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DESIGN QUALITY PROCESS MANAGEMENT FOR IMPROVEMENT OF ENGINEERING DESIGN PERFORMANCE

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1 Introduction

The management of design quality assurance (QA) process has a significant impact on engineering design performance in cycle time acceleration, rework cost reduction, product development risk control, and customer expectations satisfaction. To achieve these high performance goals in design, it is critical to have systematic methods for modelling the design QA processes, to perform various analyses of the underlying process models with different performance perspectives, and to implement the process modelling and analysis methods together with the performance measures in software tools for practical use in quality process management.

This paper introduces a framework for managing the quality assurance process in consumer electronics design. It consists of QA process modelling and performance modelling approaches, model variable analysis techniques, and ontology driven software implementations to provide semantics-based quality process management services in defining, analysing, and controlling the design QA process for engineering design performance improvement. The approaches, tools and process management services developed have been applied to case studies of QA process management in the consumer electronics design.

2 Background

A design QA process is composed of a set of quality assurance activities interrelated to design activities in a design process and operated on quantitative performance indicators that measure the performance of the design process along various performance dimensions. By identifying the characteristics of the consumer electronics design QA process, this section first discusses the needs and means of design performance improvement. It then deconstructs the design performance into four constituent dimensions to be analysed by different methods. Based on these QA process characteristics and design performance dimensions, the challenges in improving design performance through process management are identified. The challenges will be addresses in Section 3.

2.1 Characteristics of design QA process in consumer product development

Design QA process is becoming more critical in consumer electronics development as market competitions intensifying for high-quality, short-lifecycle, and low-cost products. This situation puts increasing challenges on the management of the consumer electronics design QA process that is characterized by the following features:

- High customer expectations of quality for more complex designs and products;
- Faster new product development (NPD) and shorter product lifecycle;
- Dynamic process relationships and collaborations among business partners, such as suppliers, customers, outsourcing parties, and design service providers; and
- Integrated QA processes with the performance requirements on schedule, cost, risk and customer satisfaction, etc.

These characteristics require effective quality systems, QA semantics communications among business collaborators, and design quality management methods and tools, especially in the early stages of the design process, as most of the product faults, estimated at 75 per cent [1], originate in the early planning and design stages. Over the years, many studies on design quality [1, 2] and NPD process modelling [3] have been conducted and methods/tools [4, 5] developed for specifying, analysing, optimising and controlling the design performance in NPD processes. Among others, the DSM (Design Structure Matrix) [4] and QFD (Quality Function Deployment) [5] methodologies and a set of customised quality tools are selected in this research to analyse quality process interactions, to evaluate effects of process variables on process performance, and to integrate performance requirements into QA processes, aiming at the performance improvement of consumer electronics design.

2.2 Dimensions of design performance

Product design is considered as an innovative process and the design performance is often difficult to be explicitly modelled and measured by quantitative indicators. Furthermore, different types of design processes have different design performance requirements. For example, in mature and repeatable product development, the total development cost may be a primary performance focus. However, in high-tech product development, such as in consumer electronics design, the time to market and the degree of product appeal to consumers may be weighted higher in NPD performance evaluation. Sung and Mathews [6] proposed a four dimensional definition of design performance consisting of the design effectiveness, efficiency, innovation, and adaptability. Other features of design performance being studied include the product quality, time to market, cost, reliability, rate of new product introduction, return on investment, etc [7, 8]. By incorporating the general design performance features to the needs identified from the consumer electronics design QA process, we classify the design performance to be studied in this research into the following dimensions: quality of design process and final product; design process cycle time; cost; customer satisfaction. The definitions and analytic methods of the four dimensions of electronics design performance are given in Table 1.

Table 1. Definitions and analytic methods of design performance dimensions

Dimension		**Definition**	**Analysis Method**
Quality	Design Process	Process variables meet quality criteria.	Process QFD
	Final Product	Products meet customer req. specifications.	Product QFD
Time		Design process cycle time of new products.	DSM analysis
Cost		Total cost of outcomes of a design process.	Relative cost index
Customer Satisfaction		Level of satisfying customers in terms of quality, time, cost, and support.	Statistics of quality tools for Customer Belt Reject, Field Call Rate, Fall Off Rate & a customer satisfaction index

The analytic methods in Table 1 will be used to calculate the quantified metrics values and to identify/analyse the qualitative relationships between design process variables and the four performance dimensions. These relationships are further quantified through a set of performance models and a design performance evaluation metrics model in Section 3.3.

2.3 Challenges in improving design performance

The identified QA process characteristics and the design performance dimensions in the previous two sections lead us to the following research questions:

- How the core QA activities are interrelated in a design QA process and how the dependencies among these activities are described, evaluated and streamlined to achieve a high-performance design. This is referred as the process modelling issue in this paper.
- How the identified four performance dimensions influence/constrain the design activities and how to integrate them into the design process to improve engineering design performance. This is referred as the design performance modelling and analysis issues.
- How to apply the modelling and analysis methods, the QA process models and the design performance models to the quality process management, which is referred as software implementation issues here.

These three aspects are also the main challenges identified in this research for improving the electronics design performance through QA process management. They will be addressed in the next section.

