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Knowledge integration based on roadmapping and conceptual framework approach to ease innovation management

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Abstract: Knowledge management and innovation management are logically linked. However, the alignment of their respective deployment mechanisms is still not obvious. An analysis of the Innovation and Knowledge Life Cycles shows that the Knowledge Life Cycle can be deployed (partially) at each step of the Innovation Life Cycle. This implies that different, specific knowledge management tools could be used to increase innovation. Two knowledge management tools are considered in this paper: roadmaps and conceptual frameworks. A methodology is proposed for using roadmaps and conceptual frameworks within the context of integrated knowledge networks for improving efficient innovation. These two approaches aim to ease the knowledge structuring and identification in order to facilitate innovation. Two knowledge management examples in the financial services highlight how these tools contribute to the increased efficiency of the innovation process, leading to a more mature innovation deployment.

Keywords: innovation; knowledge integration; knowledge management; roadmapping; innovation management; conceptual framework.

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Biographical notes: Nicolas Perry is an Associate Professor at Ecole Centrale de Nantes and works in the Research Institute of Communication and Cybernetics of Nantes. He received his PhD degree in Mechanical Engineering from the University of Nantes and Ecole Centrale de Nantes (France) in 2000. His research topics focus on virtual engineering, knowledge management and KBE as decision tools for engineers applied to cost management.

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1 Introduction

Innovation is today widely recognised by both industry and academics as a necessity for any business that wants to remain competitive and survive and grow (Drucker, 1985; IBM's Global Innovation Outlook, 2005). Surveys such as the annual innovation survey from The Boston Consulting Group (2005), however, suggest that although the importance

of innovation is fully realised by most companies and they continue to spend more and more on innovation, many do not seem to generate satisfactory profit or competitive advantage. The problem does not seem to lie in the invention part or the generation of innovative ideas, but more in the successful management of the innovation process from an idea to a successful product in the market (Löf and Heshmati, 2002; Kemp et al., 2003).

More and more researchers are emphasising the importance of knowledge management for supporting the efficient management of innovation (Johannessen et al., 1999; Pérez-Bustamante, 1999; Carneiro, 2000; Burgelman et al., 2001; Darroch and MacNaughton, 2002; Lemon and Sahota, 2004). The way in which knowledge is used, spread and stored by an organisation's employees determines whether this organisation has a culture stimulating or restraining innovation. Innovation in effect happens through the novel combination of existing internal and new external knowledge. In order to innovate effectively and sustainably, existing knowledge should, therefore, not only be captured, but also shared and integrated. By sharing best practices, inefficient redundancy in innovation is greatly reduced, whereas the integration of knowledge helps to exploit complementarities among knowledge assets and to achieve coordination. Actual practises of achieving this sharing and integration is, however, currently not well understood (Du Plessis, 2005; Leiponen, 2006).

The purpose of this paper is to present the mutual enrichment of using on the one side conceptual framework to structure and clarify knowledge, and on the other side roadmaps as methods of working. A methodology has been developed for an efficient application of these two elements – as knowledge management support tools – for the improved management and deployment of innovation projects. These tools are specifically aimed at capturing, modelling, contextualising and sharing of existing enterprise knowledge in order to improve the process of innovation.

The paper starts with a brief overview of the innovation process and knowledge management. This is followed by a section explaining a methodology developed by the teams. The methodology entails the application of roadmaps and conceptual frameworks as knowledge management support tools for the management of innovation. Finally, example applications in financial services companies are discussed. We will end the discussion with the open issues of knowledge maturities evaluation and the knowledge networks that become the new informal structure of collaboration.

2 Innovation management

Over the last few years much has been written about innovation and many have tried to uniquely and precisely define innovation (Drucker, 1985; Tidd et al., 2001). Innovation is traditionally viewed as a linear progression from research to invention, from engineering design to product, and from manufacturing to marketing. This model suggests that innovation can be increased by increasing R&D inputs (technology push). Innovation is, however, much more complex than a sum of knowledge inputs. It is

about successful market outcomes and the process by which those outcomes are generated. A very thorough definition of innovation is provided by Salvendy (1992, p.1170):

“Innovation is not just one simple act. It is not just a new understanding or the discovery of a new phenomenon, not just a flash of creative invention, not just the development of a new product or manufacturing process; nor is it simply the creation of new capital and markets. Rather innovation involves related creative activity in all these areas. It is a connected process in which many and sufficient creative acts, from research through service, are coupled together in an integrated way for a common goal.”

The 21st Century Working Group has defined innovation as follows: “Innovation transforms insight and technology into novel products, processes and services that create new value for stakeholders, drive economic growth and improve standards of living” (Donofrio, 2004). This definition acknowledges that innovation is a complex and multidimensional activity that cannot be characterised by a single input measure.

Innovation is, therefore, not simply an invention or novel idea, but is the complete process of developing the idea and successfully exploiting it in the enterprise and the market.

Tidd et al. (2001) view innovation as a process that needs to be managed. According to them organisations essentially have to manage four different phases in the innovation process of turning ideas into successful reality:

- 1 *Scan*: Scan and search their environments (internal and external) to pick up and process signals about potential innovation.
- 2 *Select*: Strategically select from this set of potential triggers for innovating those things which the organisation will commit resources to doing.
- 3 *Plan*: Having chosen an option, organisations need to resource it – providing (either by creating through R&D or acquiring through technology transfer) the resources to exploit it.
- 4 *Implement*: Finally organisations have to implement the innovation, growing it from an idea through various stages of development to final launch – as a new product or service in the external market place or a new process or method within the organisation.

Innovation management is, therefore, about learning to find the most appropriate solution to the problem of consistently managing this process. This paper suggests an innovation management framework that is based on the successful management of knowledge along the complete Knowledge Life Cycle as defined in the following section.

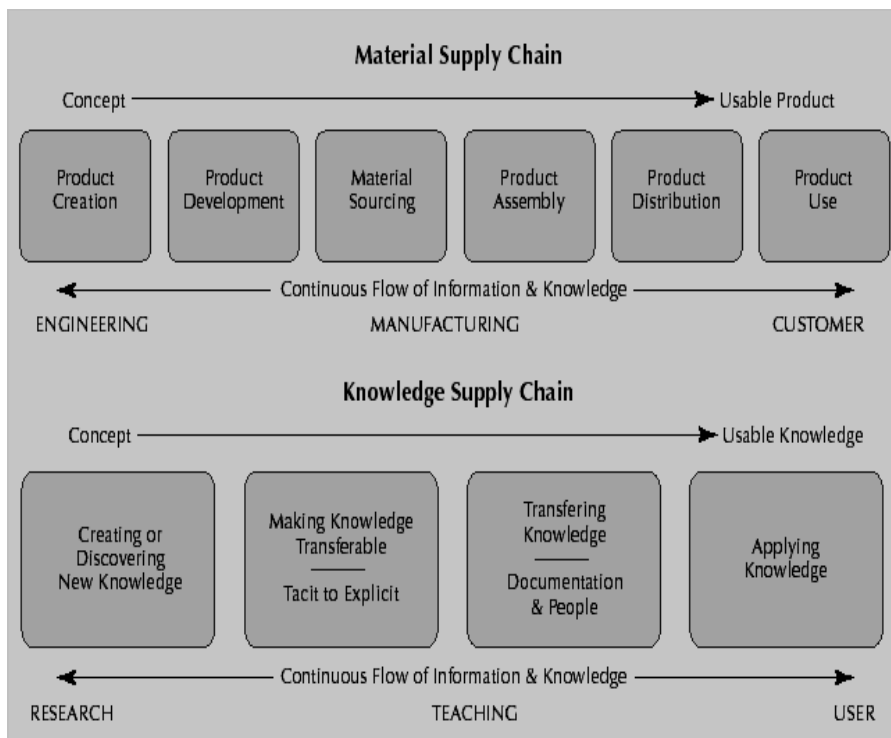
3 Knowledge integration as support for innovation management

Knowledge management leads to knowledge integration in order to ease and optimise works efficiency. It has received widespread attention in recent years as an important basis for competitive advantage (Grundstein and Rosenthal-Sabroux, 1999; Prax, 2000).

