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Facility Model for Life-Cycle Maintenance System

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Abstract
For bringing out full capabilities of manufacturing facilities, various maintenance activities are necessary throughout the facility life cycle from design to the end of its life. We have been proposing the necessity of a support system for achieving efficient and consistent life cycle facility management based on a facility model. In this paper, the structure of the facility model is presented. The model can represent the hierarchical structure of facilities. It also provides flexible means to represent various technical information relevant to the facility management. The effectiveness of the model is shown by a deterioration evaluation system of the facility.

Keywords: computer models, maintenance, life cycle

1. Introduction

Recent requirements for agility in the manufacturing process involve not only rapid development of products but also of facilities. It is no longer feasible to take several months after the installation of facilities to get them running at full capability. It is indispensable, therefore, to evaluate the design of the facility at the early stage of the development process from the viewpoint of reliability and maintainability. At the same time, modern advanced automated facilities are expected to be utilized for longer periods under a variety of operating conditions than conventional ones, since they are flexible enough to adapt various types of products. This makes the role of maintenance activities during the operation phase much more important than in the past.

Where maintenance is concerned, most of information we need in the facility development phase and in the operation phase are common. In the development phase, it is essential to know the real operating situations and the problems experienced in the past. On the other hand, it is necessary to have exact design information for executing proper maintenance in the operation phase. This understanding has brought us a concept of life cycle maintenance in which all activities and information should be integrated and managed consistently throughout the facility life cycle. In practice, TPM (Total Productive Maintenance), for example, promotes integration of maintenance information so as to be usable in the facility development process in terms of MP (Maintenance Prevention) activities. However, there are few support systems which can integrate all information relevant to the facility life cycle and provide the platform for enabling analysis and evaluations of the facility in any phase of facility life cycle.

Therefore, we have been proposing a computer assisted life cycle maintenance system (CALMS) [9]. In this system, we have adopted a model based approach. The system maintains all information associated with the facility life cycle in terms of a facility model. It is created in the course of the facility development process and used for various analysis and evaluations carried out to improve the design and to prepare for production and operation. In the operation phase, maintenance planning and actions can be effectively performed based on the facility model. It also provides the base for recording operation and maintenance histories including improvement and remodeling.

In this paper, we first discuss the requirements for the facility model and then describe the proposed structure of the model. The effectiveness of the model from the maintenance point of view is shown by an example of deterioration evaluation of the facility. Results of the deterioration evaluation of a centrifugal pump by using an experimental system are presented.

2. Requirements for the Facility Model

The facility model for CALMS should support various functions and activities of the facility. Here we summarize the requirements of the facility model.

(1) Representation of basic information of the facility: Engineers consider facilities from various aspects during their life cycle in various applications such as geometric design, kinematic analysis, thermal analysis, assembly planning and maintenance planning. Besides, multiple aspects of the above often have to be taken into account at the same time. Therefore, the model should consistently support these applications by representing information that is commonly required.

(2) Representation of hierarchical structure of the facility: Facilities have hierarchical structures ranging from geometric elements of parts to whole systems. The model should be able to represent these hierarchical structures. However, their definitions are not definite and depend on the view point required by applications. Therefore, we need flexible representations for them. For example, connections between different levels of hierarchy such as between sub-assemblies and parts should be permitted. We also need to change the scope of the model. For example, the scope can vary from viewing the sub-assembly as a single part to viewing the structure inside the sub-assembly.

(3) Capabilities of representing various information: Various data and knowledge should be able to be attached to the model depending on the applications. Such information includes design intention and information related to maintenance activities such as the degree of deterioration. The model should also record changes in the state of facilities along with changes in time. Functions and behavior of the facility should be able to be derived from the information described in the model. For example, we need to predict consequences of modifications or failures of

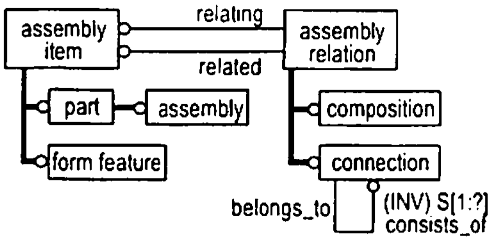

Figure 1 Structure of the facility model

the system. The expressive power of the model should also be expandable to conform to requirements for new applications.