3 A Framework for Quality Process Management

This section proposes solutions to the research questions identified in Section 2.3 under a framework for managing the QA process to improve consumer product design performance.

3.1 Quality process modelling approach

The product design is a key process to assure the consumer electronics with high quality and to satisfy other performance requirements. If all the important aspects of a design QA process, such as core activities and their relationships, as well as the performance information transformations between them can be explicitly defined in a QA process model, the design quality and other performance concerned would be readily analysed to uncover the causes of performance issues, then the causing factors and interactions of process variables be effectively controlled for performance improvement. That is why a process modelling approach is taken in this study.

The development of design QA process models mainly involves modelling of both the structure of QA activities and the interaction of information items among these activities. The following approach is introduced to handle these QA process modelling issues in a hierarchical way.

The modelling process starts with defining process architectures for design QA activities. The existing industrial best practices are used as references to define process architectures that describe high level process structures and activity categories contributing to design quality assurance. Examples of the activity categories include the translation of customer requirements into process and product specifications; prediction of product quality level; evaluation of product development risk; analysis of customer feedback; etc. By moving down the hierarchy of the QA process, more sub-structures and sub-activities are identified. They may be further decomposed until a manageable detail level of activities is obtained. The identified activities are then organised in order, by taking into the considerations of the informational, functional or other dependencies among them. The informational dependency influences the activity orders most, as the activities are basically linked with each other according to flows of information among them. The information flow is described by the I/O behaviour of each activity, which defines the set of information items that the activity requires in order to execute, and the set of information that the activity is able to produce. By identifying these I/O behaviours and linking process activities, their sequences, resources required, execution conditions, and other process elements accordingly, a design QA process model is constructed.

The process models can be represented hierarchically by process trees, by Petri nets or other representation formats. The ARIS graphic notation is used in this paper for representing design QA processes. Fig. 1 shows a part of an ARIS process model for the activity category of *creation and execution of product quality plan*.

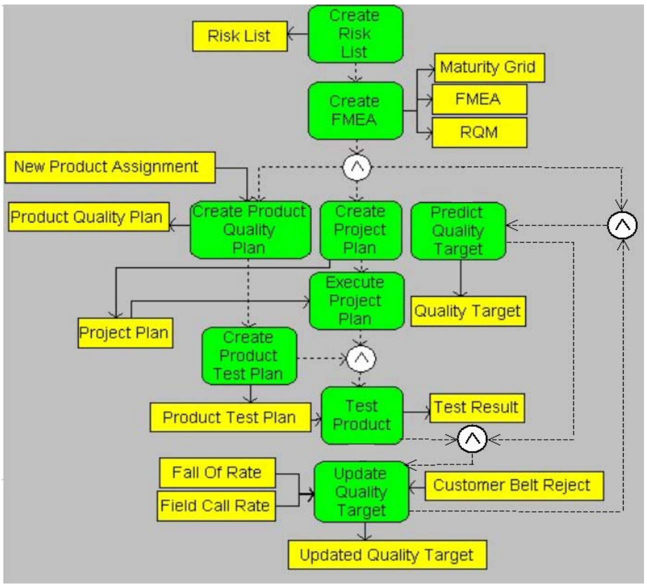


Figure 1. An excerpt of a QA process model in ARIS

3.2 Design process dependency analysis by DSM

The dependencies among activities in the QA process model can be represented as a process graph to facilitate the computational analysis of the model. A process graph (PG) is a directed graph with a vertex denoting an activity and a directed edge denoting a dependency, i.e.

$$PG = \langle AS(PG), DS(PG) \rangle \tag{1}$$

where $AS(PG)$ is a set of activities in the process model; $DS(PG)$ is a set of dependencies among these activities.

Each dependency is associated with an ordered pair of activities. Specifically, a dependency D from j to i, labelled as $D_{i,j}$, indicates that the activity i is dependent on activity j. Take the partial QA process model in Fig. 1 as an example. Table 2 summaries all the activities and dependencies in this process model.

Table 2. Process activities and dependencies in Fig. 1

S/N	**Activity**	**Dependency**
a1	Create risk list	
a2	Create FMEA	$D_{2,1}$
a3	Create quality plan	$D_{3,2}$
a4	Create product test plan	$D_{4,3}$
a5	Predict quality target	$D_{5,2}$; $D_{5,9}$
a6	Create project plan	$D_{6,2}$
a7	Execute project plan	$D_{7,6}$
a8	Test product	$D_{8,4}$; $D_{8,7}$
a9	Update quality target	$D_{9,8}$; $D_{9,5}$

According to Eq. (1) and the activity and dependency representations in Table 2, the process graph for this example can be expressed as:

$$PG = <\{a1,a2,a3,a4,a5,a6,a7,a8,a9\}, \{D_{2,1},D_{3,2},D_{4,3},D_{5,2},D_{5,9},D_{6,2},D_{7,6},D_{8,4},D_{8,7},D_{9,8},D_{9,5}\}> \qquad (2)$$

The graphic representation of the process graph in Eq. (2) is shown in Fig. 2.

