Holon based framework of quality problem processing in complex product development

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Abstract
To analyze and handle quality problem during product development and manufacture, a holonic quality problem closed loop (HQPCL) framework is proposed in this paper. Some holons which encapsulate the technology resources and management resources are built in the HQPCL. A series of holonic units such as quality problem locating holon, quality problem source-tracing holon, quality problem mitigation holon, quality problem closed loop holon and assist holons were built. A sequence diagram of the HQPCL was given by the UML (Unified Modeling Language) in this research. A function-behavior-resource model which describes the functions, behaviors and resources of the above holons is proposed. The KQML (Knowledge Query and Manipulation Language) is used for the communication of the quality holons. The self-similarity in HQPCL is analyzed for reducing the complexity to integrate new components and enables easy reconfiguration of the system. Finally, a case study is given to validate the framework.

Keywords : Quality improvement, Holon, KQML, Self-similarity

1 Introduction

To analyze and handle quality problem during product development and manufacture holds significant value to the quality improvement. For the complex products, such as aerospace vehicle, airplane, missile, railway vehicle and steamship etc, the mechanism of the quality problem is more complex because of the various customer requirements, sophisticated components, high-end technology and challenging management (LI Bohu, 2002). The quality control of complex products is an interdisciplinary, complex and long cycle process (Zhang Genbao, 2010). For a long time, how to analyze and deal with quality problem in complex product development and manufacture has become the common focus of both academia and industry. A lot of works have been done in the process of the quality problem handling and prevention. A comprehensive model was proposed for process selection by JERUSALEM MA, this model integrated quality, cost, and delivery time as well as offline and online quality control (JERUSALEM, 2016). The PDCA which is possible to use for the continuous quality improvement of products, processes and services in organizations is introduced by M. Sokovic (M. Sokovic, 2010). Six sigma is a measure of quality that strives for near elimination of defects using the application of statistical methods (Jiju Anton, 2004). The Poka-Yoke method is to eliminate or minimize human errors in manufacturing processes and management as a result of mental and physical human imperfections (M. Dudek-Burlikowska, 2009). The methods which mentioned above are focused on quality problem management with standard processing procedures; they are lack of the combining of the management resources and technology resources. Given this, the quality problem processing framework named “Quality Problem Closed Loop” has been introduced in this paper. The framework has arisen in China aerospace industry and attracted wide attention from academia (QJ3183-2003). Quality Problem Closed Loop (QPCL) was first put forward in 1990s and was defined as: “The quality problems arising in periods of design, production, experiment and service should be analyzed and corrected in both technology aspect and management aspects, and preventive measures should be taken to avoid the repetitions of potential problems with similar context (QJ3183-2003 China)”. QC-s-linkage model was constructed to describe the relationships and based on which a quality problem processing framework was proposed (Duan, 2013).
Wen put forward a new hierarchical process modeling and closed loop controlling method based on workflow (Wen Jinqian, 2009). DUAN advanced a quality problem processing procedure model with a network of multi-level, multi-connection and closed loop to improve the capability and collaboration of QPCL (Duan, 2008). A new problem is that how to combine the management resources and technology resources in the QPCL.

The concept of the holon was introduced to the manufacturing in recent years. A manufacturing execution system (MES) was presented by using the holonic manufacturing system (HMS) concepts based on a typology of manufacturing system elements (products, resources, orders) (Blanc et al., 2008). Holonic manufacturing systems provide a flexible and decentralized manufacturing environment to accommodate changes dynamically, so holonic concept is considered a solution for next generation manufacturing systems (Zhao, 2010. RADU et al. 2006). A problem solving environment for the composition of minimal cost processes in HMS is proposed by Fu-Shiung Hsieh (Hsieh et al. 2011). Some studies are presented on the application of the holonic manufacturing paradigm to virtual enterprise control by Biqing Huang. A holonic framework for virtual enterprises is proposed and control mechanisms of virtual enterprises under this framework are then discussed (Biqing Huang, 2002). Duan has proposed an autonomy quality problem resolving framework, but haven’t built the practical holons (Duan, 2015). The holonic manufacturing system was widely used in industry because of its flexible characteristics.

In the process of complex product development, a variety of participants in different areas, technology resources covers interdisciplinary and multi-level management resources are involved. In the implement of the QPCL, it is very difficult to coordinate these participants and its resources. For this, the holon would work well because of its autonomy and cooperation. In the light of the above, the holonic method and model are introduced into the fields of QPCL, as well as a framework for holonic quality problem closed loop (HQPCL) in complex product development in this paper. The framework aims at building the holons which encapsulate the technology resources and management resources in the QPCL and worked autonomy and cooperated with other holons. The mentioned framework for HQPCL consists of five types of basic holons: the quality problem locating holon, the quality problem source-tracing holon, the quality problem mitigation holon, the quality problem closed loop holon and the assist holons.