3. Model Structure

Based on the above considerations, we choose an assembly structure of the facility as the base of the model structure. Assembly models have been studied associated with product modeling [4],[6],[8]. There are researches from the aspect of design and the aspect of analysis and planning. Concerning the design, top-down modeling approaches starting from functions is adopted [3],[7]. And concerning analysis and planning, the detailed physical structures are primary looked at [2]. We use object oriented data structure to represent the basic structure of the facility model in order to conform to both aspects.

3.1 Assembly items and assembly relations

The model consists of *assembly items* and *assembly relations* between the *items*, as shown in Figure 1. Notations in the figure are based on EXPRESS-G [5] where an attribute is shown as a thin line with its name on it and marked with a circle at the value end. A thick line shows a class hierarchical relation, with a circle attached to the sub-class side.

An *assembly item* represents a physical substance in the facility. *Assembly items* are classified into *part* and *form feature*. A *part* is an individual physical substance. We consider an assembly a kind of *part* that can be divided into multiple *parts*. This concept facilitates a function of changing the scope in the model.

Form feature is a group of geometric elements that carries some functions or behavior. Note that it does not necessarily belong to a single *part*. An assembly feature is a *form feature* that mates other *form feature* of a different *part* or sub-assembly to make an *assembly*, such as holes/pins and grooves/extrusions. To conform to the change of the scope, we provide the access function for the model to get *assembly item*'s *form features*. If the *item* is an *assembly*, *form features* of the *parts* that are mated with those outside the *assembly* are identified by the function.

Two types of *assembly relations* are identified to represent assembly structures. *Connection* is an *assembly relation* between two *items* that have no inclusion relations with each other, e.g., a *part* to a *part*, an assembly feature to an assembly feature. As hierarchical information, *connection* has a pointer to the *connections* in which it participates. For example, a *connection* between two parts may consist of several *connections* between two assembly features; they have a pointer to the parent *part-to-part connection*.

Composition is an *assembly relation* between an *assembly item* and another *assembly item* that consists of

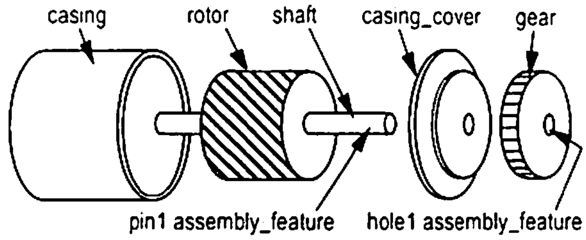

Figure 2 Motor with gear

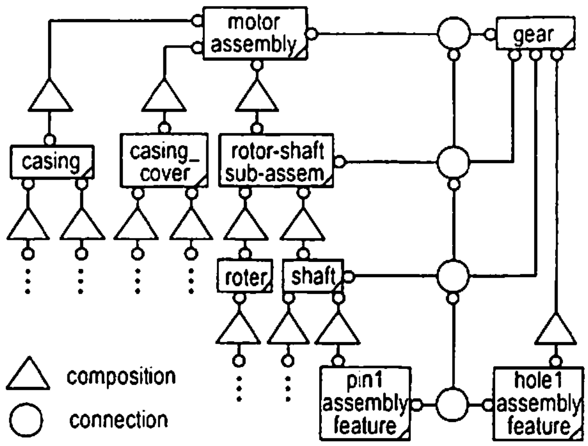

Figure 3 Model representation for Figure 2

it. *Composition* has a transformation that represents the position and orientation of the child *item* in the coordinate space of the parent *item*.

Note that both *assembly items* and *assembly relations* can have technical information in addition to configuration structures. *Connection*, for example, contains technical information that represents the state of the *connection*, such as the motion of a joint. This characteristic makes it possible to perform technical simulations and analysis based on the model.

Figure 3 is the model of a motor assembly with a gear shown in Figure 2. Note that Figure 3 is an instance-level diagram. Attribute names have been omitted. *Connections* and *compositions* are represented as circles and triangles. The entire model is not presented because of space limitations. The hierarchy of *assembly items* are arranged vertically. The motor *assembly* is related to the rotor-shaft sub-assembly by *composition*; and the rotor-shaft sub-assembly is also related to the rotor and the shaft in turn. In this example, you can see that any level of *assembly items* can be related using *connection* thanks to object oriented representation. The gear *part* is related by *connection* to the shaft *part*, to the rotor-shaft sub-assembly and to the motor *assembly*.