Before discussing the importance of knowledge management for the efficient management of innovation, the concepts of knowledge and the Knowledge Life Cycle, as well as knowledge management needs to be defined.

The Cambridge dictionary defines knowledge as the understanding of, or information about, a subject which has been obtained by experience or study, and which is either in a person’s mind or possessed by people generally. Knowledge is the baseline from which innovation occurs, and against which innovation is measured. Without knowledge, innovation would be a random, uncontrollable and unsustainable activity. Figure 1 illustrates how knowledge evolves from a concept to usable knowledge while supporting the innovation process associated with the material supply chain. Knowledge is thus an asset that must be collected, protected, accessed, maintained and managed – therefore, the need for knowledge management and toolsets that makes this possible.

Figure 1 The knowledge supply chain



3.1 Roadmapping and conceptual framework for knowledge management

Various definitions for knowledge have been given in the research literature. According to Davenport and Prusak (1998), knowledge is

“a fluid mix of framed experience, values, contextual information, and expert insights and grounded intuitions that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of the knower. In software organizations, it often becomes embedded not only in documents or repositories, but also in organisational routines, processes, practices and norms.”

The debate normally goes around the differences between data, information and knowledge (Frank and Gardoni, 2005). Davenport and Prusak (1998) view the differences between data, information and knowledge as gradual, different levels of the same thing in which human interpretation makes the

difference. Data becomes information if one adds context, categories or calculations. Information turns into knowledge if humans add their experience, judgement, values and beliefs to use it for comparison, decision-making and conversations. Bellinger (2004) adds to the definition of knowledge by adding that beyond context and relation there is a pattern that embodies both a consistency and completeness of relations which, to an extent, creates its own context. Pattern also serves as an archetype with both an implied repeatability and predictability. According to Bellinger, when a pattern relation exists amidst the data and information, the pattern has the potential to represent knowledge. It only becomes knowledge, however, when one is able to realise and understand the patterns and their implications. We postulate that knowledge results from the use of information created by human interpretation.

Knowledge can further be classified into tacit or explicit knowledge (Nonaka, 1991). Explicit knowledge is the kind of knowledge that can be codified in documents, such as a case study, a technical description or procedures (which comes

close to the definition of information). Tacit knowledge, on the other hand, is what resides in people's heads and comes out during action, as they make decisions or value judgements. According to Wenger et al., (2002, p.9) tacit knowledge consists of 'embodied experience – a deep understanding of complex, independent systems that enables dynamic responses to context-specific problems'. Therefore, 'Sharing this kind of knowledge requires interaction and informal learning processes such as storytelling, conversation, coaching and apprenticeship'. Although these distinctions between knowledge and information on the one hand and tacit and explicit knowledge on the other seems to overlap, the importance of these distinctions lies in the fact that only information and explicit knowledge can be exchanged through documents, while the more tacit knowledge can only be exchanged during human interaction. "Organisations need to find a balance between managing tacit and explicit knowledge, taking advantage of both the informal learning processes, as well as keeping track of it by codifying knowledge" (Van't Hof, 2003).

Knowledge management has been defined in many different ways. Rus et al. (2001) has compiled the following definition from different sources:

"Knowledge management is seen as a strategy (or practice, systematic process, set of policies, procedures and technologies) that creates, acquires, transfers, brings to the surface, consolidates, distils, promotes creation, sharing, and enhances the use of knowledge (or information, intellectual assets, intellectual capital) in order to improve organisational performance; support organisational adaptation, survival and competence; gain competitive advantage and customer commitment; improve employees' comprehension; protect intellectual assets; enhance decisions, services and products; and reflect new knowledge and insights."

Therefore, the activities of knowledge management should enable the creation, communication and application of knowledge; and they should drive the capability of creating and retaining a greater value onto the core business competencies (Tiwana, 2001; Gunnlaugsdottir, 2003).

A knowledge management methodology and tool should support all the life cycles phases of knowledge. Consolidated from MOKA (MOKA Consortium, 2001) and Kads (Wielinga, 1992) methodology, a synthetic Knowledge Life Cycle is illustrated in Figure 2. It is designed to generalise the integration of expertise in computer-aided systems.

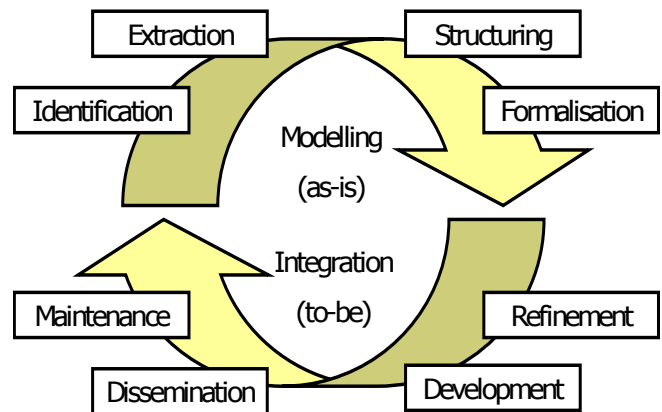
This Knowledge Life Cycle consists of the following phases:

- 1 *Identification and Extraction*: Identifying and collecting valuable knowledge from internal and external sources, as well as generating new knowledge.
- 2 *Classification, Structuring, Formalisation and Storage*: Methods of structuring and storing knowledge. Somehow the knowledge has to be classified and valued in terms of context, relevance and lifespan.

- 3 *Refinement, Development, Sharing and Dissemination*: Giving access to knowledge and distributing or transferring it.
- 4 *Diffusion*: The application and use of knowledge in processes, products and services.
- 5 *Maintenance*: Measuring the value and improving assets/KM - The knowledge has to be evaluated and improved.

In order to support the Knowledge Life Cycle, tools are required to navigate, structure, formalise and share the piece of knowledge. In the next sections, we will describe how conceptual frameworks and roadmaps are tools to support knowledge management.

