $B(n)U(n)$ should be adjusted. The objective of this model is to make the output of the quality characteristics of each assembly activity under monitoring and controlling and prevent the variation transfer to the later operations as soon as possible.

The core concept in the control model is to combine the attributes of control activity and the factors of control process. The object attribute offers the control object and some control specifications. The function attribute provides the control tactic for the control vector $U(n)$. The state attribute of the former activity gives the value of $X(n-1)$. Meanwhile, some results should be fed back to some attributes of the corresponding control activity. According to the combination, the control process can be watched by monitoring the attributes of the control activity, and then some control measures can be adjusted in time.

The model provides an operable control method for each assembly activity. It is the embodiment of the rules of quality control activity, as well as the basis of the process-driven QDM.

4.5 Control flow model

Generally speaking, a single control activity cannot control the multiple correlative assembly operations in the process. So the logical relations of control activities should be considered, and the united control activities should be carried out. The quality control activities usually include checking the conformity of quality characteristics against inspection specification, collecting and recording sampling data, monitoring the state of process characteristics, and so on. Control plan is composed of quality control activities in each assembly phase. The control essence is that different activities which have different effect on assembly quality

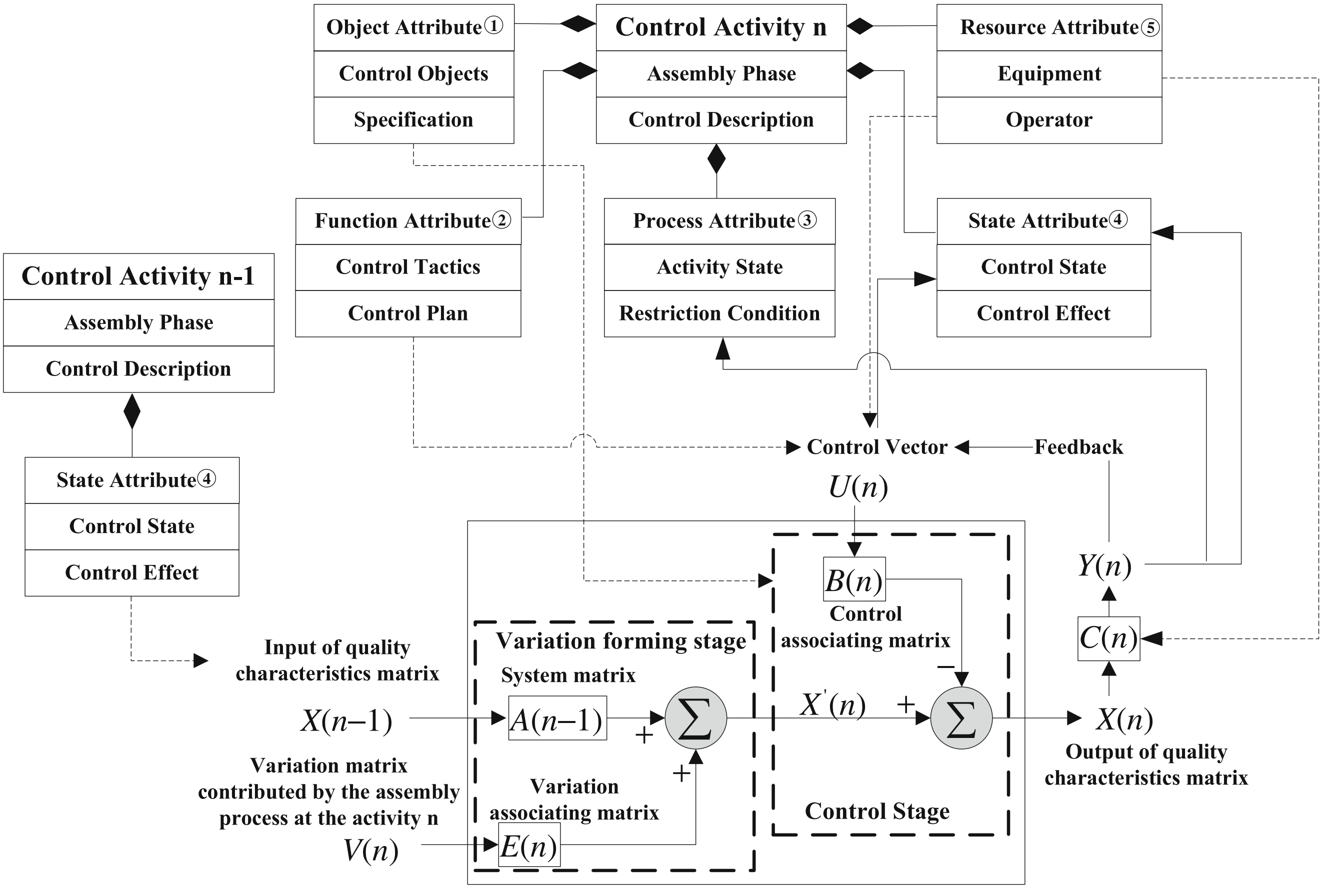


Fig. 10 Control model of assembly activity

output are controlled by different control tactics and measures. The sequences of the activities from the control flow model of the assembly process are shown in Fig. 11. The control flow represents the logical relations of control activities. The real lines denote the control flows of the assembly activities, and the dotted lines denote the flows of the quality documents.