3.2 Group

In many applications, engineers want to relate information to a set of *assembly items* and/or *assembly relations*. We define *group* as that which includes any number of arbitrarily selected *assembly items* and *assembly relations*. It can be used as a catchall for various information. For example, a fastening function using a bolt is not realized by the bolt alone. The nut and the holes in the flanges also participate in the function as shown in Figure 4. We can define the *assembly items* and *assembly relations* involved in bolt fastening as the bolt-*group* as shown by the shaded section in Figure 5. Engineers may want to substitute the bolt fastening for rivet fastening. *Groups* can be used for this purpose. It is also possible to provide

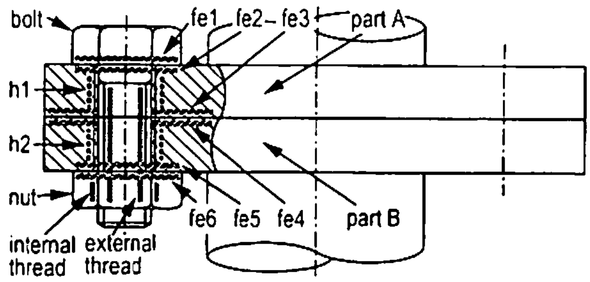

Figure 4 Bolt fastening flange coupling

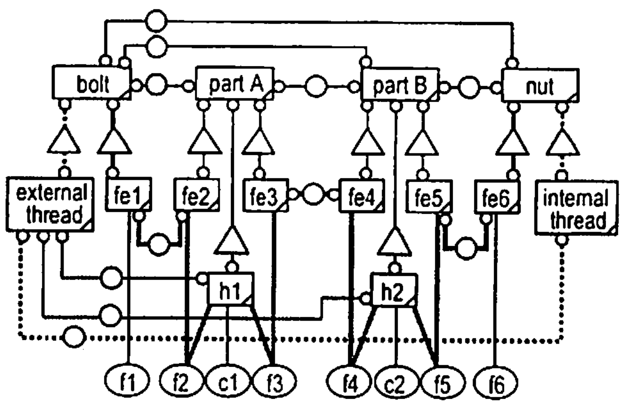

Figure 5 Model representation of bolt group of Figure 4

various fastener *groups* as a library. You may select any fastener *group* from the library and put it in an arbitrary place or substitute it for an existing fastener *group*. This is an example of the effectiveness of a *group*. In this way, we can add to *groups* various information or functions depending on applications.

4. Model Based Deterioration Evaluation

The role of life cycle maintenance is to maintain the facility in a proper condition to fulfill its required functions throughout the facility's life cycle. The reason we have to maintain the facility lies in the fact that the functions of the facility degrade mainly due to deterioration. Deterioration is a physical and/or chemical process occurring at various parts of the facility depending on operational and environmental stresses. To realize systematic maintenance, it is essential to predict potential deterioration. With this knowledge, proper maintenance strategies can be selected. Deterioration prediction is also required to design for reliability and maintainability. Therefore, we have developed a system for predicting the deterioration of facilities.

First, we describe the model for representing deterioration. Then, the deterioration evaluation system based on this model as well as the facility model is described.

4.1 Modeling of the deterioration processes

Mechanisms, such as fatigue, wear, and corrosion, which induce deterioration at certain areas of parts or assemblies are called deterioration mechanisms. The resultant deteriorated states are distinguished by deterioration modes. The deterioration mechanism is caused by a certain set of conditions which we call causal factors. They are classified into three categories: 1) Inherent characteristics such as geometry, material and surface finish. 2) Exerted stress such as mechanical stress, thermal effects and electro-magnetic effects. 3) Relative motion. 4) Operating environment such as in a gas, in a liquid, or in particles.