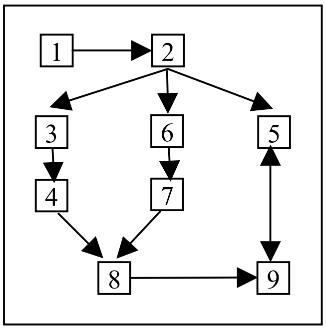


Figure 2. Process graph example

In order to analyse the QA activity dependencies by DSM, the process graph in Fig. 2 is translated into a matrix, i.e. its adjacency matrix $M = (m_{ij})$.

$$m_{ij} = \begin{cases} 1 & \text{if there is a dependency from } j \text{ to } i \text{, for all } i, j = 1,2, \ldots, n; \\ & n \text{ is the number of activities.} \\ * & \text{if } i = j. \\ 0 & \text{otherwise.} \end{cases}$$

Fig. 3 below illustrates the adjacency matrix of the process graph in Fig. 2.

$$\begin{array}{c|ccccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & * & & & & & & & & \\
2 & 1 & * & & & & & & & \\
3 & & 1 & * & & & & & & \\
4 & & & 1 & * & & & & & \\
5 & & 1 & & & * & & & & 1 \\
6 & & 1 & & & & * & & & \\
7 & & & & & & 1 & * & & \\
8 & & & & 1 & & & 1 & * & \\
9 & & & & & 1 & & & 1 & * \\
\hline
\end{array}$$

Figure 3. Adjacency matrix

By applying the DSM analysis [5] to the matrix in Fig. 3, the interdependent activities, such as a5 and a9 in Table 2, can be analysed for streamlining. By removing or redefining activity dependencies and iteration loops in the matrix to increase the process execution concurrency, the process duration would be reduced. The resulting matrix of the DSM analysis can also be used to reveal the critical activities in a process by identifying the dependency path [7]. The detailed DSM analysis to the QA process model developed in Section 3.1 will be elaborated in a case study in Section 4.2.

3.3 Performance models

A performance model explicitly defines the relationships between a set of performance control variables and a performance measure. Four performance dimensions, i.e. quality, time, cost, and customer satisfaction, are identified in Section 2.2 to measure the performance of a design process in consumer electronics development. This section constructs performance models for these dimensions.

3.3.1 Quality matrix

A quality performance model describes the compliance level of a product with its totality of features and characteristics that bear in its ability to satisfy given needs [9]. The product quality characteristics must be highly optimised to customer desires. Based on this principle, the quality performance model is developed as a function of several quality performance attributes, including the customer requirements, process steps and parts, relations between the customer requirements and the processes/parts identified, product and process FMEA, Customer Belt Reject (CBR) target, and production Fall Off Rate (FOR) target. These quality performance attributes may be represented in different formats, such as in charts or forms, but integrated into a quality matrix as shown in Fig. 4. Some of the quality performance attributes listed above will be analysed by the design process QFD in Section 3.4.

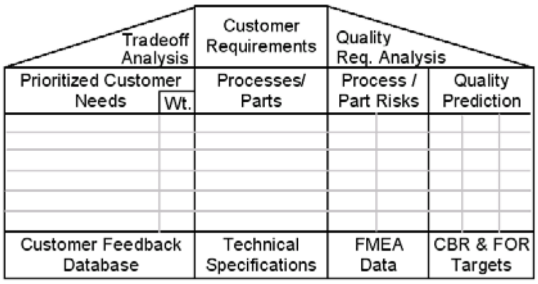


Figure 4. Quality matrix

3.3.2 Design cycle time

The design cycle time refers to the total duration between the initiation and the completion of a design process. It is determined by a serial execution time of the interrelated design activities under certain resource constraints. The main purpose of modelling the time performance is to analyse and control over the design process duration, as well as to evaluate the total cost of outcomes of a design process through a schedule overdue function (refer to the next section for details). In this research, the design cycle time performance model, $DCT(t)$, is defined as a function of the following performance attributes and described by a metric model: design capacity C; design progress, $P(t)$, at a given time t; schedule overdue of activity i at time t, $O_i(t)$; and resource constraints to perform activity i at time t, $R_i(t)$; i.e.

$$DCT(t) = f(\,C,\, P(t),\, \sum O_i(t),\, \sum R_i(t)\,) \qquad (3)$$

3.3.3 Relative cost index

A cost performance model is used to assess whether the total cost of outcomes of a design process meets a budget. The design costs could be modelled as a function of the optimal design cycle time, $DCT_{opt}(t)$, when the available resource (such as the size of a development team) is allocated optimally. The cost performace may also be affected by other factors, such as the product functional requirements or the level of the activity concurrency. Therefore the design process cost model could be very complex in real design cases. Instead of trying to predict the design cost in absolute measures, a relative cost index is defined here as the performance model to evaluate the consumer electronics design cost performance, with its simplicity and precision good enough for practical use. The relative cost index is defined in such a way that it takes a lower value if design activities scheduled can be completed before the due date and it takes a relatively larger value otherwise; and that it also takes into account the impacts (F_{impact}) from those factors such as the percentage of design rework, activity concurrency level, etc. The definition of the relative cost index, *RCI,* is shown in Eq. (4).

$$RCI = \sum O_i(t)|_{t=t1} + F_{impact} \tag{4}$$

where $O_i(t)$, the schedule overdue of activity i at time t, is the same as defined in Eq. (3); and $F_{impact} = \sum w_j r_j$; r_j is the rating of the jth influencing factor on the cost and w_j is the weight of r_j.