Figure 2 The Knowledge Life Cycle (Candlot et al., 2005) (see online version for colours)



3.1.1 Roadmaps

Roadmaps are structures that are becoming increasingly popular mechanisms to represent project paths, life cycles and processes (Kappel, 2000; Kostoff and Schaller, 2001; Phaal et al., 2004). Various definitions have been given for roadmaps and roadmapping:

- 1 "A roadmap is a layout of paths that exist (or could exist) in some particular geographical space. It is a metaphor for planning science and technology resources" (Co-operative Technology Roadmapping, TOA, TU Delft 2003).
- 2 Definition of the European Industrial Research Management Association (EIRMA): "The generic roadmap is a time-based chart, comprising a number of layers that typically include both commercial and technological perspectives. The roadmap enables the evolution of markets, products and technologies to be explored, together with the linkages and discontinuities between the various perspectives. The roadmapping technique can be seen to draw together key themes from the technology strategy and transitions literature, by the use of its layered structure in conjunction with the dimension of time" (Phaal et al., 2004).

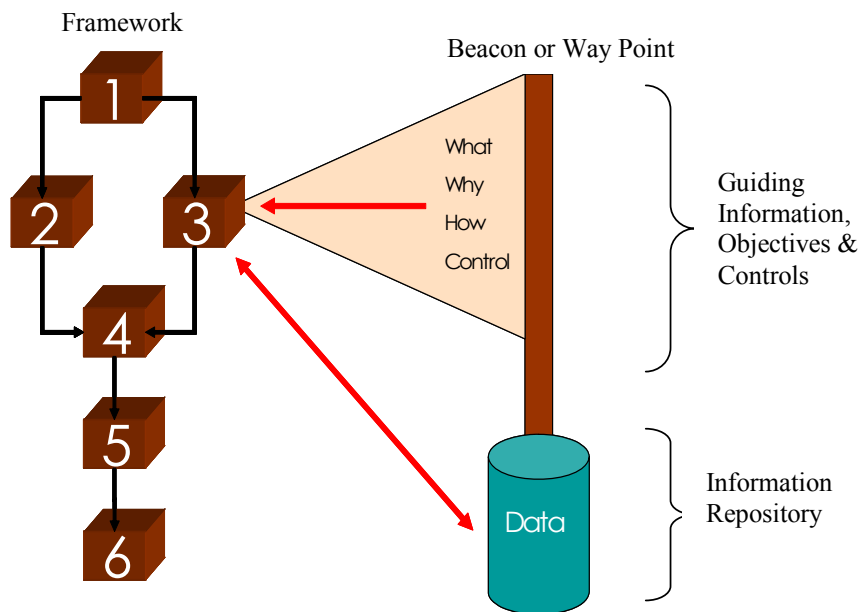
For the purpose of this paper a roadmap is defined as a layout of descriptive paths that multidisciplinary teams can use as a guiding framework for collaborative efforts towards a common goal. The roadmap consists of beacons or waypoints that describe ‘where’ to go, ‘how’ to get there in the best possible way, and the ‘what’ in terms of specific targets or goals to aim for. The beacons or way points should also have controls to ensure that the traveller reach the goals effectively and efficiently. All information collected while travelling on the roadmap path or paths should also be collected and managed to ensure that the actual trails followed can be backtracked in case he or she gets lost or to make it easier for future travellers. To summarise, a roadmap should contain the following elements (refer to Figure 3):

- 1 A structured high-level framework consisting of desired beacons or way points (‘where’).
- 2 Objectives indicating ‘what’ to aim for in order to reach a beacon or way point.
- 3 Descriptions and guiding information defining best practise methods on ‘how’ to reach the beacons or way points.

- 4 Controls in order to manage efficiency and effectiveness.
- 5 Information repository to collect information while travelling along a path.

A roadmap, therefore, provides the guiding structure that helps collaborative teams to focus endeavours within a set of project constraints, while still sustaining an environment with enough freedom for teams to innovate. Roadmaps can also be part of other roadmaps. They are all built up out of steps where one step in one roadmap can also be part of another roadmap. This means that one roadmap can have a relation with many other roadmaps, while the other roadmaps do not necessarily have to be related. This also means that information within these roadmaps can be shared and used in many other roadmaps. This network of roadmaps contains relationships between different points of information and because of these relations all information in the roadmap network is actually an ontology. This implies that there are different ways to get to the same piece of information or said otherwise, out of different perspectives. The same thing is possible with geographical roadmaps; the shortest route, the fastest route or the most cultural route. They will all take the traveller from point A to B and might use the same places or roads.

Figure 3 Roadmap with guiding structure and beacons (see online version for colours)



The beacons or way points can be organised in two ways:

- 1 Along a logical time-based progression towards specific goals or objectives (e.g. a life cycle of a project), or
- 2 In a classification structure organised according to the function, behaviour, or construction components of a specific domain (e.g. an organisational structure). In this arrangement the beacon points provide guidance for locating specific entities, instead of a time-phased journey towards a specific destination (the roadmap structure in this case, therefore, serves the purpose of a guiding structure to be used in an information repository)

Roadmaps can be used as an important tool for structuring and managing the information and explicit knowledge required for innovation. Specifically, it supports the following aspects of innovation:

- 1 *Planning for innovation:* Roadmaps help to strategically direct and plan for innovation efforts. They can be used for example to map technology developments or market changes and to setup a Master Plan for the implementation of innovation projects. Innovation is driven by a number of external and internal drivers. It is important to align a sustainable plan for execution with these drivers. Roadmapping can be extensively used for this alignment and common understanding.

- 2 *Implementing innovation*: Roadmaps provide the structure to guide the efficient implementation of innovation.
- 3 *Knowledge management*: A repository roadmap structure can be used for the management of knowledge to guide users in capturing, storing and finding information in context. It is also useful for mapping the life cycle of knowledge.
- 4 *Life cycles*: Roadmaps provide the structure to manage the life cycle of an entity such as an enterprise, product, technology, knowledge, etc.

Figure 3 shows a graphical depiction of a roadmap structure with beacons containing guiding information, objectives and controls, as well as an information repository.

Roadmaps serve as a mechanism to guide stakeholders along the path of reaching a certain goal as well as a means to collect information, in context of the journey, during the journey. Roadmaps, however, are not good mechanisms to provide one with the understanding of the terrain – in terms of entities and their relations – encountered during the journey. The next section will describe how conceptual frameworks address this gap.

3.1.2 Conceptual frameworks

Conceptual frameworks are aimed at providing stakeholders with a common understanding of how everything fits together, although they do not focus on the way to reach the goals set out in roadmaps. Conceptual frameworks can be compared to tourist guides describing the culture, vegetation, animal life, scenic sites, restaurants, etc. of the areas one are passing through during the hypothetical journey. A conceptual framework enables stakeholders to understand the different aspects of their environment and serves as a mechanism to contextualise any entity in the given environment. This improved understanding then facilitates the process of analysing the environment in order to make appropriate decisions or take the desirable actions.

Conceptual framework is defined as: “A conceptual framework is a formal way of thinking (i.e. conceptualising) about a process/system under study” (Racunas et al., 2003). For the purpose of this paper the definition was broadened by substituting the terms ‘process/system’ in the definition above for the term ‘domain’ in order to make the definition more widely applicable. Moreover, a domain is defined as: “An area of knowledge or activity characterised by a set of concepts and terminology understood by practitioners in that area” (Booch et al., 1998).