Assembly activity control The left part of Fig. 11 shows that the flows of the control measures and the quality data in the assembly process are for different activities. For general activities (*GA*), the fast and simple control measures are enough to meet the requirements in production cycle and to save the cost of quality control. For critical assembly activities (*CA*), some strict control measures such as stabilizing working state (*SWS*) on operators, equipment, and methods should be taken, and the first article inspection (*FAI*) by operators and inspectors should be used. In situations such as changes of the assembly fixture or assembly process plan, the measure of *FAI* should be taken for the first product to validate the effect of the changes for the quality of the assembly products. Reverse checking (*RC*) should be taken in situations such as the omitting parts failure or wrong arrangement failure that may happen in some activities. The assembly process could keep running if the measure of *RC* works. Otherwise, if it turns unsuccessful, the abnormal control process has to be started. When the assembly process has been completed, the test and delivering (*TD*) needs to be done to validate the integration of products and quality documents.

Nonconformance control The right part of Fig. 11 shows the flow chart in nonconformance control and the quality data in the nonconformance disposal process with different severity. The disposal principle is that different severity decides different level of disposal flow. If the quality problems occur in SI or RC sections, the nonconformance control process has to be trigged. The problems, such as logical relationship failure, precision failure, and so on, found in SI or RC should be analyzed by FMEA or FTA to have severity evaluation first [2]. After the severity grade of the problem has been assessed, the corresponding reviewing level could be fixed. If the severity grade is low, the initial review would be taken and the production can be continued. If the severity grade is high, the final review has to be taken and production process has to stop. If more serious problems are found in the lower level, the review team needs to decide whether the higher-level review should be trigged or not. Furthermore, the control measures such as rework, repairing, and so on

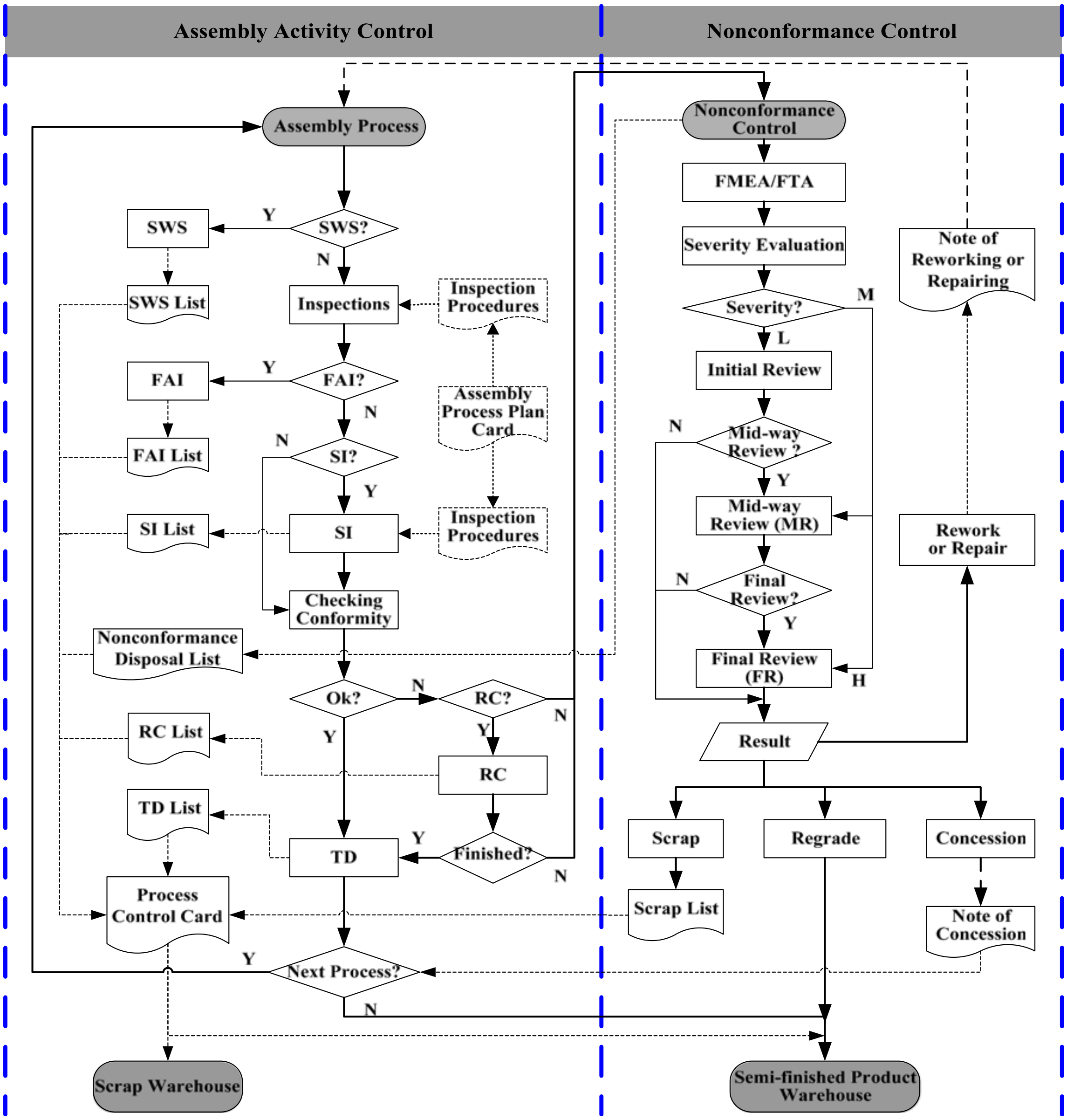


Fig. 11 Control flow model of assembly process

should be taken according to the conclusion after the reviewing work has been completed.