After a brief introduction into the quality improvement and problem processing and application of holon, the paper discusses the concept of the HQPCL in the section 2. Section 3 describes the structure of the HQPCL framework. The KQML is used for the communication of the quality holons in the section 4. Section 5 describes the importance of the self-similarity in this framework. Finally, a case study is given to validate the framework.

2 The concept of the HQPCL

Hendrik Van Brussel gave an overview of the holonic reference architecture for manufacturing systems (Hendrik, 1998). A theory in the holon is that complex systems will evolve from simple systems much more rapidly if there are stable intermediate forms than if there are not. Thus the intermediate forms which called quality holon were built in this paper. In the process of complex product development, multiple companies are involved. The products quality is difficult to be controlled. Because of the autonomy and cooperation of the holon, the technology resources and management resources from the different companies are encapsulated in the quality holons, as shown in Figure 1. Then the locating of the quality problems, the source-tracing of the quality problems and the mitigation of the quality problems will be controlled by the holons rather than the companies. This is a transmission from company-centric to product-centric. Then the quality problems of the product will be handled efficiently.
Some intermediate forms which named quality elements, the quality atom and the quality molecule were built for better understanding the quality holons.

2.1 Quality Elements

Definition 1. Quality elements (QE), the QE is an abstract concept, it means a class of resources in the total quality management (TQM).

For instance, the QE may be the inspectors, the lathe, the cmm and so on (as shown in Table 1).

| QE no. | Enterprise Resource |
|--------|---------------------|
| QE1    | inspectors          |
| QE2    | lathe               |
| QE3    | cmm                 |
| ......  | ......               |

2.2 Quality Atom

Definition 2. Quality atom (QA). Comparatively to the QE, the QA is a specific concept; it is an instance of the QE and referring to a specific resource.

For instance, John is an inspector, lathe001 is a lathe and its number is 001, cmm002 is a cmm and its number is 002 and so on. (as shown in Table 2).

| QA no. | Enterprise Resource |
|--------|---------------------|
| QA1    | John                |
| QA2    | lathe001            |
| QA3    | cmm002              |
| ......  | ......               |

The relationship of the QEs and QAs is 1: m (as shown in Figure 2).
2.3 Quality Molecule

The quality molecule (QM) is not a specific resource, but a quality activity which include the man, the machines, the materials, the methods, the measurements and the environments (5M1E) etc. (as shown in Table 3).

Table 3 the examples of QM

| QM no. | QM name | QA no. | Enterprise Resource |
|--------|---------|--------|---------------------|
| QM1    | Turing  | QA1    | Join                |
|        |         | QA2    | lathe001            |
|        |         | QA3    | steel               |
|        |         | QA4    | turning             |
|        |         | QA5    | calipers            |
| QM2    | Milling | QA1    | Join                |
|        |         | QA6    | miller001           |
|        |         | QA3    | steel               |
|        |         | QA7    | milling             |
|        |         | QA5    | calipers            |

The relationship of the QAs and QMs is n: m (as shown in Figure 3).

2.4 Quality Holon

Quality holon (QH) composed of one or many QMs. (as shown in Table 4).

Table 4 the examples of QH

| QH no | QH name         | QM no. | QM name |
|-------|-----------------|--------|---------|
| QH1   | cylinder machining | QM1    | turning |
|       |                  | QM2    | milling |
| QH2   | Flat-machining   | QM2    | milling |
|       |                  | QM3    | grinding |
The relationship of the QMs and QHs is n: m (as shown in Figure 4).

![Figure 4 The relationship of the QM and QH](image)

### 2.5 Characteristic of quality holons

The quality holons possess the characteristic as other holons proposed by the HMS consortium.

1. Autonomy: the capability of an entity to create and control the execution of its own plans and/or strategies;
2. Cooperation: a process whereby a set of entities develops mutually acceptable plans and executes these plans;
3. Holarchy: A system of holons that can co-operate to achieve a goal or objective. The holarchy defines the basic rules for cooperation of the holons and thereby limits their autonomy.