A domain may, therefore, represent a knowledge area (e.g. manufacturing), a department in an organisation (e.g. Sales and Marketing), a certain information system (e.g. an ERP system), etc. It further has a defined scope and consists out of certain components (i.e. entities) having interactions/dependencies (i.e. relations) on other components of the domain. Generally, these domain components can be modelled as entities and the various interactions/dependencies as relations between the entities of the domain resulting in a network/framework for the given domain.

For the purpose of this paper, the term Conceptual Framework (CF) will mean: ‘A formal model of a given domain, consisting out of the domain components (i.e. entities) and the relations existing among these components, used for understanding and analysing the domain in question’.

The conceptual framework, therefore, contains the generic entities, i.e. ‘things’ that are significant in the domain in question. Employees, projects, suppliers, raw material, products, parts, strategic objectives, departments, deliverables, documents, information systems, etc. are examples of typical conceptual framework entities of an organisation. In order to maximise the value embodied in a conceptual framework, and to avoid misinterpretation and misunderstandings, the syntax (i.e. structure) and semantics (i.e. meaning) used in the conceptual framework need to be clearly defined.

On a higher level, the conceptual framework can be viewed in the context of a broader management framework (Phaal et al., 2001) depicted in the diagram below (Shehabuddeen et al., 2000).

Figure 4 shows the relation between the representation of a given system (i.e. domain) and the approach in which this representation is used to achieve certain actions, and decisions concerning the system. The four dimensions illustrated in this picture may be explained as follows:

- 1 *Conceptual*: Concerned with the abstraction or understanding of a situation.
- 2 *Applied*: Concerned with concrete action or application in a practical environment.
- 3 *Static*: Concerned with the structure and position of elements within a system.
- 4 *Dynamic*: Concerned with causality and interaction between the elements of a system.

Similarly, the conceptual framework needs to include these dimensions in order to assist stakeholders to have a common understanding of the domain – in terms of structure and interaction between the entities – to facilitate the process of making sensible abstractions about the entities of the domain necessary to instigate appropriate, concrete actions to benefit the domain as a whole.

As example, Figure 5 illustrates a partial view of a conceptual framework of an insurance company in terms of the relations among a number of its key entities. This conceptual framework was built using Organon which is an ontology viewer and editor. This particular example shows that Admin Clarks and an information system called Phoenix, are required to execute the Claims process. It further shows that the Claims process is described in a document called Claims Process Definition and that another document, called Phoenix Requirements, contains the specifications of the Phoenix system. This simple view enables the user to quickly assess the entities related to the Claims process and serves as starting point for exploring the relevant conceptual framework further using appropriate software.

Figure 4 A meta-framework for management representations and approach

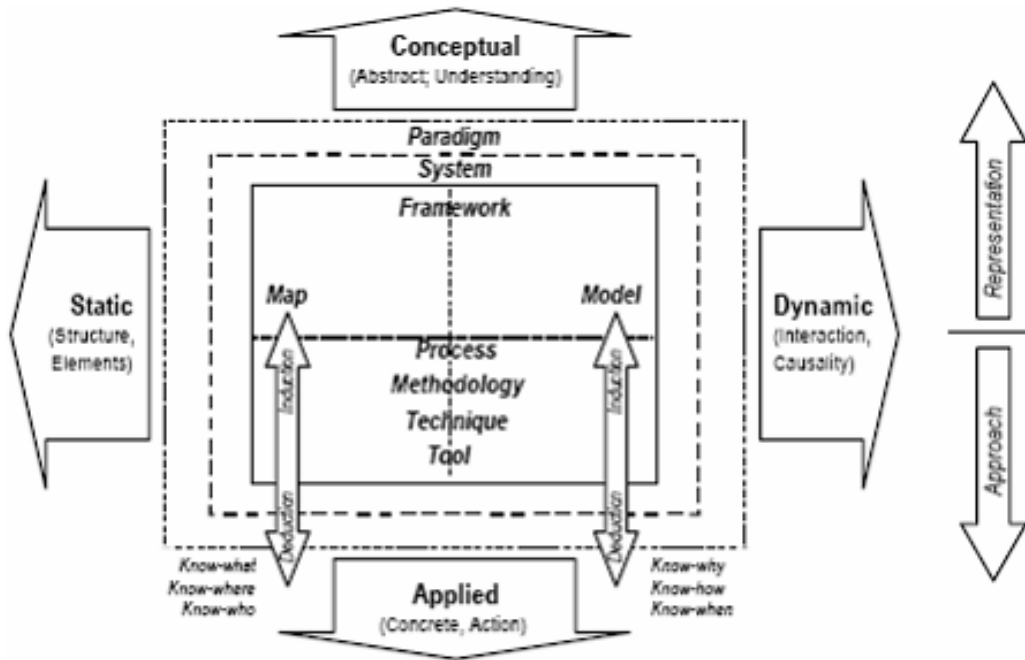
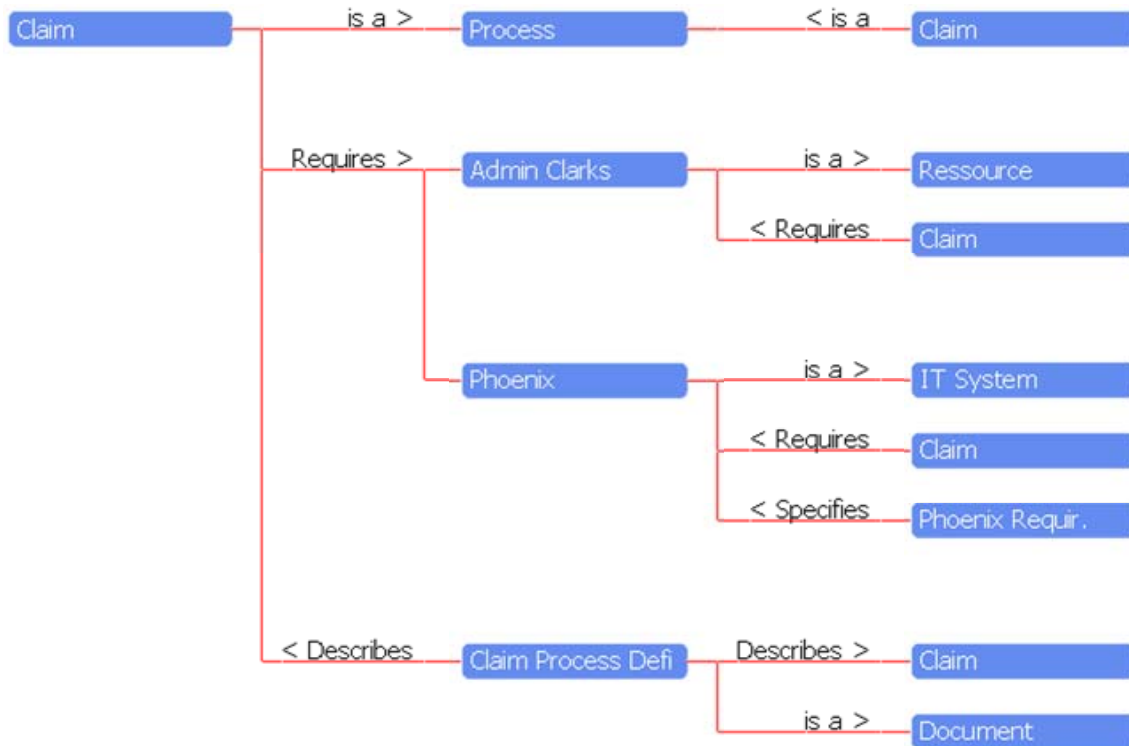