5 Quality data model

Quality data model should be designed based on APM and ACM discussed above. Quality control in process-driven strategies requires that quality data should be gradually collected in the implementation of the corresponding control measures to ensure the quality data maturity during the whole assembly process and its subprocesses. Collecting points are laid out along the assembly line. The quality data collected can be used to monitor the corresponding activities and to timely catch the problems in the process. The quality data collected should be well organized and matched with production batch and product. An assembly activity (the nondivided activity) is the unit of collected objects in the model.

5.1 Data-collecting mode

Collecting strategy and mode for quality data decides the organizing structure of quality data. So, it is necessary to study the collecting mode before the QDM is presented. The process-driven quality data-collecting mode by the idea of process-driven quality control is shown in Fig. 12.

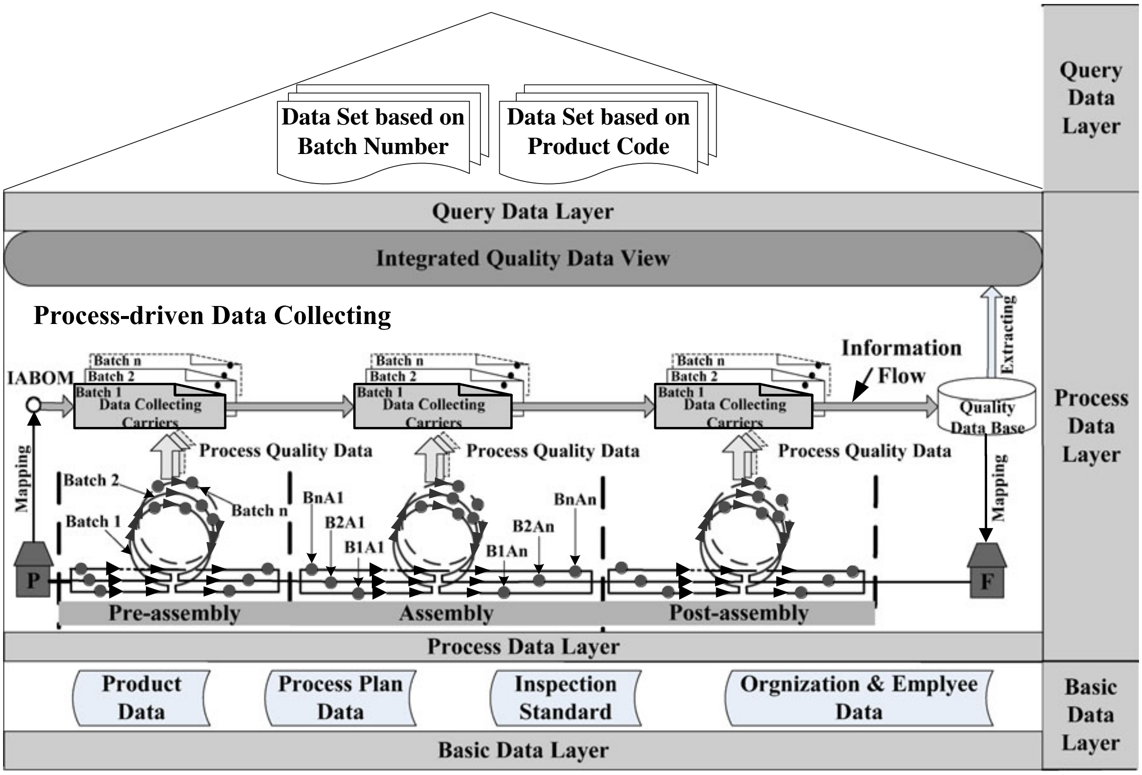


Fig. 12 Process-driven mode for quality data collection

The mode can be divided into three data layers: the basic data layer, process data layer, and query data layer (see Fig. 12).

Basic data layer It is the basis of the process data layer as well as the basis of the whole mode. This layer includes product data, process plan data, inspection standard, and so on. The data are the basis of the assembly process running and the advanced data to be organized.

Process data layer It is the implementation part of the process-driven quality data-collecting mode. In this layer, the flow of the collected quality data follows the flow of the APM (see Fig. 5) as a whole for quality assurance.

Before starting the preassembly stage, the mapping of product bills of materials (PBOM) to assembly bills of materials (ABOM) and ABOM to instance of ABOM (IABOM) should be set up. The procedure of transforming PBOM to IABOM is as follows:

$$\text{PBOM} \xrightarrow{C_A} \text{ABOM} \xrightarrow{ABN} \text{IABOM} \tag{15}$$

PBOM is transformed into ABOM with constrained conditions (C_A), and ABOM is instantiated with instantiation conditions (assembly batch number). IABOM is the real carrier of quality data collecting in the assembly process. The product code and batch number of the IABOM are a united clue of each data-collecting carrier. The data-collecting carrier is the set of quality data described as the following formal expression:

$$\begin{cases} D_{B-num}^{P-code} = \left\{ D_{q1}^{Pc|Bn}, D_{q2}^{Pc|Bn}, \cdots, D_{qn}^{Pc|Bn} \right\} \\ D_{q1}^{Pc|Bn} = \left\{ d_{q1}^{(1)}, d_{q2}^{(1)}, \cdots, d_{qi}^{(1)} \right\} \\ D_{q2}^{Pc|Bn} = \left\{ d_{q1}^{(2)}, d_{q2}^{(2)}, \cdots, d_{qj}^{(2)} \right\} \\ \vdots \\ D_{qn}^{Pc|Bn} = \left\{ d_{q1}^{(n)}, d_{q2}^{(n)}, \cdots, d_{qk}^{(n)} \right\} \end{cases} \tag{16}$$