3.3.4 Customer satisfaction

A customer satisfaction index, *CSI*, is defined to measure the level of satisfying customers in terms of their expectations on quality, time-to-market, cost, and technical support of final products. The *CSI* is defined by:

$$CSI = \sum w_i\, r_i \,/ \sum w_i \tag{5}$$

where $i = 1, 2, \ldots n$; n is the total number of customer expectations in the *CSI*; $r_i \in [0,1]$ is the performance rating of each customer expectation; w_i, in percentage, denotes the importance of each expectation, and $\sum w_i = 100\ \%$.

3.3.5 Design performance evaluation metrics model

The design performance evaluation metrics model simplifies the calculation of design performance indicators at the early design stage using approximate and predicted data, as many detailed process data are not available yet. It can also be used to evaluate the risk of a design project. The metrics model integrates the influences of the following performance attributes on the success of a design project: early indication of product quality, process capability, part reliability, design maturity, customer and supplier relationship, product development model, and so on. Under each attribute, sub-factors are identified to illustrate detailed performance measures and ratings. For example, the *process capability* attribute contains the sub-factors of process capability index, overall performance of operators, efficiency of technical support, number of process stations, automation level, and number of high risk/unknown processes. The formula of the design performance evaluation metrics model, *DPE*, is defined as follows.

$$DPE = \frac{10}{m} \sum_{i=1}^{m} \frac{\sum_{j=1}^{n} w_i r_{ij}}{\sum_{j=1}^{n} w_i Max(r_{ij})} \tag{6}$$

where $i = 1,2,\ldots m$, m denotes the number of performance attributes; $j = 1,2,\ldots n$, n denotes the number of sub-factors under one performance attribute; r_{ij} denotes the rating of the jth sub-factor under the ith performance attribute; w_i denotes the importance weight of ith attribute, $Max(r_{ij})$ denotes the full rating of the jth sub-factor under the ith performance attribute.

The metrics model in Eq. (6) has been implemented in a design QA process management software tool to be described in Section 3.5. Its evaluation services have been used in a case study for comparison and improvement of design performance in consumer electronic product development.

3.4 Impact analysis of process variables on design performance by QFD

3.4.1 Method

The structured process QFD [5] provides a means for identifying and carrying the customer's voice throughout each stage of product development. In this paper, the QFD technique is used to analyse impacts of customer requirements, projected by process variables, on the design performance especially the quality performance. To do so, two types of QFD are defined: the product QFD and the design process QFD. A product QFD identifies and then analyses the design technical requirements towards the customer expectations and the competitive requirements, by relating the technical objectives to the customer wants based on the competitive analysis inputs. The customer wants are prioritised by importance rankings included in the QFD matrix. A house of quality (HoQ) for product design, reflecting all these aspects mentioned above, is shown in Fig. 5. On the other hand, a design process QFD concentrates on analysing the critical process variables to satisfy customer requirements, by relating these variables to the design process performance measures. Each process variable is given a weight to indicate its relative importance. Similar to the HoQ for product design, a HoQ for design process can be defined.

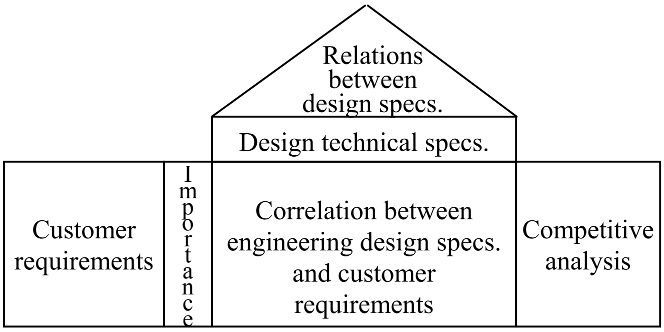


Figure 5. HoQ for product

In practice, these two types of QFD analyses are often used together:

- To transform customer requirements into specific technical objectives, through the product QFD analysis.
- To identify, at different abstraction levels, the design activities that deliver what customers want, according to the technical objectives identified in the previous step. This identification process could be aided by other QFD matrices that correlate the design

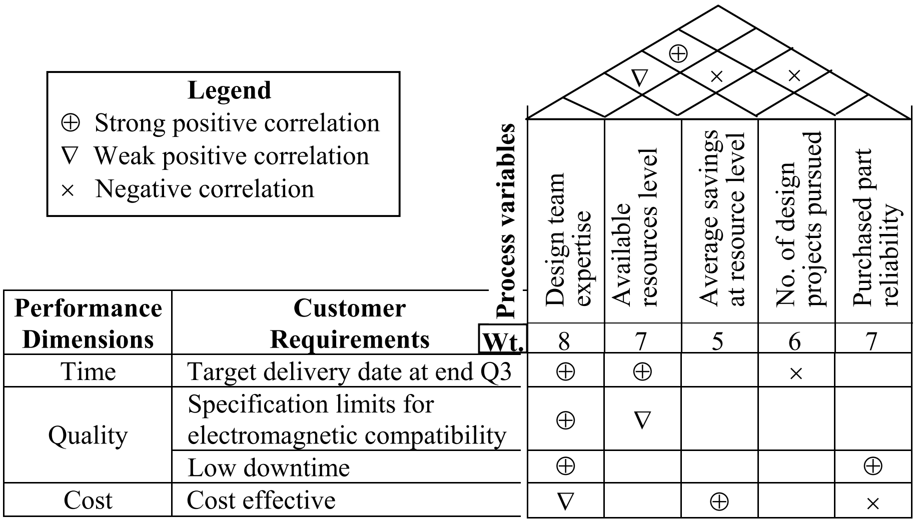
technical specifications to the critical design activities, and further to the performance requirements imposed to these activities.