Figure 5 Example of entities and relations in the CF of a life insurance company (see online version for colours)



In summary, conceptual frameworks can be exploited as a tool for contextualising and analysing the information and explicit knowledge required for innovation. The following facets of innovation are supported by conceptual frameworks:

1 *Planning for innovation:* Conceptual frameworks may be used to understand the relations between the different drivers for innovation in order to align views of high-level stakeholders to arrive at a common understanding. Furthermore, the conceptual framework can be used to

highlight the main entities impacted by the changes implied by the planned innovation project. This supports the assessment of the planned innovation, which is required to determine the right course of action in terms of realising innovation.

2 *Implementing innovation:* Conceptual frameworks provide a mechanism to analyse the domain in question to determine the most suitable actions required to realise the efficient implementation of innovation.

- 3 *Knowledge management*: Conceptual frameworks contextualise the entities of interest in the domain where the innovation project is implemented. More specifically, it explains the relations between different terminology sets and bridges the views from different stakeholders, e.g. procurement, design, production, marketing, quality insurance, etc. It aims to provide one with the bigger picture of the landscape where the innovation project is implemented as well as with the details of the various entities present in this landscape and how they are related.
- 4 *Life cycles*: Conceptual frameworks give the interdependencies or relations between the different life cycles of interest in the domain in question, e.g. enterprise, product, technology and Knowledge Life Cycles.

3.2 *The relationship between the knowledge and innovation life cycles*

Park and Kim (2005) notes that the relation between Knowledge Management (KM) and Research and Development (R&D) management is intrinsically close, because R&D processes can primarily be seen as KM processes, transforming information on technological advancements and market demands into the knowledge needed for new product concepts and process designs. Interestingly and even surprisingly, however, the link between KM and R&D management has been virtually inexistent. They conclude that, no matter how large the database is, how fast the engine is, or how exquisite the portal is, the KM system is futile unless it contributes to the creation of lucrative innovations and the development of new products.

Pérez-Bustamante (1999) explains different types of innovation as a flux of knowledge: defensive innovations take into account information about the competitive situation and the market demand, while offensive innovations exploit information about scientific and technical advances in order to reach a favourable position in the market. Radical innovations are the product of putting together unlikely bits of information in an irregular, serendipitous process which is not encouraged by bureaucratic and non-agile organisations. Agility and speed to innovate in response to the environment may arise from: commitment to activities that create new knowledge bases, deployment of incremental innovations, exploitation of corporate intelligence, adoption of a horizontal management style that avoids unnecessary communication layers with management, and achieving a full integration and dissemination of knowledge within the organisation while maintaining its flexibility.

Swan et al. (1999) concluded that KM initiatives that encourage active networking are key to interactive innovation processes, but warns that an over-emphasis on building IT-based network links may ironically undermine rather than increase this.

There is thus consensus that successful and sustainable innovation is dependent on the ability of innovators to use knowledge management tools and techniques to:

- 1 Analyse market needs, trends and opportunities,
- 2 Capture the outputs of innovation projects to preserve 'corporate memory' for analysis and future use,
- 3 Re-use the outputs from previous projects or other groups, to accelerate the current innovation efforts with the co-operative knowledge captured before, and
- 4 Link innovation project members together and collaborate with other groups so as to expand the participating community, therefore, expanding the ability to learn from others and innovate faster.

Both innovation and knowledge have specific, but related life cycles. The authors' view of the Innovation Life Cycle is described as part of the proposed methodology in Section 3.1. The Knowledge Life Cycle consists of the following phases:

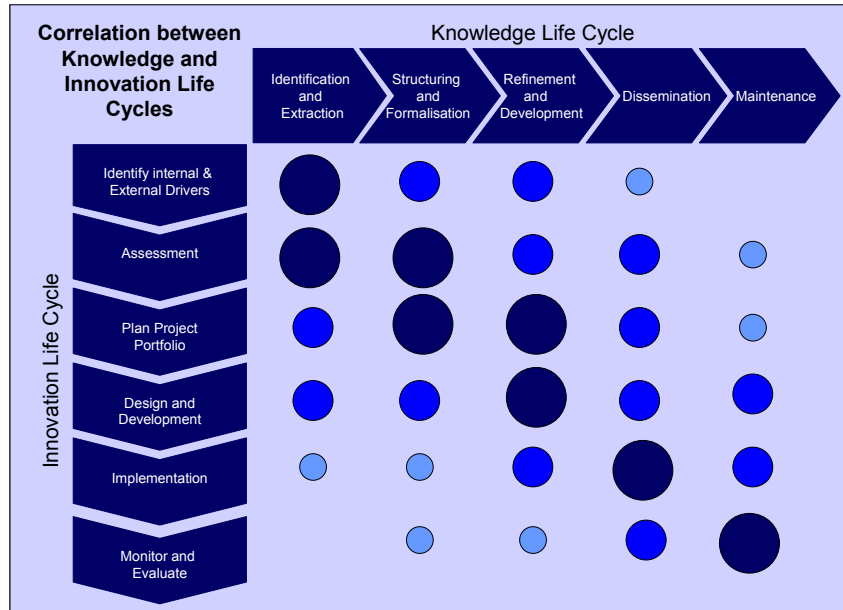
- 1 *Identification and extraction*: Knowledge is identified and extracted from other sources.
- 2 *Structuring and formalisation*: Knowledge is structured and formalised in the selected knowledge management tools.
- 3 *Refinement and development*: Knowledge is analysed, refined and further developed.
- 4 *Dissemination*: Distribution of applicable knowledge to people that requires it.
- 5 *Maintenance*: Maintaining the knowledge, to ensure it remains up to date and applicable to the domain.

An innovation project will typically incorporate more than one Knowledge Life Cycle. The authors argue that there is actually a Knowledge Life Cycle 'spiral' that happens during the execution of an innovation project, whereby the knowledge is repeatedly captured, refined, disseminated and maintained, depending on the progress and success of each phase of the innovation project, and the knowledge sub-domains under investigation during the project phase. Figure 6 illustrates the correlation between the Knowledge and Innovation Life Cycles (large circles in this Figure depict strong, positive correlation between the phases of the two life cycles, whereas smaller circles present lower correlation levels between phases). For example, during the 'Identify Internal and External Drivers' phase of the Innovation Life Cycle, most of the Knowledge Life Cycle is addressed, but most of the energy is spent on the 'Identification and Extraction' phase, and nearly nothing on the 'Maintenance' phase.

However, this illustrates that throughout the Innovation Life Cycle, there is a significant dependence on knowledge management.