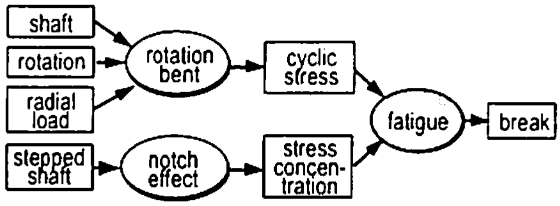

Figure 6 Example of the deterioration process

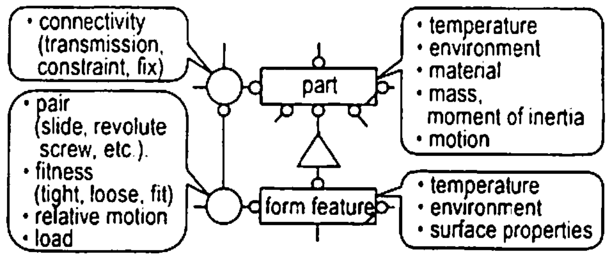

Figure 7 Attributes defined in assembly items and relations

Although there seems to be an infinite number of phenomena recognized as deterioration of the facility, we can identify a certain set of deterioration mechanisms which are basic and common for many types of facilities [1]. We call them fundamental deterioration mechanisms.

In many cases a chain of multiple fundamental deterioration mechanisms are related to failure. For example, fatigue failure could be initiated by a notch created by corrosion. In this way, one of the causal factors of a deterioration mechanism could be provided by other deterioration mechanisms. There is also a case where some of the causal factors are provided by mechanisms other than deterioration mechanisms, which we call causal factor formation mechanisms. An example of this type of mechanism can be seen when the rotation of a shaft with a radial load creates cyclic stresses which lead to fatigue at a stepped part of the shaft. The chain of deterioration mechanisms and causal factor formation mechanisms is termed a deterioration process. Figure 6, for example, schematically represents the deterioration process of fatigue for a spindle.

4.2 System for deterioration evaluation

The system carries out qualitative evaluations of deterioration based on the facility model and a deterioration data base. It generates potential deterioration processes which may occur at particular parts of the facility.

(1) Deterioration data base: The deterioration data base contains the fundamental deterioration mechanisms and the causal factor formation mechanisms. They are expressed in terms of a set of causal factors and the resultant deterioration modes or causal factors. This data base can be prepared independently from facilities.

(2) Facility model: The facility model represents the structure and properties of a facility to be evaluated. The properties are represented in terms of values of attributes defined in assembly items and relations. Figure 7 shows attributes currently defined in the model. The model has a mechanism to inherit the values of attributes from those of higher level items in the hierarchy, unless they are explicitly defined at their level.

(3) Inference of deterioration of form features [10]: This is conducted for every form feature of every part defined in