In Eq. 16, the D_{B-num}^{P-code} denotes the set of quality data produced in assembly process with two tags named *B-num* (Batch Number) and *P-code* (Product Code) respectively, and which are the basis of the query data layer. The expression $D_{q1}^{Pc|Bn}, D_{q2}^{Pc|Bn}, \cdots, D_{qn}^{Pc|Bn}$ means numerous kinds of quality data in case of given *Pc* (the shortening of *P-code*) and given *Bn* (the shortening of *B-num*). The expression $D_{q1}^{Pc|Bn} = \left\{ d_{q1}^{(1)}, d_{q2}^{(1)}, \cdots, d_{qi}^{(1)} \right\}$ means the $q1th$ quality data $D_{q1}^{Pc|Bn}$ in case of given *Pc* and given *Bn* with i quality data-collecting items which are $d_{q1}^{(1)}, d_{q2}^{(1)}, \cdots, d_{qi}^{(1)}$, respectively.

The data-collecting carriers organized by product code and batch number could avoid the confusion of quality data caused by the change of batch size of production and meet the need of the mixed batch size or multimode production.

The quality data are collected by data-collecting carriers on the control points in the process. The collected quality data can show the basic characteristics of the problems in time. The data-collecting action is discrete because of the discrete assembly activity, but the data-collecting process is a time series process in time domain as a whole, which means that the amount of collected data has some increasing characteristics. Consequently, quality data are refined gradually with control activities executed along the time axis. The data-collecting process is considered as an integrated system, in which an inherent mapping relationship of quality data vs. time exists. This inherent mapping can be defined by:

$$D_{B-num}^{P-code} = D^{Pc|Bn}(t) = D_0^{Pc|Bn} + \int_{t_s}^{t_e} d^{Pc|Bn}(t)dt \qquad t \in [t_s, t_e] \tag{17}$$

In Eq. 17, the expression $D_{B-num}^{P-code} = D(t)$ means that the quality data are a function vs. temporal variable t. This characteristic is further described by the expression $D_0^{Pc|Bn} + \int_{t_s}^{t_e} d^{Pc|Bn}(t)dt$, and $D_0^{Pc|Bn}$ shows the initialized quality data before the beginning of the process, while $\int_{t_s}^{t_e} d^{Pc|Bn}(t)dt$ denotes the addition of quality data at the moment t. The symbol t_s denotes the time when the mechanical assembly process starts, and t_e denotes the time when the process ends. Because quality data are being collected gradually along the time axis, the function of quality data addition $d^{Pc|Bn}(t)$ is an increasing function, so $D_{B-num}^{P-code} = D^{Pc|Bn}(t)$ also has an increasing characteristic as shown in Fig. 13. That accords with the actual situation of the quality data-collecting process. The symbol d*D*/d*t* in Fig. 13 reflects the change rate at the moment *t*, and its physical significance is the increasing extent of collected data in some assembly operation at that moment. If the d*D*/d*t* is considerable, there will be more increased information in some assembly operation, and some problems of this operation may be found from the increased information.

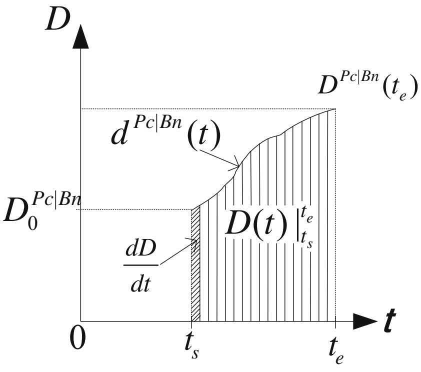


Fig. 13 Increasing characteristics of process-driven quality data collection in time domain

After the products are completed, the quality documents attached on the finished products by product code and batch number should also been done in time to be placed on file. The mapping procedure of quality data $D^{Pc=M|Bn=N}$ and the corresponding product $Prod^{Pc=M|Bn=N}$ with constrained conditions (*Pc-M* and *Bn=N*) is as follows:

$$D^{Pc=M|Bn=N} \xrightarrow{M,N} Prod^{Pc=M|Bn=N} \tag{18}$$

Meanwhile, the quality database has also been built and the integrated quality data view could be extracted for the query data layer. This form of data organization is the important basis of the signal tracing to batch number as well product code in the query data layer. The procedure of integrated data set extracting from quality data is as follows:

$$\left.\begin{array}{l} D_{Tal} \xrightarrow{Pc=M} DS^{Pc=M} \\ D_{Tal} \xrightarrow{Bn=N} DS^{Bn=N} \end{array}\right\} \xrightarrow{Pc=M, Bn=N} DS^{Pc=M|Bn=N} \tag{19}$$

In Eq. 19, the expression D_{Tal} means all sets of quality data stored on quality database. The expression $DS^{Pc=M}$ means data set with constrained condition (*Pc=M*), while $DS^{Bn=N}$ means data set with constrained condition (*Bn=N*). The expression $DS^{Pc=M|Bn=N}$ means data set with constrained condition (*Pc=M* and *Bn=N*).