- To analyse and improve the design process performance by controlling the process activities and the process variables to meet customer requirements, through the design process QFD analysis.

3.4.2 Design process QFD analysis

The impact analysis of process variables on design performance by the design process QFD is discussed in this section. The similar method can be applied to the product QFD analysis in Fig. 5 for defining the correlations between the customer requirements and the design technical specifications.

Many variables are involved in a design QA process. If a variable is directly controllable or independently changeable in the process, it is then identified as a process variable. For example, the available resource level for conducting activities of the QA process in Fig. 1 can be directly controlled. The purchased part reliability can also be specified/controlled. They are therefore considered as the process variables. The controllable variables impact one or more design performance dimensions, such as those identified in Fig. 6. However, the quantitative impacts between a design performance dimension and a set of process variables are not easy to establish. As such, the QFD is used to describe the qualitative relationships between them. Fig. 6 illustrates one of such QFDs used for qualitative impact analysis in a DVD design.



Legend
⊕ Strong positive correlation
∇ Weak positive correlation
× Negative correlation

Performance Dimensions	Customer Requirements	Design team expertise	Available resources level	Average savings at resource level	No. of design projects pursued	Purchased part reliability
	Wt.	8	7	5	6	7
Time	Target delivery date at end Q3	⊕	⊕		×	
Quality	Specification limits for electromagnetic compatibility	⊕	∇			
	Low downtime	⊕				⊕
Cost	Cost effective	∇		⊕		×

Figure 6. QFD matrix for the design QA process

From Fig. 6, it is known that the *design team expertise* has a strong positive influence on the performance dimensions of *time* and *quality*, as well as a weak positive influence on *cost* performance. These qualitative relationships can be transformed into quantitative relationships by several techniques. For example, by assigning coefficient values to the symbols used in Fig. 6, the quantitative impacts of the process variables on the performance dimensions can be established. These quantitative relationships can then be used as constraints in the optimisation of a multi-objective function of the performance dimensions [7]. In the current research, the quantified impacts of process variables on the design performance are derived from the QFD quantitative relationships in Fig. 6 multiplied by their respective weighting factors. These weighted impacts are used in the design performance evaluation metrics model in Eq. (6) to determine and evaluate the most effective controls over the process variables in order to achieve better performance in consumer electronics design.

3.5 Software implementation for design QA process management

The quality process modelling approach, the DSM dependency analysis method, and the design performance evaluation metrics developed in the previous sections have been used to guide the implementation of an ontology-driven software system to provide semantics-based design QA process management services, such as the quality process configuration and integration services, DSM analysis services, performance metrics calculation services, etc. These process management services are based on the process and performance models described early. The use of these services is shown in Section 4 through use scenarios.

3.5.1 Service ontology for QA process management

Consumer electronics design involves multidisciplinary efforts typically from mechanical, electrical and electronic, optical, software engineers and other supporting professionals, as well as the external business collaborators of suppliers, outsourcing partners, etc. Each design collaboration participant needs to generate, consume, and exchange instances of shared domain entities with others, but possibly using proprietary information models and formats with different meaning definitions, which often causes the semantic interoperability problems. Ontologies represent a formal and shared understanding about the domain entities. They provide declarative definitions to the semantics of domain concepts and service functionalities. In particular, the OWL-S [10] upper ontology, with capabilities of semantic markup of Web-based domain services, enables richer semantic descriptions for more flexible and automatic discovery, composition and invocation of the application services, such as the QA process management services discussed below.

Take a typical QA process management scenario as an example. Table 3 gives a detailed decomposition of the QA process into elementary tasks and sub-processes. The corresponding OWL-S process types are also shown in the table.

Table 3. Main tasks in the design QA process management

Task	Type	OWL-S Process Type
Define quality process	Sub-process	Composite (sequence)
Analyse quality process	Elementary	Atomic
Configure quality process	Elementary	Atomic
Calculate quality data	Sub-process	Composite (any order)
Calculate product design FMEA	Elementary	Atomic
Calculate production process FMEA	Elementary	Atomic
Calculate quality statistics	Elementary	Atomic
Predict risk	Elementary	Atomic
Execute quality plan	Elementary	Atomic
Login	Elementary	Atomic

By mapping the sub-processes and elementary tasks in Table 3 into the respective process types of OWL-S, and instantiating the OWL-S upper service model with the domain concepts identified from the QA management applications, an application-specific service ontology for design QA process management is constructed, which will be used for service discovery and invocation in a use scenario in Section 4.1.