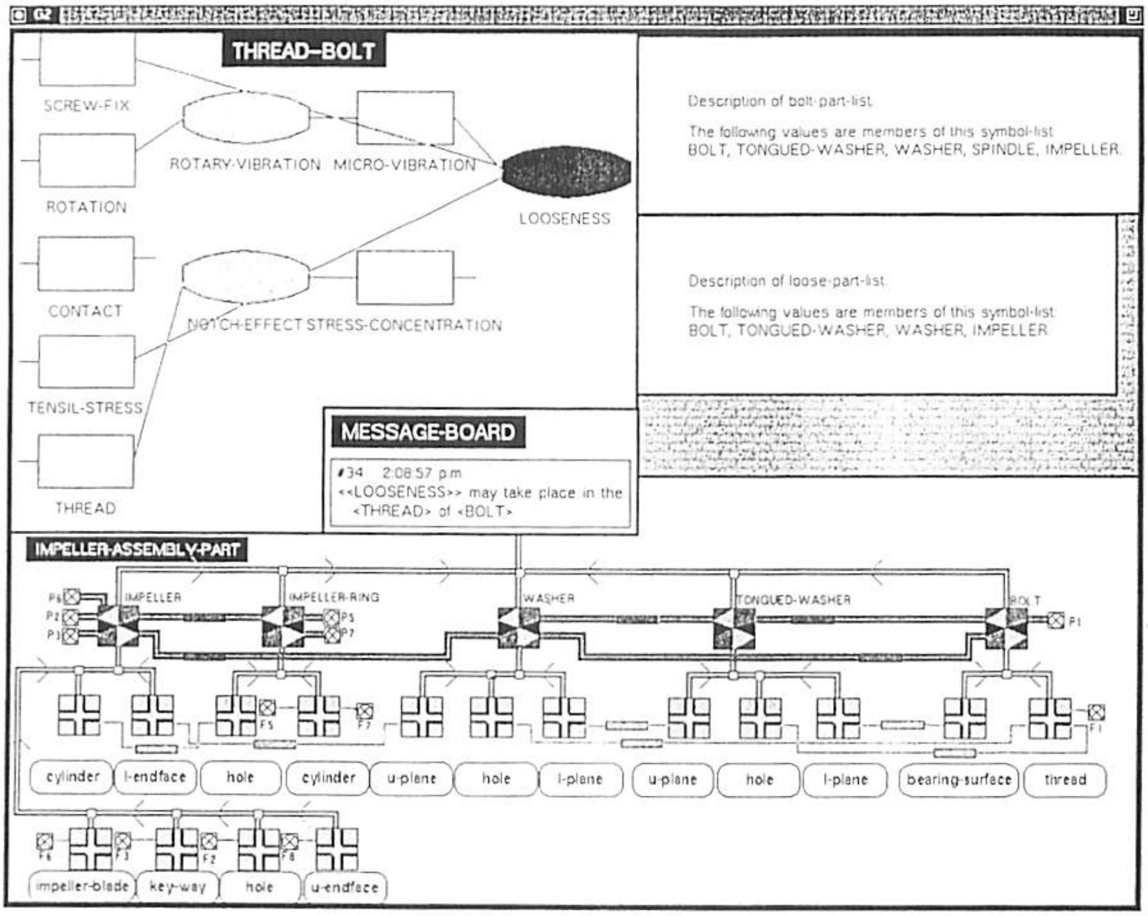

Figure 8 The system output of deterioration evaluation for the bolt which fixes the impeller to the spindle