Furthermore, the quality data tables could also be customized according to the practical requirements based on the data mode. The mode could be recognized as the basis of the statistics and query.

Query data layer This layer is the advanced quality data extracted for further analysis. Based on the integrated quality data view formed in the process data layer, the query data layer can supply three kinds of data sets, i.e., data set based on batch number $DS^{Pc=M}$, data set based on product code $DS^{Bn=N}$ and data set based on the both $DS^{Pc=M|Bn=N}$. Both of batch number and product code in

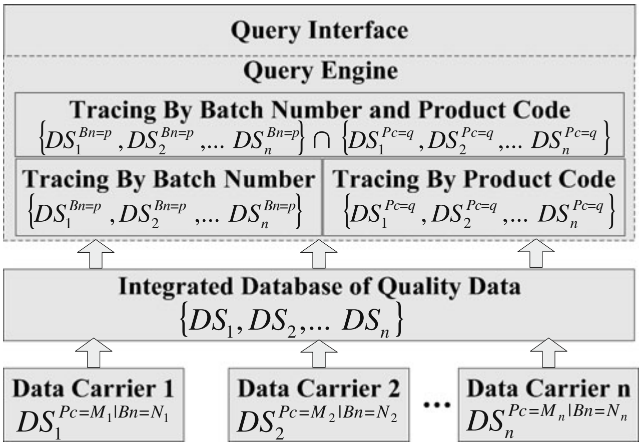


Fig. 14 Implementation of query data layer

the process-driven collecting mode is the foundation of the formed data sets. The implementation process of query data layer is shown in Fig. 14.

5.2 Quality data model in QAS/MA

QDM is the basis of the QAS/MA development, which provides the information of the layer of datasheet, the restriction relationship among them, and data structure. The process-driven QDM based on the above mode is shown in Fig. 15 [13–15].

Data-collecting carriers Data-collecting carriers are comprised of instantiation objects of PBOM, which is then transformed into quality data carriers with organization parameters appended for quality management.

Business process According to the APM, quality assurance is of process-dependent characteristics, and then quality data carriers can also be process dependent to organize quality data. Assembly business process includes premanagement, assembly process control, and postvalidating. Of course, these subprocesses mentioned above should be divided into more detailed subprocesses or activities gradually. All the quality data produced in this layer are integrated via quality data carriers on IABOM.

Control activity APM follows the "process–subprocess–activity" model. The partition of the business process can mainly guide the classification and organization of quality data. And quality data come from control activities by certain quality departments and employees. Control activities are planned by quality engineers based on product features, enterprise regulations, manuals, standards, and specifications to guide quality control in the assembly process. Business process and control objects can be bridged by control activities.

Control object Control objects contain abstract sets of control activities, which can be classified as input objects, output objects, resource objects, etc. Input objects include entities like assembly planning and inspection planning. Output objects include entities like test report, quality data, and process control card. And resource objects include entities like equipment, employee, and so on.

Quality physical data Quality physical data are mapped by control object in physical space. The format of quality physical data should meet the requirements of the special characteristics of quality data. Their formats are in accordance with database, office, XML, and so on.

A process-driven QDM is given to ensure the feasibility in system modeling. The collected and organized quality data based on this model is a firm basis for acquisition of