3.5.2 Software System Design

A service-oriented approach is taken in the software system design. The approach encapsulates diverse functionality of services (e.g. domain services, query processing, data semantics mapping) behind common interfaces to facilitate the discovery, composition and invocation of the Web-enabled QA process management services. Fig. 7 presents a diagram of the software architecture for the QA process management system. It outlines the main conceptual structure and system functionality of the process management prototype. The prototype in Fig. 7 provides three types of services as described below.

Domain functional services. The individual application tools are developed for design QA process configuration and integration; activity dependency analysis; and design performance evaluation. All these applications are virtualised as the Web-based services and described by OWL-S ontologies, so that their data elements and functionalities can be interpreted and transformed in a semantically consistent way. Besides providing modelling and analysis services, these tools also facilitate the integration of performance models into QA processes by specifying the relations between the two. Using these relations, such as the task-performance correlation matrix in this study, the design performance targets about quality, schedule, cost, risk, etc are linked to the individual process steps in the QA process configurations.

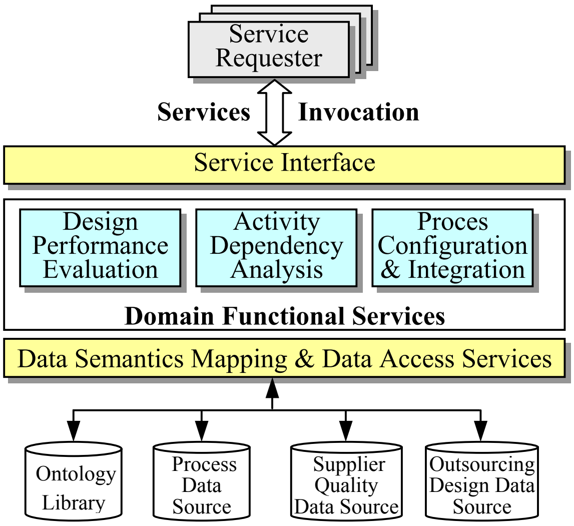


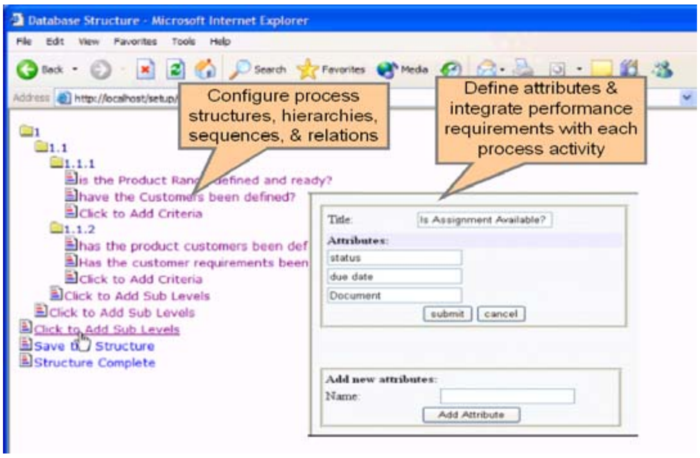
Figure 7. System architecture

Interfacing services. The Service Interface in Fig. 7 provides incoming service requests with a set of methods to establish communications between the requesting applications and the individual domain functional services in Fig. 7. It also facilitates the interpretation of solutions, given by the execution of the domain services, to the requesting applications. If no suitable domain services can be found to match a request, it will route the service request to other agents in a network.

Data semantics mapping and data access services. The mapping services annotate the meaning of the information elements in a local conceptual schema, such as a database schema of the supplier quality data source in Fig. 7, according to the shared service ontology defined in Section 3.5.1 and stored in the ontology library of Fig. 7. Based on these mapped, commonly understood semantic definitions, the data access services manipulate the data sets in each data source for their use in modelling and analysing the QA processes and performance.

3.5.3 Software implementation

The domain functionalities described above are implemented as individual application tools and exposed as Web-enabled semantic services under the system architecture of Fig. 7. A client application invokes the QA process management services through a Web browser. Fig. 8 shows the implementation for the process configuration and integration functionality, while Fig. 9 for the design performance evaluation metrics.



Configure process structures, hierarchies, sequences, & relations

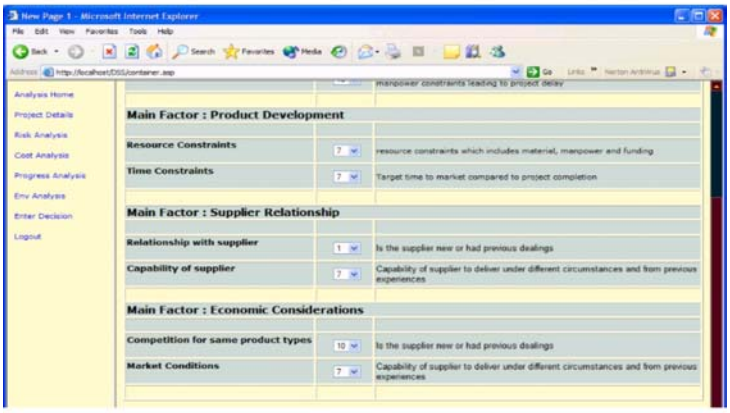
Define attributes & integrate performance requirements with each process activity