Self-similarity: a quality holon also can be constituted by several other quality holons, the quality holons have some “fractal” feature. (As shown in Figure 5)

![Figure 5 The Self-similarity of the quality holons](image)

### 3 Structure of the HQPCL framework

The name HQPCL stands for holonic quality problem closed loop. The QPCL advocated finding out the variation sources of the quality problem and mitigate it completely. The main process of the QPCL is as follows (as shown in Figure 6):

1. Find the quality problem; (locating)
2. Analyze the quality problem, trace the variation sources of the quality problem; (source-tracing)
3. Handle the quality problem, mitigate the quality problem by discussing and implementing the solving measures; (mitigation)
4. Learn by analogy to avoid similar problem and quality problem closed loop review. (closed loop)
3.1 Basic holons

There are four main steps of the process in the QPCL, so the structure of the HQPCL framework is built around four types of basic holons:

1. Quality problem locating holon;
2. Quality problem source-tracing holon;
3. Quality problem mitigation holon;
4. Quality problem closed loop holon.

Another holon is the assist holon which provides some information and resources to the other holons, so there are five kinds of holons in the HQPCL (as shown in Figure 7). Each of them is responsible for one aspect of the QPCL.

3.2 The model of the framework

According to the process of the QPCL, a model of the framework is proposed in this paper. This model consists of five kinds of quality holons, the quality holons can be constituted by several quality molecules which can be constituted by several quality atoms. Then the quality holon encapsulate the technology resources, management resources and other resources. The processes of the QPCL are implemented by the quality holons (as shown in Figure 8).
3.3 Sequence diagram of the HQPCL

The unified modeling language (UML) has already been used in the analysis, design and implementation of many systems. It makes use of various types of diagrams, such as class and sequence diagrams, for designing processes in system development (Takaaki, 2014). The UML is used to describe the working process of the HQPCL (as shown in Figure 9).

The working process of the HQPCL is composed with the following steps:

Step 1. The quality problem locating holons find the quality problem and estimates the reasons & responsibility, then takes this quality problem to the quality problem source-tracing holon;
Step 2. The assist holons provide the staff information, the equipment information and the other information which are related to this quality problem;
Step 3. The quality problem source-tracing holons find the variation sources of this quality problem and send the information(such as 5M1E) of the variation sources to the quality problem mitigation holon;
Step 4. The assist holons provides staff information, equipment information and other information which are related to this mitigation process;
Step 5. The mitigation plan is generated by the quality problem mitigation holons and the mitigation plan would be sent to the closed loop holon;
Step 6. The closed loop holons learn by analogy to avoid similar problem and review the quality problem closed loop process. Then put this closed loop method to the QPCL database.
3.4 Function-Behavior-Resource model

A class diagram in the UML is a type of static structure diagram that describes the structure of a system by showing the system's classes, their attributes, operations (or methods), and the relationships among objects (https://en.wikipedia.org/wiki/Class_diagram). The class diagram could describe the functions and the resources in the quality holons, but the behavior could not. So the function-behavior-resource model was proposed to describe the quality holons in this paper instead of the class diagram. The behaviors are mapped by the functions of the quality holons, and the resources are mapped by the behaviors of the quality holons. The resources may be the technology resources, management resources and other resources (as shown in Figure 10).

3.4.1 Quality problem locating holon

The functions of the quality problem locating holon are these to find the quality problem and to estimate the reason & responsibility, and to find the variation sources. The behaviors of the quality problem locating holon are these to provide staff informations, equipment informations and other informations, and to transfer the mitigation plan. The resources of the quality problem locating holon are these to provide staff informations, equipment informations and other informations, and to learn by analogy to avoid similar problem and review the quality problem closed loop process.
reasons & responsibility of this quality problem, then sends these information to the quality problem source-tracing holon. In order to realize these functions, the behaviors of this holon should contains inspecting the measured value and obtaining the theoretical value of the quality characteristic, then to judge whether this quality characteristic is qualified. Another behavior is obtaining the basic information of this quality problem, for instance, the time, the place, the model and other information etc. In order to realize these behaviors, the inspection resources, the design resources and the manufacture resources should be possessed by this holon. These resources are provided by the assist holons (as shown in Figure 11).

Figure 11 Function-Behavior-Resource model of the quality problem locating holon

3.4.2 Quality problem source-tracing holon

The functions of the quality problem source-tracing holon are these to analysis the reasons of a quality problem and decide whether to decompose the responsibility. If it is necessary to decompose this quality problem to sub quality problems, then a new QPCL process should be started, otherwise, the quality problem source-tracing holon sends these information to the quality problem mitigation holon. The behaviors were described from two aspects, one is technical behaviors and the other is managerial behaviors. The quality problem source-tracing holon finds the mechanism of the quality problems and vulnerabilities of the management system, then repeats the problem and makes a repetition. In order to realize these behaviors, the information about this quality problem which from the quality problem locating holon is needed. Other related resources such as the design resources, the manufacture resources, the management systems and the experiment resources should be possessed by this holon. These resources are provided by the assist holons and the quality problem locating holon (as shown in Figure 12).
3.4.3 Quality problem mitigation holon

The functions of the quality problem mitigation holon are these to generate the mitigation plans to the quality problem and send these mitigation plans to the quality problem closed loop holon. In order to realize these functions, the behaviors of this holon should contains discussing the solving measures, implementing the solving measures and validating the measures. The resources of this holon should contains the vibration source, the variation propagation path, the mitigation plan, the design resources and the manufacture resources. These resources are provided by the assist holons and the quality problem source-tracing holon (as shown in Figure 13).