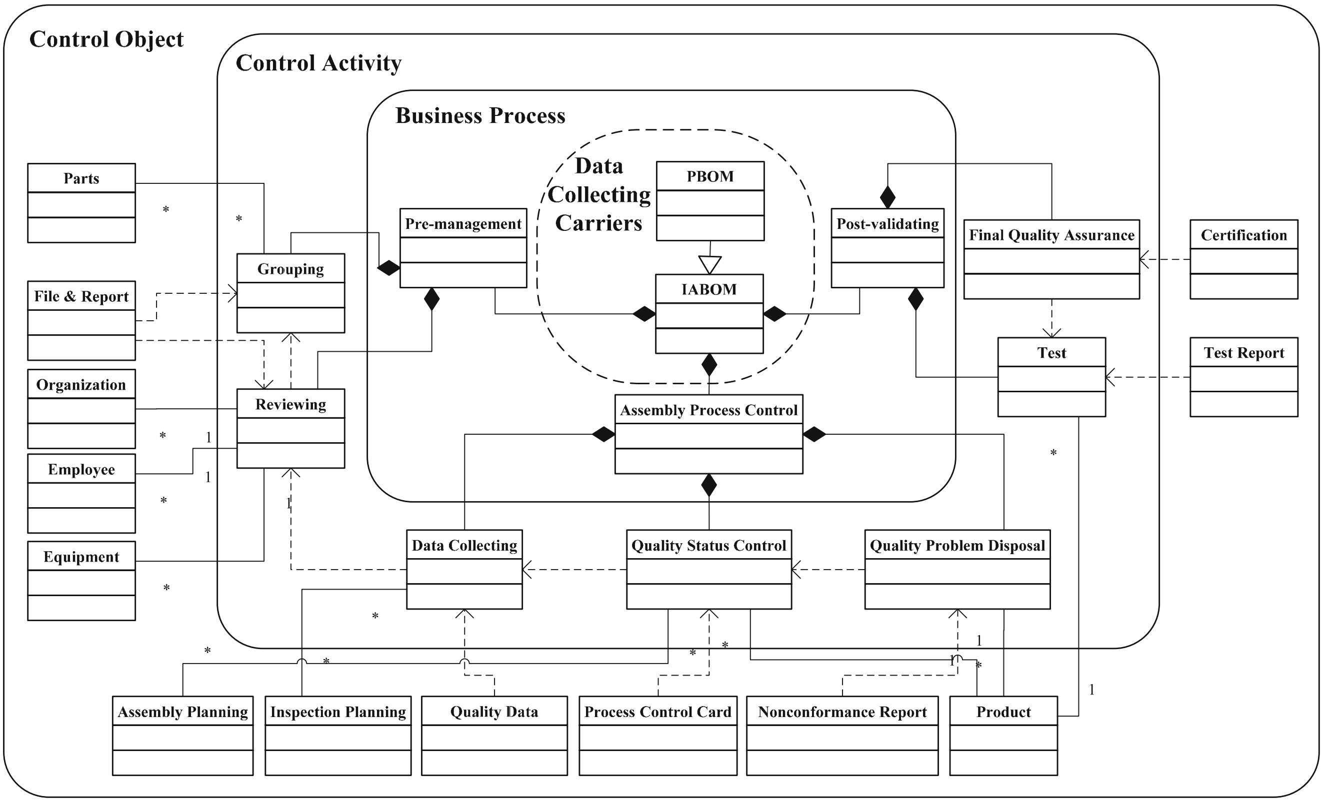
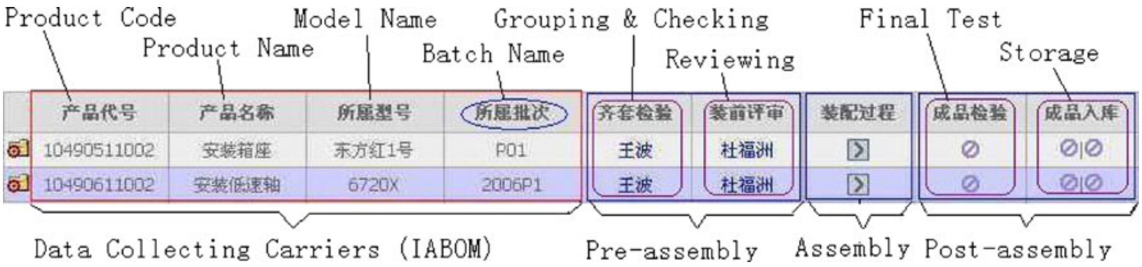


Fig. 15 Process-driven QDM



产品代号	产品名称	所属型号	所属批次	齐套检验	装前评审	装配过程	成品检验	成品入库
10490511002	安装箱座	东方红1号	P01	王波	杜福洲	>	⊘	⊘|⊘
10490611002	安装低速轴	6720X	2006P1	王波	杜福洲	>	⊘	⊘|⊘

Fig. 16 Data-collecting carrier of QAS/MA

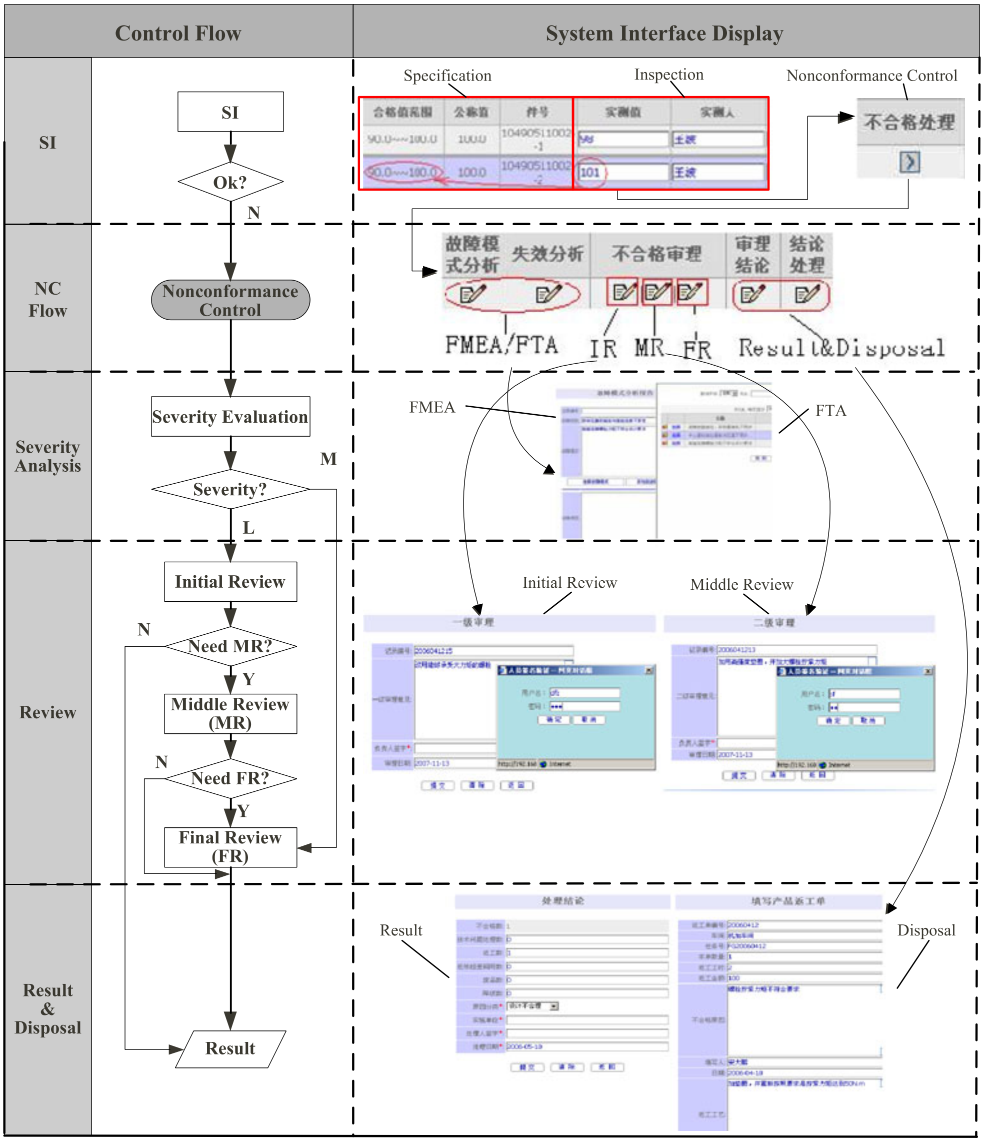
clear quality data flow. Successive quality data organized by the collecting mode and structured by the data model can efficiently support quality data query with multiple clues and aid control activities throughout assembly process, including quality improvement, quality diagnosis, and so on.