To summarise, innovation feeds on the abundant availability of reliable and applicable knowledge, and the ability to access, analyse, synthesise and share this knowledge. In turn, the outputs of innovation projects contribute to the pool of knowledge, thereby incubating opportunities for future innovation.

Figure 6 The correlation between knowledge and innovation life cycles (see online version for colours)



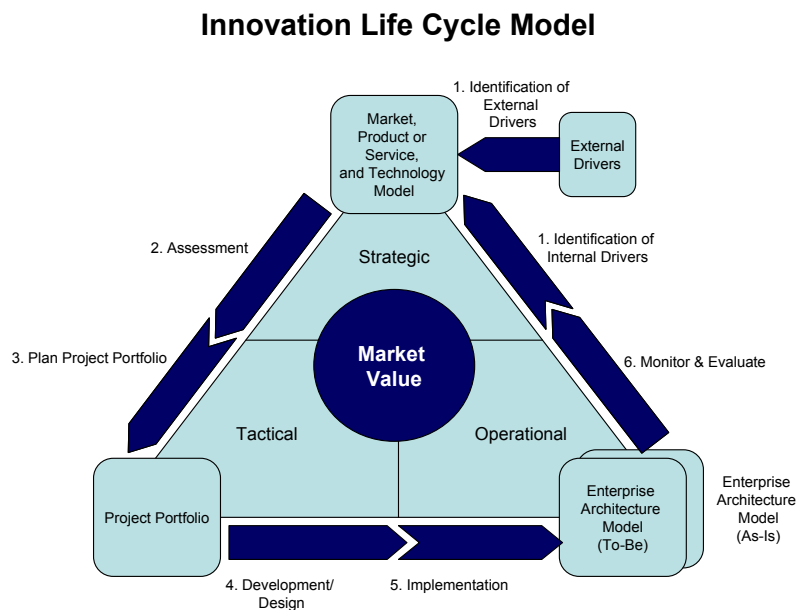
4 Roadmapping and conceptual framework-based methodology for supporting innovation management

The previous sections highlighted the importance of innovation for the competitiveness of a business. In order to have successful innovations, enterprises should learn to successfully manage the complete process of innovation. Since innovation within in an enterprise goes hand in hand with the adoption or development, and diffusion of new knowledge, knowledge management is a very important supporting function for innovation management. The concepts of roadmaps and conceptual frameworks were also explained in previous sections. This section describes the suggested methodology framework for using these knowledge management tools as support for innovation management.

4.1 Proposed methodology

The proposed methodology (framework) describes how the knowledge management tools (conceptual frameworks and roadmaps) support the management of innovation along its life cycle. This methodology focuses on the internal development and market diffusion of innovative services, products, or business models by a commercial enterprise. Similarly it also focuses on the successful and/or innovative exploitation of externally developed innovations (which could be either new or old technology) within an enterprise. This framework is depicted in Figure 7. It shows the proposed general Innovation Life Cycle model that serves as the framework for the proposed methodology. At the core of this innovation model lays market value. The aim of the whole innovation effort should be to increase the market value of the enterprise.

Figure 7 Innovation life cycle model (see online version for colours)

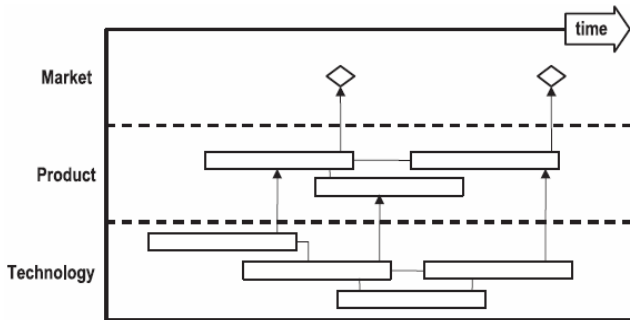


The three planning terms – strategic, tactical and operational planning – distinguish the different types of projects within the enterprise. We assume that innovation should be driven using a top down approach by planning and developing innovation projects on a strategic and tactical level, and then deploying and monitoring/evaluation on an operational level. The methodology is described according to the following steps of the proposed Innovation Life Cycle:

- 1 *Identification of internal and external innovation drivers:* The innovation process can be initiated by various internal and/or external drivers. If innovation is to help a business grow and improve its competitiveness, it is important to plan the innovation carefully. Though some innovation drivers may change unpredictably, an organisation requires a strategic vision of how it wants the business to develop. This will help to focus its innovative efforts on the most important areas. Innovation has to be a product of an ongoing well-structured process that captures and evaluates innovation regularly. It should not wait for the innovation to happen arbitrarily, but should proactively plan for regular periodical meetings that will address innovation, market trends, competitive landscape, new technology availability and changes in customer preferences in order to create an environment conducive to innovative thinking. Roadmaps can serve as a very useful tool in this stage of the innovation process to strategically direct and coordinate team efforts for innovation. Its main application in this stage is to map current and future technology developments or market changes. Roadmapping provides a focus for scanning the environment and a means of tracking the performance of individual, including potentially disruptive, technologies. It represents a powerful technique for supporting innovation planning, especially for exploring and communicating the dynamic linkages between technological resources, organisational objectives and the changing environment. The final result of this stage of the innovation process should, therefore, be roadmaps that capture and contextualise knowledge about the evolution of markets, products and technologies to be explored, together with the linkages and discontinuities between the various perspectives (refer to Figure 8).
- 2 *Assessment:* This stage of the innovation process involves assessing the impact of the identified potential innovation drivers from the previous stage. The next step is to determine what the impact will be of such changes on the current enterprise. This will identify and clarify potential innovation projects. Due to complex interdependencies inherent in the systems of interacting parts of the enterprise and its projects, models are required to gain a better understanding of the As-Is state of the enterprise. This will assist to determine which improvements are required to achieve the To-Be state of the enterprise, and what will be the impacts on the organisation. At present, only a fraction of the enterprise domain is covered by available modelling conventions and tools. Conceptual frameworks are proposed as a way of modelling enterprise concepts or entities within the whole enterprise domain, along with their relations. This will improve understanding of the domain, and also helps with the identification and evaluation of potential innovation projects.
- 3 *Planning the project portfolio:* This stage of the innovation process involves the identification and prioritisation of projects that, once implemented, will result in an organisation moving from a current (As-Is) state to a future (To-Be) state. Transition paths are identified and evaluated. Once these transition paths are combined, with clearly defined objectives and allocated resources and budgets, a Master Plan roadmap is used to specify and select projects for deploying the transition paths. Once selected and prioritised, the different projects are then arranged in a portfolio of innovation projects. The basic function of the Master Plan roadmap is to define and build the infrastructure (the ‘what’) and the architecture (the ‘how’) for the project or projects that needs to be initiated to drive the enterprise through the required change. The outcome of the Master Plan is a prioritised list of innovation projects (which defines the innovation project portfolio). By ordering the implementation of a variety of innovation projects it ensures that the required resources and knowledge are available during each project and that there is integration between different projects.
- 4 *Development/design:* The Master Plan roadmap in the previous stage defined different innovation projects to be implemented. These innovation projects were planned on a tactical level. When these innovation projects are finally launched for implementation, the first stage of the project involves a detailed design or development of the proposed innovation. Different design teams are normally involved in such an innovation project, and they all need to be guided throughout the design phase of the project (in terms of their specific design objectives as well as providing them with best practise experience from previous designs). Roadmaps, constructed according to the required activities of the different design teams, provide the structure or framework to guide the design activities of the different teams by providing them with best practise knowledge and information in context with where it is required. The design roadmap also provides the structure for capturing and storing all design information and explicit knowledge developed during the design process. This is important for ensuring a successful implementation of the innovation and the transfer of the innovation to operations.
- 5 *Implementation:* The implementation phase entails the roll-out of the completed designed or developed innovation within the enterprise. It is, therefore, the handover from design to operations and involves the actual use or operation of the new innovation within the enterprise. Roadmaps are again useful to manage the handover of the newly developed knowledge to the operational side of the enterprise. At this stage the conceptual framework model of the enterprise should be updated to reflect the new enterprise architecture. This conceptual framework model of the new enterprise can then be used in the next innovation cycle.