3.4.4 Quality problem closed loop holon

The functions of the quality problem closed loop holon are these to close the quality problem. In order to realize this functions, the behaviors of this holon should contains learn by analogy to avoid similar problem and review the
quality problem closed loop. The technical reports and managerial reports are also needed. The resources of this holon are quality problem mitigation plans, the design resources and the manufacture resources. These resources are provided by the assist holons and the quality problem mitigation holon dynamically (as shown in Figure 14).

![Quality problem closed loop holon](image)

**Figure 14 Function-Behavior-Resource model of the quality problem closed loop holon**

### 3.4.5 Assist holons

The functions of the assist holons are these to provide the technology resource and management resource to other holons. This holon is different from other holons which mentioned above. The assist holons composed of other holons, for instance, the product holon, the staff holon, the CAD holon, the CAM holon and the schedule holon etc.

![Assist holons](image)

**Figure 15 The assist holons**

### 4 The communication of the quality holons

#### 4.1 KQML

Some techniques have been developed for the communication between agents (SUDO, 2010). But these techniques were not suitable for the holons. The knowledge query and manipulation language (KQML) is a language and protocol for communication among software agents and knowledge-based systems (Finin T, 1994). It was developed by the ARPA to provide a standard interface that is independent of the implementation and platform (Rafael Bates, 1999). A KQML message consists of a performative and a number of parameters (keywords) with their respective values. A KQML message consists of a performative, its associated arguments which include the real content of the message, and a set of optional arguments transport which describe the content and perhaps the sender and receiver. An example could be shown in Figure 16.
In this message, the KQML performativa is “tell”, the sender is “holonA”, the receiver is “holonB”, the reply-with is “id1”  and the content of this message is “if quality problemA is closed”. More information about KQML will be available from the.

4.2 Implementation of the KQML

An advantage of the KQML is that it provides a standard interface which is independent of the implementation and platform. Xml is used for the implementation of the KQML in this paper. For example, in Figure 17, the holonA sends the message1 to holonB for asking “if quality problemA is closed”, and the message2 which from holonB to holonA is that “yes”. The value of “reply-with” in message1 should be as same as the value of “in-reply-to” in message2. In this example, the value of reply-with in message1 and the value of in-reply-to in message2 were “id1”.

5 Self-similarity in the HQPCL

Self-similarity in the HQPCL is an important characteristic which partly determines the reconfigurability of the HQPCL system. Take the China aerospace science & industry Corp (CASIC) as an example. The CASIC was composed of some institutes which were composed of some factories and the factories were composed of some workshops (as shown in Figure 18).
The HQPCL framework shows ‘horizontal’ and ‘vertical’ self-similarity. Horizontal self-similarity relates to self-similarity across different specializations on one level of aggregation. Vertical self-similarity refers to self-similarity across different levels of aggregation: higher-level quality holons work similar to lower-level quality holons.

5.1 Horizontal self-similarity

The framework of the HQPCL models the heterogeneous nature of the institutes, the factories and the workshops in a homogeneous way. All quality holons, quality problem locating holon, quality problem source-tracing holon, quality problem mitigation holon, quality problem closed loop holon and assist holons are self-similar across different institutes, factories and workshops (as shown in Figure 19).
The functions, the behaviours and the resources of the quality holons in a factory are the similar to the other factories. A holon which communicates with another holon can use a common interface and it does not need to be aware of the mechanism of that holon (as shown in Figure 20).
Take the quality problem locating holon as an example. The functions of this holon are these to find the quality problem and estimate the reason & responsibility. The quality problem locating holon in factory 1 was composed of the CMM, the operator \(1\), the surface etc. The quality problem locating holon in factory 2 was composed of the callipers, the operator \(2\), the depth etc. (as shown in Table 5). The quality problem locating holons in different factories were composed of different QMs, but they all communicate with another holons by a common interface.

| Measure Tools | Factory 1 | Factory 2 |
|---------------|-----------|-----------|
| CMM           | Callipers |
| Operator      | Operator 1|
| Measuring Element | Surface   |
| ...           | ...       |
| ...           |...        |

5.2 Vertical self-similarity

The functions, the behaviors and the resources of the quality holons in the workshops are the similar to the same holons in the factories, the institutes and the CASIC. A workshop could be a quality holon in a factory and a factory could be a quality holon in a institute. The workshops could be decomposed into some workstations; these workstations could be treated as subholons to the holons of the workshops.