The above data-collecting mode and QDM provide a series of methods for the data structure design and development of QAS/MA. And this model can be used for many kinds of mechanical assembly products.

6 Case study

The models presented above are tried in production to deal with quality assurance in the assembly process of satellite

Fig. 17 Activity control flow in QAS/MA



合格值范围	公称值	件号	实测值	实测人
90.0~~100.0	100.0	10490511002-1	98	王波
90.0~~100.0	100.0	10490511002-2	101	王波

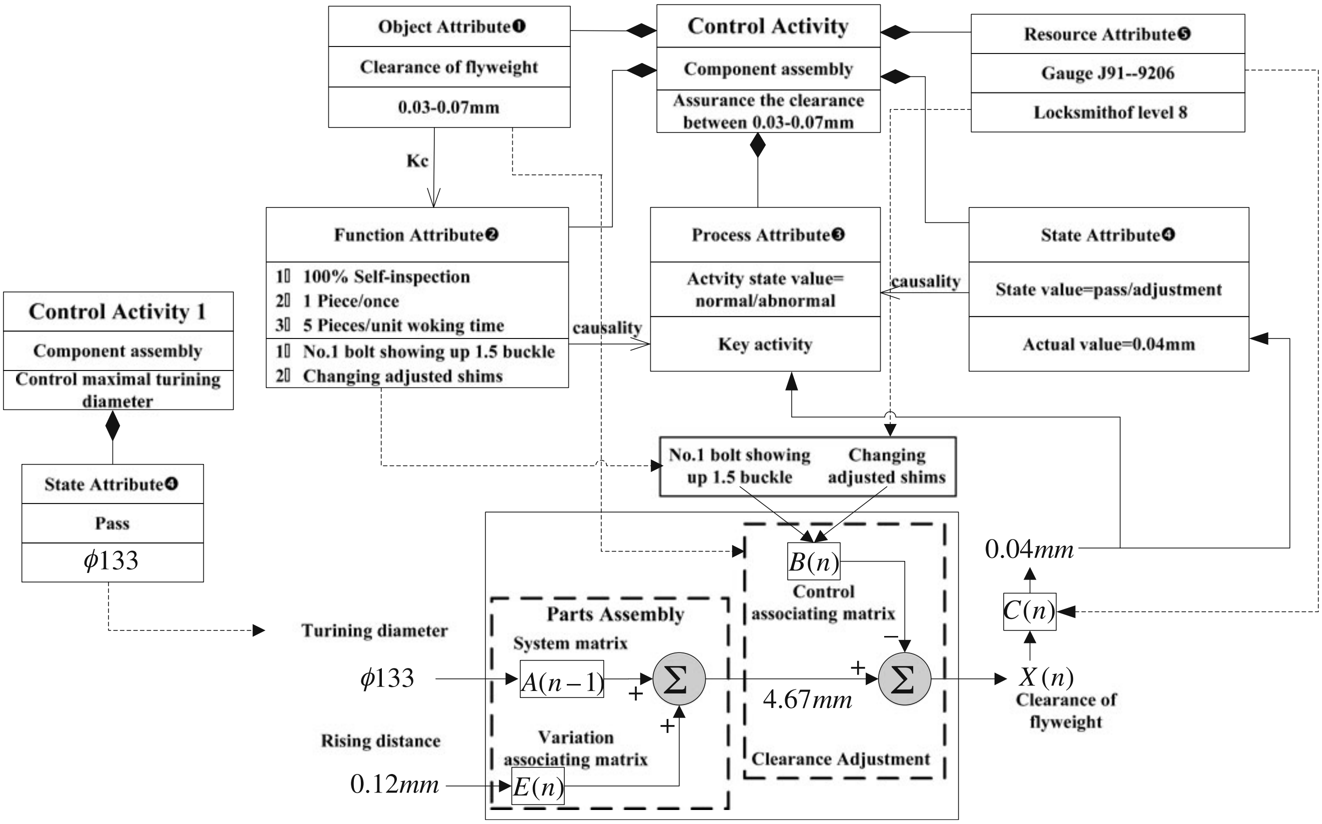
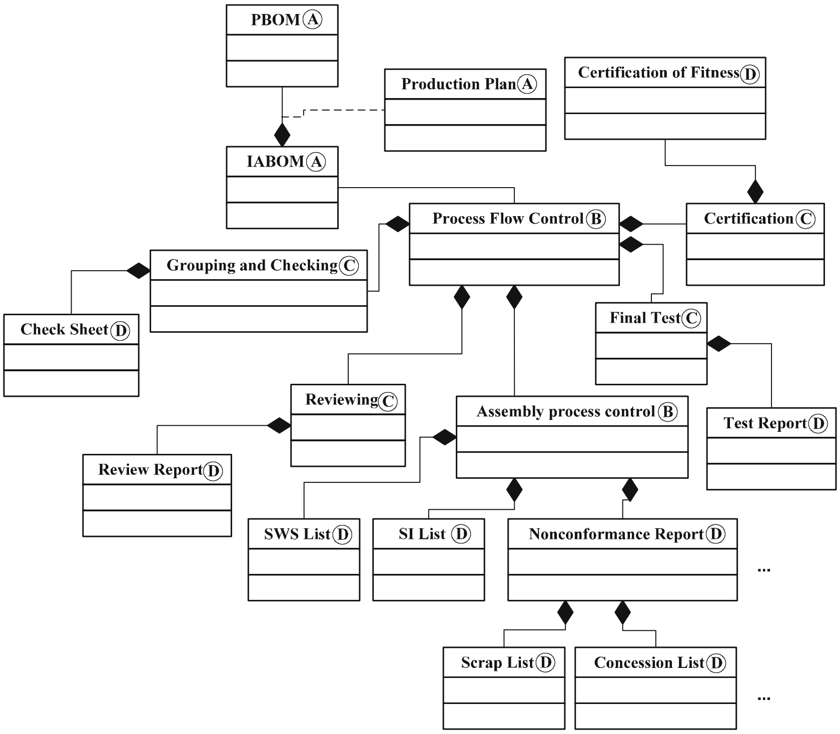