1
1.1
1.1.1
is the Product Range defined and ready?
have the Customers been defined?
Click to Add Criteria
1.1.2
has the product customers been def
Has the customer requirements been
Click to Add Criteria
Click to Add Sub Levels
Click to Add Sub Levels
Click to Add Sub Levels
Save the Structure
Structure Complete

Title: Is Assignment Available?
Attributes:
status
due date
Document

Add new attributes:
Name:

Figure 8. Implementation for process configuration and integration



		manpower constraints leading to project delay
Main Factor : Product Development		
Resource Constraints	7	resource constraints which includes material, manpower and funding
Time Constraints	7	Target time to market compared to project completion
Main Factor : Supplier Relationship		
Relationship with supplier	1	Is the supplier new or had previous dealings
Capability of supplier	7	Capability of supplier to deliver under different circumstances and from previous experiences
Main Factor : Economic Considerations		
Competition for same product types	10	Is the supplier new or had previous dealings
Market Conditions	7	Capability of supplier to deliver under different circumstances and from previous experiences

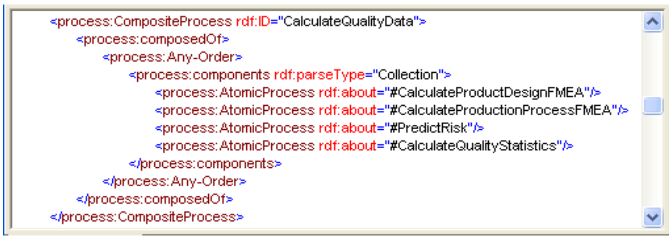
Figure 9. Implementation for performance evaluation metrics

4 Use Scenarios

Three use scenarios are discussed here to illustrate the use of the QA process management methods and the prototype in the design process of consumer electronics, such as CD players and DVD+RW recorders.

4.1 QA process modelling, configuration, and management services discovery

The methods and prototype are used to generate the QA process models compliant with company's best practices that are used as the build-in templates with the prototype, for different design projects. A project-level process configuration is conducted to assemble and tailor the templates for specific project needs by using the Process Configuration and Integration module of the prototype. The resultant configuration is further integrated with the project-level performance requirements through the integration relations (the user-task allocation matrix and task-performance correlation matrix) implemented in the prototype. The integrated QA process configuration is then used to provide domain concepts and application logics for construction of OWL-S models as described in Section 3.5.1. Based on these OWL-S ontologies, the services semantics can be understood, queried, reused and shared in the design quality process management community, thus to facilitate the design collaboration. For example, the OWL code in Fig. 10 describes the control structure of a composite process for *CalculateQualityData* in terms of four constituent atomic processes. One of them is the *PredictRisk* atomic process. It has an input type *Factor*, which is defined as an intersection of several restrictions on its three instance attributes: *mainFactor*, *subFactor*, *and weight.* The *mainFactor* and *subFactor* are restricted by *allValueFrom* a *userData* type, and *weight* by *hasValue* of an integer type. Described by these formal semantics, consequently, the service *CalculateQualityData* can be discovered based on the property types/values of these semantic descriptions.

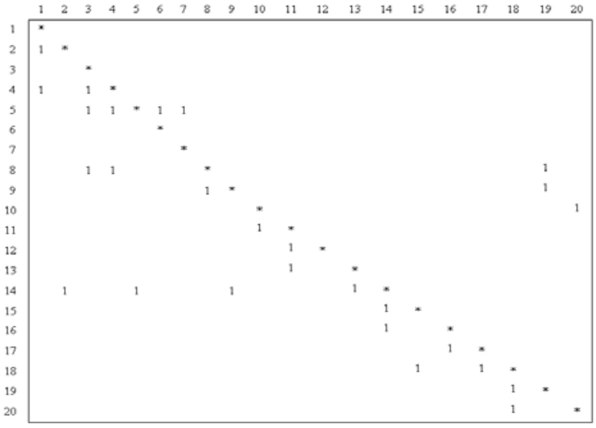


```
<process:CompositeProcess rdf:ID="CalculateQualityData">
    <process:composedOf>
        <process:Any-Order>
            <process:components rdf:parseType="Collection">
                <process:AtomicProcess rdf:about="#CalculateProductDesignFMEA"/>
                <process:AtomicProcess rdf:about="#CalculateProductionProcessFMEA"/>
                <process:AtomicProcess rdf:about="#PredictRisk"/>
                <process:AtomicProcess rdf:about="#CalculateQualityStatistics"/>
            </process:components>
        </process:Any-Order>
    </process:composedOf>
</process:CompositeProcess>
```