Reconfiguring the system becomes easier because the holon has “fractal” feature (Leitão, 2006). A quality holon can be integrated in any holarchy without changing the functioning of the quality holon, nor the functioning of the holarchy. If a new quality holon added to the system, it could communicate with other quality holons by the common interfaces. So a quality holon does not need to be adapted to a specific functioning of a holarchy, it may be a member of several holarchies at the same time if necessary.
6 Case study

In this section, an internal combustion engine manufacture is introduced to validate this framework. Engine is one of the important assemblies of the vehicle, which translates chemical energy to mechanical energy by air input, compression, power and output strokes and provides power to drive vehicle (shown in Figure 21) (Yuan, 2011). It is decomposed into some components, such as rocker, exhaust channel, cylinder header, cylinder, piston, connecting rod etc.

Two factories were taken part in the manufacturing of this internal combustion engine. The factories were decomposed into some workshops and the workshops were decomposed into some holons.

The holons which related to this internal combustion engine are shown in Figure 23. The “1” in the cross joint means that the row component is manufactured by the column holons.
A quality problem is faced that the effective power of engine could not satisfy the customer requirement. The quality problem locating holon of the workshop 1 found this quality problem and estimated the reasons & responsibility. The variation source of this quality problem is that the air inlet is inefficiency. This quality problem must be decomposed to sub-problem and start a new QPCL because of the air inlet could not be mitigated directly (as show in Figure 24).
The new quality problem is the out-of-tolerance of the cylinder in the machining. The cylinder is machined in the workshop2, the machining information are provided by the assist holons using the KQML (shown in Figure 25).

```
<?xml version=“1.0″?>
<kqml>
    <tell sender=“foundation holons”          receiver=“workshop1 holons”
    reply-with =“id1”
    content =“Cylinder was machined in workshop2”>
        <tell>
            <kqml>
                foundation holons
                workshop1
            </kqml>
        </tell>
    </tell>
</kqml>
```

Figure 24 An example of the HQPCL framework

Figure 25 The messages between the assist holons and the workshops
So the workshop\textsubscript{1} sends the quality problem of the cylinder to the workshop\textsubscript{2} to start another QPCL. The quality problem source-tracing holon of the workshop\textsubscript{2} finds all of the QMs and QAs in the workshop\textsubscript{2} (shown in Figure 26),

![Figure 26: The hierarchy of the holons, the QMs and the QAs in workshop\textsubscript{2}](image)

The enterprise resources of the workshop\textsubscript{2} were listed in Table 6.

| Quality Molecule | Quality Atom | Enterprise Resource |
|------------------|--------------|---------------------|
| QM1              | QA1          | emp1                |
|                  | QA2          | turning             |
|                  | QA3          | lathe001            |
|                  | QA4          | calipers            |
| QM2              | QA5          | emp2                |
|                  | QA6          | milling             |
|                  | QA7          | miller001           |
|                  | QA8          | CMM                 |

All of the QAs are analysed to find the unusual one and the result is that the vibration source is the QA3. The machining precision of the lathe001 is not qualified. The quality problem source-tracing holon sends this message to the quality problem mitigation holon and the mitigation plan provides by the quality problem mitigation holon is that to change the lathe001 with a qualified one. The quality problem closed loop holon learns by analogy to avoid similar problem and reviews this quality problem.

7 Conclusion

QPCL is one of the most important parts of the quality improvement. A HQPCL framework for complex products development has been presented in this paper. This framework is composed of five kinds of quality holons: quality problem locating holon, quality problem source-tracing holon, quality problem mitigation holon, quality problem closed loop holon and assist holon. Each quality holon focuses on the different responsibilities of the QPCL system. The quality holons transmit the information and other resources of the quality problems respectively. The KQML is used for the communication of the quality holons and implemented by the xml. The HQPCL has a high degree of self-similarity, which reduces the complexity to integrate new components and enables easy reconfiguration of the system. After comparing HQPCL with existing quality control approaches, it is concluded that HQPCL implements the processes of the QPCL by building several holons which encapsulate the technology resources and management resources.
Future work needs to focus on developing a prototype system, establishing a methodology to go from this generic framework to a specific system framework for one specific enterprise.

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