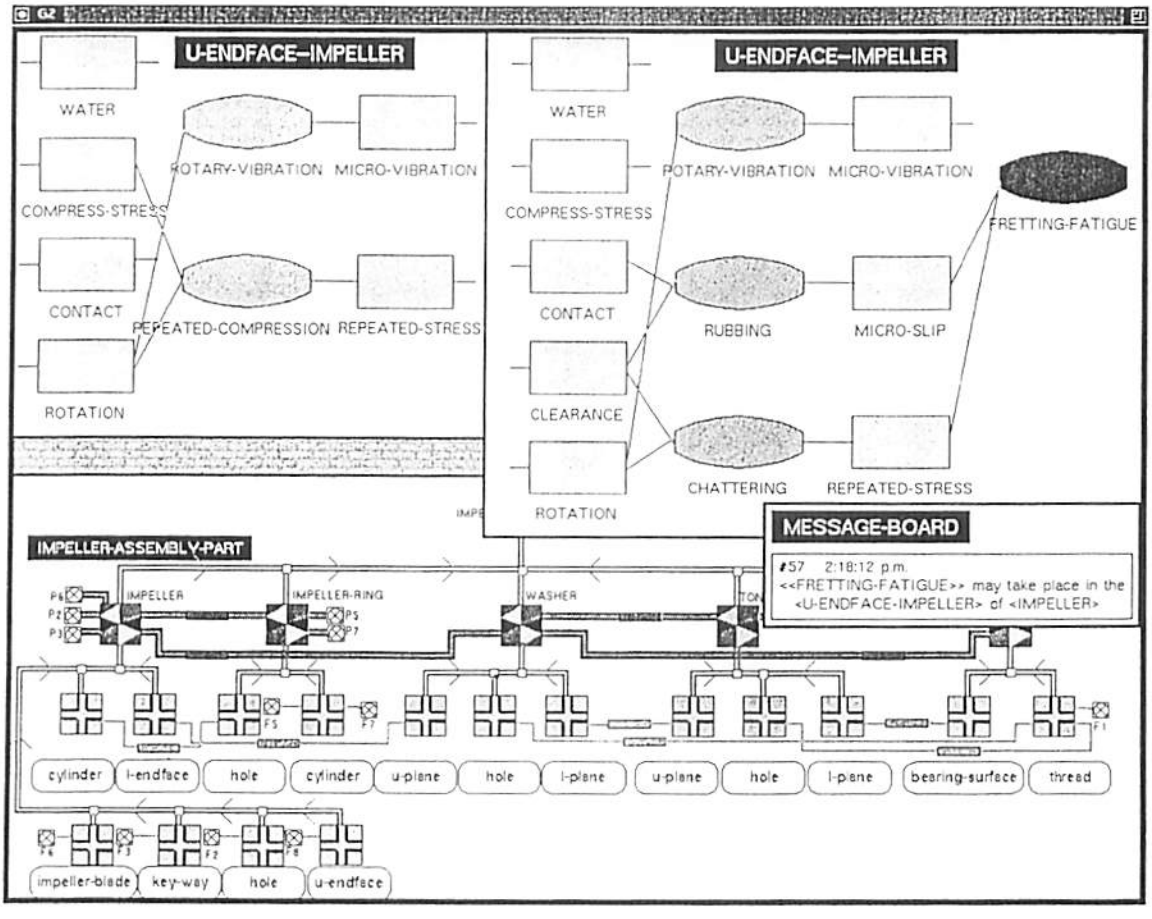

Figure 9 The effect of the loose bolt on the deterioration of other part

the facility model, since different form features have different causal factors even in the same parts. The causal factors associated with a particular form feature are identified from the facility model, that is, the attributes of the form feature itself, the related form feature connection and the part on which it is defined. The system searches mechanisms in the deterioration data base whose causal factors match with those identified in the model and generates potential deterioration processes which could occur at the form feature.

(4) Inference of range of effects of deterioration: In the above procedure, the effects of causal factors and deterioration modes are considered within the specified form feature. However, there are causal factors and deterioration modes which also have effects on other form features or parts. The following three cases have been identified: 1) Some types of deterioration, such as loose bolt fastenings, have ranges of influence involving multiple parts or part connections. 2) Effects of causal factors, such as vibration and heat conduction, propagate from one part to another. 3) Effects of deterioration change environmental causal factors of other form features or parts. For example, leakage of coolant due to a damaged seal makes a bearing wet. In the system, the first and the second cases are dealt with. Inference algorithms were developed for the first case. For the second case, the propagation rules for the corresponding causal factors were defined.

An example of the algorithms for the first case, that for inferring the extent of the effect of a loose bolt, is explained by using Figure 4 and Figure 5. The inference process consists of two steps: 1) inferring parts fastened by the bolt and 2) inferring the unstable parts among them. If the bolt group is defined in the facility model, it is not necessary to carry out the first step. In case it is not defined, the system searches for the mating part which is connected to the bolt with a thread. The search path is shown by a thick broken line which connects the bolt and nut in Figure 4. Then the system traces the mating assembly features of the flanges fastened by the bolt and nut starting from the bearing surface of the bolt to that of the nut. The tracing path is shown by the thick line which passes through the assembly features and their faces indicated by ovals in the figure. The parts which have assembly features involved in the traced path are identified as loose parts.

In the second step, the system checks whether any of these parts are fixed to a base part via connections other than those traced in the first step. If a part has such connections, the system identifies the part that is stable and excludes it from the loose part list.

5 Experimental System

The experimental system has been developed by using the object oriented expert shell G2. An interface with a solid modeling system has been established. The assembly items and relations of the facility model are defined as object classes. The deterioration mechanisms and causal factor formation mechanism are also described as objects. The inference is executed by production rules.

Taking a centrifugal pump as an example, the deterioration evaluation was performed. Twenty four major parts were examined by the experimental system. The model of the impeller assembly are shown at the bottom of Figure 8. The upper left part of the figure shows that the system identified the looseness of the bolt as the potential deterioration. The bolt fixes the impeller to the spindle. The result of inferring the extent of the effect of a loose bolt is shown at the upper right part of the figure. The bolt-part-list represents the inferred list of the parts fastened by the bolt. The loose-part-list, on the other hand, shows the list of unstable parts among them. It is noted that SPINDLE is not included in the loose-part-list, because it is supported by a bearing which is fixed to a casing. The effect of the loose bolt on the deterioration of other parts is demonstrated in Figure 9. It shows the results of the deterioration evaluation of the upper end face which is one of the assembly features of the impeller. The upper left part of the figure shows the result of the evaluation before the loose bolt has been identified. The system did not suggest any deterioration mode. However, when the loose bolt was identified, the clearance was added as one of the causal factors as shown at the upper right part of the figure. Then, the system identified fretting fatigue as the potential deterioration of this assembly feature.

6 Conclusion

In this paper, we have proposed a structure of the facility model for a computer assisted life cycle maintenance system. It provides a flexible representation scheme for technical information as well as for the physical structure of the facility. The effectiveness of the model was demonstrated by the model based deterioration evaluation system of the facility.

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