Figure 10. Control structure of *CalculateQualityData*

4.2 DSM analysis

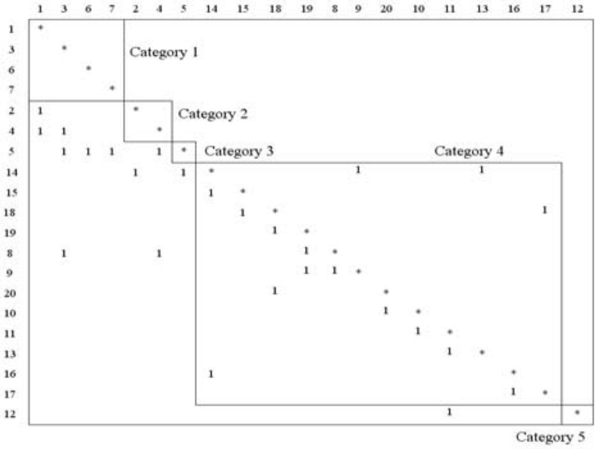
Following the DSM analysis approach in Section 3.2, the activities and their dependencies in the full ARIS model of the QA process in Fig. 1 are represented as a process graph. Fig. 11 shows its adjacency matrix.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	*																			
2	1	*																		
3			*																	
4	1		1	*																
5			1	1	*	1	1													
6						*														
7							*													
8			1	1				*											1	
9								1	*										1	
10										*										1
11										1	*									
12											1	*								
13											1		*							
14		1			1				1				1	*						
15														1	*					
16														1		*				
17																1	*			
18															1		1	*		
19																		1	*	
20																		1		*

Figure 11. Adjacency matrix of the QA process graph

By invoking the DSM *activity dependency analysis* services of the prototype, the initial matrix in Fig. 11 is transformed into a structured matrix in Fig. 12, which is used to identify the model structure for streamlining the process activities.



	1	3	6	7	2	4	5	14	15	18	19	8	9	20	10	11	13	16	17	12
1	*																			
3		*																		
6			*																	
7				*																
2	1				*															
4	1	1				*														
5		1	1	1		1	*													
14					1		1	*					1				1			
15								1	*											
18									1	*									1	
19										1	*									
8		1				1					1	*								
9											1	1	*							
20										1				*						
10														1	*					
11															1	*				
13																1	*			
16								1										*		
17																		1	*	
12																1				*

Figure 12. DSM analysis resulting matrix

Five different activity categories are visible in Fig. 12 with an interaction loop, {8,9,10,11,13,14,15,16,17,18,19,20}, involving 12 activities. If the dependencies between 13 and 14, 17 and 18 in Fig. 11 could be removed, the activities involved in the loop of the structured matrix would be reduced from 12 to 6: {8,9,14,15,18,19}. Fewer activities in a loop results in a faster process duration. Another way to reduce the process duration is through enhancement of the degree of concurrency among activities. To do so, the following actions can be taken:

- To remove or redefine the dependencies among activity categories. For example, by removing the 4 to 5 dependency in Fig. 11, the Category 3 could be combined with Category 2, resulting in reduced number of categories from 5 to 4. This would improve the concurrency of the process as activity 5 in Category 3 could be performed concurrently with activities 2 and 4 in Category 2.
- To replace coupled activities with an alternative activity that has non-cyclic dependencies with other activities. For example, if the coupled activities of 5 and 9 in Fig 2 could be replaced by a combined activity of them, then the coupled relationship in Fig. 3 would be replaced by a sequential one, so that the concurrency of activities are improved.

4.3 Performance comparison and improvement

The OPU (optical pickup unit) design process is taken as an example to illustrate the use scenario for design performance evaluation and improvement here. Table 4 lists a performance comparison of two models of OPU designs by applying Eq. (6).

Table 4. Performance comparison

Main Factor	**Weight**	**Sub Factor**	**Rating of Model A**		**Rating of Model B**	
Process capability	7	Process capability index	7	0.74	4	0.61
		Overall operators performance	4		4	
		Efficiency of technical support	10		10	
		No. of assembly stations	10		7	
		Automation level	10		10	
		Filtering cap. of measurement stations	1		1	
		No. of high risk/unknown processes	10		7	
Part reliability	9	Fall Off Rate	10	0.70	10	0.64
		Relationship with supplier	10		10	
		Capability of supplier	4		4	
		Quality of supplier sources	1		1	
		Number of new/unknown parts	10		7	
Design maturity	8			0.85		0.70
Customer relationship	3			0.70		0.70
Product dev. model	7			0.78		0.85
Team coordination	4			0.55		0.70
DPE from Eq. (6)			**7.2**		**7.0**	

The evaluation in Table 4, together with the DSM, QFD analyses and the use of process management tools, has been used to guide the new OPU model designs with improved performance in assessing process variables and their impacts for bottleneck identification and preventive actions; controlling critical activities and their interactions for less rework and better design quality; streamlining QA activities for process duration reduction; and improving the quality and timeliness of process data for more effective stage-gate decisions.

5 Conclusion

A framework for QA process management in consumer electronics design has been developed to maximise the process management capability and design performance. A Web-enabled process management prototype is also implemented to support the practical use of this framework in design projects. The use scenarios show that the modelling framework and the prototype are able to enhance the QA process modelling capability; the quality process configurability and performance analysis capability; and the semantic interoperability of process information and services for better design collaboration, therefore contribute to the design performance improvement.

The future research includes the support for dynamic process configuration, optimisation of process variables, and product lifecycle performance evaluation and improvement.

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