6 *Monitor and evaluate*: This is the optimisation phase of the new implemented innovation. Once in operation the performance of the new innovation can be monitored and adjustments made to improve the innovation. Knowledge obtained from the operation of the innovation should be collected and stored in both a roadmap structure as well as the conceptual framework in order to guide future improvements or re-designs.

Figure 8 Schematic technology roadmap, showing how technology can be aligned to product and service developments, business strategy and market opportunities

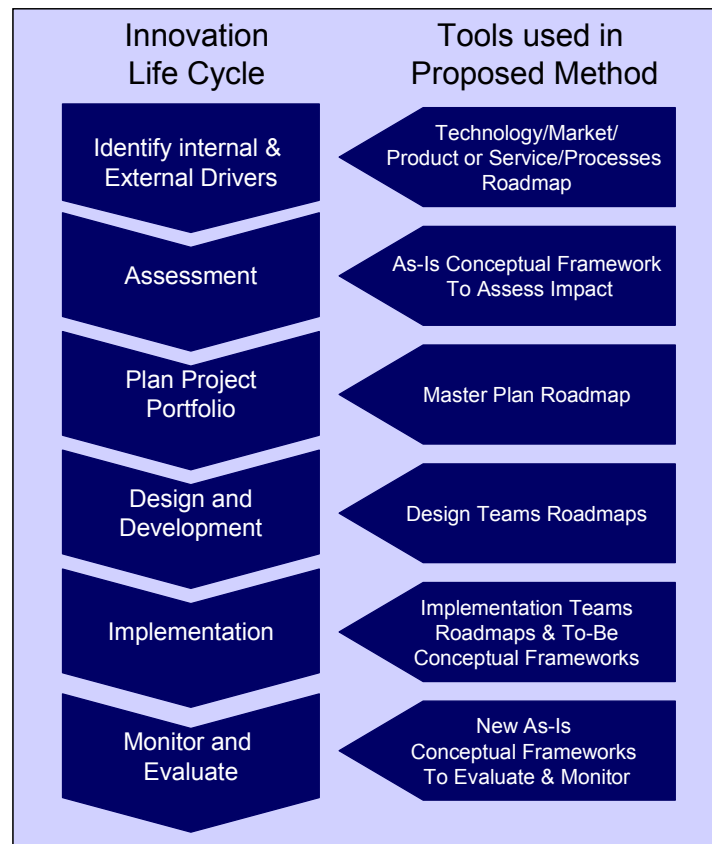


In order to support the use of knowledge in the Innovation Life Cycle, a number of tools can be used. We propose

using roadmapping and conceptual frameworks throughout this life cycle as shown in Figure 9:

- 1 During the analysis of the drivers and the setup of the Market, Product or Service and Technology models, roadmapping can be used to guide the users, and capture the knowledge within context.
- 2 In order to assess the current situation (As-Is), conceptual frameworks can be best used to understand the inter-relations within the current situation.
- 3 When planning the Project Plan portfolio, a Master Plan Roadmap can again be used to create the overall structure and direction.
- 4 As each subproject is planned and executed in the Design and Development phases, several corresponding roadmaps can be used by each team.
- 5 During implementation (roll-out) roadmaps as well as conceptual frameworks can again be used to understand the impact of the roll-out schedule, and how to best sequence the roll-out.
- 6 And, eventually, when the final service or project needs to be maintained, a new updated conceptual framework, that now models the new (To-Be) situation, can be used for support.

Figure 9 Tools to be used in the proposed methodology (see online version for colours)



4.2 Knowledge maturity for innovation

As illustrated in the previous section, innovation actually involves the identification, development and diffusion of new knowledge to an enterprise. In order to effectively use knowledge for the management of innovation, an enterprise should achieve a certain level of maturity with regards to the management of knowledge. The goal is to ensure that the innovation process can be accelerated, is repeatable and sustainable.

In order to ensure efficient innovation management, two aspects have to be measured. On the one hand, it is important to determine the value added by the innovation so as to evaluate the impact of knowledge gained and innovation achieved, and on the other hand, the organisational maturity to reflect the ability to change and evolve quickly to reach the goals.

The value could be directly linked to the innovation project, but could also be more widely distributed within the global enterprise. Value indicators can be for the product (design or manufacturing), the time to delivery reduction, the technology gap with competitors, or the manufacturing rate. As presented in the introduction, the enterprise value no longer only applies to the physical aspects, but shifts to intellectual capital and knowledge assets that are more abstract and are, therefore, more difficult to define, model and evaluate. The overall knowledge can be measured by quantifying the conceptual framework's network size. But does the network's size reflect the real knowledge relevancy? The efficiency of the knowledge application can be illustrated within the roadmapping mechanism. Still, the number of times a given document has been accessed, reflects a value of interest and relevance for the users within the context of the roadmap, but may miss the global value that reflects the completeness, the relevancy and the efficiency of this piece of knowledge given the user's specific requirements.

A good criterion to assess the value of knowledge is an indicator obtained from the user showing whether the knowledge object addressed his specific problem or not. From the innovation point of view, a value criterion could be derived from the number of new innovations created, and may also be linked with the number of new knowledge objects created. Another criterion may be a measurement of the impact that knowledge (new or already existing) had on speeding up innovation.

All of the mechanisms proposed for the evaluation of innovation and knowledge capability basically rely on measuring maturity. This measurement should serve as an indicator of the ability of the enterprise to evolve. By positioning an enterprise in the maturity domain, it becomes possible to then indicate how such enterprise may evolve within the innovation maturity life cycle. Maturity levels are thus part of the innovation value indicator.

For knowledge management maturity, four levels are proposed:

1 *LEVEL 1 – Product and process knowledge:* It describes the core competencies of the company and is constituted of cumulated experiences of experts. Best practices may, however, not be shared and the global process may not be

formalised and optimised. This level is characterised by a high proportion of tacit knowledge. These experts may decide to formalise their way of working and decide to introduce rational operational decision process. This then leads to the second maturity level.