Fig. 18 Activity control model in QAS/MA

Fig. 19 Quality data model of QAS/MA



mounting box. There are only one to two pieces in a batch. For every batch of the product, a relevant data-collecting carrier (as shown in Fig. 16) is created by the procedure of transforming PBOM to IABOM, which includes all stages and assembly activities according to the process model. In the assembly process, the assembly activities are executed following the activity control flow (as shown in Fig. 17), and every activity is controlled by ACM (as shown in Fig. 18). The produced quality data in the assembly process are collected according to the process-driven data-collecting mode. Finally, all data are stored in the database designed according to the QDM (as shown in Fig. 19). Furthermore, QAS/MA is developed on the basis of QAMA.

The system provides fine-grained access to all quality data whenever or wherever it is recorded. According to the application of the system, the assembly quality of the products could be improved remarkably, the major assembly problems could be solved, the produced quality data in the assembly process could be traced clearly to ensure the traceability of the quality data, and the quality cost could be cut down. The examples are shown in the following three parts with some simulated data.

6.1 Process model in QAS/MA

The three stages including preassembly, assembly, and postassembly are linked by data-collecting carriers IAOM in QAS/MA. The subprocesses like grouping, checking, and reviewing are also linked by the corresponding stages. The subprocesses are divided into some control activities, and the control activities are linked by the corresponding subprocesses. It suits the principle "process–subprocess–activity."

6.2 Activity model in QAS/MA

The example focusing on the nonconformance control activities flow in the assembly process is shown in Fig. 17. This example represents the nonconformance control flows of QAS/MA as a whole, which follows the control rules that different activities which have different effects on assembly quality output are controlled by different control tactics and measures. The left part of Fig. 17 describes the control flows of the nonconformance control, and the right part of Fig. 17 describes the corresponding system interface.

Furthermore, an assembly activity of a product component named flyweight is given as an example for ACM to express more detailed situations. The content of attributes, control factors, and their interactive combination are shown in Fig. 18.

6.3 Quality data model in QAS/MA

This system provides fine-grained access to all the quality data whenever or wherever it is recorded. Figure 19 shows the instance of process-driven QDM including all kinds of classes of the quality data in the system. The properties and operations of the classes have been canceled to simplify the description.

Classes with names symbolized as "Ⓐ" belong to the definition of data-collecting carriers. Classes with symbol "Ⓑ" represent the business process of instantiation condition. Classes with symbol "Ⓒ" are the definition objects of control activities. Classes of control objects are identified by the symbol "Ⓓ."

7 Conclusions

The quality assurance, a critical issue in mechanical assembly, is studied and discussed. The QAMA constructed based on APM, ACM, QDM is put forward after analyzing the major problems and objects during the mechanical assembly process from industrial practice.

Product quality assurance generally belongs to management layer in an enterprise, but in practice the importance of quality assurance should be attached to execution layer. Therefore, the APM, ACM, and QDM are modeled from microcosmic level to realize better quality control in those two layers. These three models provide a systematic and valuable approach for the quality assurance of mechanical assembly products.

The combination of the process logical, control rules, and data structure given by those three models, respectively, may be a good idea for system design since the QAS/MA is developed and applied to the guidance of QAMA, and the application example of a small-batched production illustrated the utility of QAMA.

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