- 2 *LEVEL 2 – Improvement knowledge:* This is the explicit enterprise knowledge that resides formally in company documents and procedures. Experts build maps of the products and processes deployed and refine them for a better efficiency to obtain a more standard, but flexible knowledge structure. To drive this improvement properly, the concerned stakeholders may feel the need to formalise knowledge to a higher level, considering their way of working together. The optimised enterprise knowledge can subsequently be enriched with tactical management knowledge.
- 3 *LEVEL 3 – Collaboration knowledge:* The best practices linking fields and experts in Level 2 are now formalised. Previously, stakeholders introduced enhancements based on a static knowledge mapping representation. In this level, the knowledge mapping is now systematised creating a dynamic representation that tactically drives the operational choices. This dynamic mapping is usually generalised or obtained from a higher level of abstraction corresponding to more domain-independent strategic knowledge.
- 4 *LEVEL 4 – Generalisation knowledge:* When the Level 3 methodology is mature enough, it can be formalised and re-used by other teams or other domains in the form of a standard. This bottom-up approach may be compared to a top-down strategic decision to use standards in project management (PMBOK), quality (ISO 9001) or on environmental issues (ISO 14001) for example.

The challenge for an enterprise is to position itself on this maturity scale, which requires a thorough understanding of the terms innovation and related knowledge supply chain.

The possible expansion of this knowledge maturity classification mechanism to also include innovation maturity is currently being researched by the two research teams involved in writing this paper. By having the ability to assess maturity of their organisations, managers can identify weak areas and determine a road ahead as to best address those weaknesses.

5 Example application in the financial services domain

In this Section, two example applications of the roadmapping and conceptual framework tools are briefly discussed. In both applications, only parts of the proposed methodology were used. The complete methodology presented in this paper was in fact constructed based on the experiences from the two example applications. The applications described here, therefore, serve to illustrate the advantages of using roadmaps and conceptual frameworks for managing innovation, as well as highlighting the problems experienced by not using these tools.

5.1 Roadmapping example

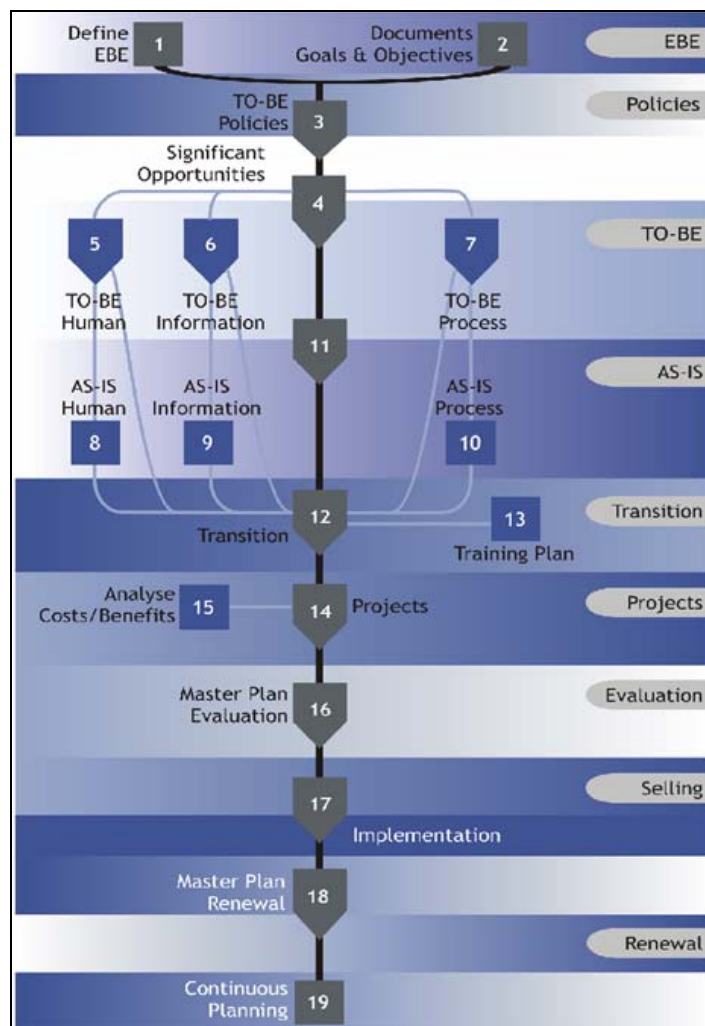
This example explains the use of roadmaps to plan and implement an innovation project within a large insurance company. This particular project had three year duration and commenced in the last quarter of 2003. The high costs and long policy issuance times for new business administration have forced the company to look for innovative ways to improve their new business process (the process for capturing new policies on their systems and issue the policies). A complete Innovation Life Cycle process has been executed during this innovation project.

5.1.1 Identification, assessment and planning of the innovation project

A Master Plan roadmap was constructed and used to guide the whole planning process of the innovation project. This Master Plan Roadmap is illustrated in Figure 10. An innovation management software platform called EDEN™ (developed by Indutech (Pty) Ltd) was used to build the roadmap and manage the knowledge and information required for and created during the execution of the innovation project.

The first phase in the innovation project was to identify possible innovative solutions for improving the insurance company’s new business process. In order to do this, it was first required to get a good understanding of the current enterprise processes, costs and strategies. Due to the lack of explicit knowledge on the processes and costs, a lot of time was spent in extracting the required knowledge from experts via interviews. Some of the knowledge was captured in process diagrams and documents, but these were incomplete and scattered around in different departments. Knowledge collected during this first phase was captured in documents and stored within the information repository of the Master Plan roadmap using the EDEN™ software environment. At the same time, information on new technologies for the insurance industry was collected by scanning the external environment. This information was also captured in the Master Plan roadmap. After a thorough understanding of the current enterprise and the problem areas was obtained (the As-Is scenario), possible innovative solutions were identified for implementation. Specifically, tele-underwriting was identified as a new technology that could significantly reduce the costs and issuance times for the new business process.

Figure 10 Master plan for insurance innovation project (see online version for colours)



The next step was to assess the impact of this new technology on the business and conceptually design and define the To-Be enterprise architecture, should this technology be implemented. Projects for implementing the new technology also had to be defined. At the end of this process a complete Master Plan Roadmap was obtained that identified the specific projects that need to be executed in order to implement the new tele-underwriting process. This Master Plan roadmap contained most of the information and knowledge the design teams required to do the detail design of the new tele-underwriting policy capturing process. This significantly speeded up the design process.

Due to the lack of an overall model of the enterprise and the fact that current knowledge about the enterprise operation was not explicitly captured and managed, a lot of time was spent initially trying to understand the current enterprise. Should a conceptual framework model of the current enterprise had been available at the start of the project, the time required for planning the innovation project could have been greatly reduced.

5.1.2 Design and implementation

This phase involved the detailed design of the tele-underwriting process (processes, information systems, etc.), as well as the implementation (roll-out and training of personnel). Again roadmaps were constructed to guide the project teams by providing them the relevant information and knowledge they require to execute their tasks (in context of where it is required). All knowledge developed during the design and implementation process was also captured for future use. Figure 11 illustrates the roadmap structures used to guide the different design and implementation teams. EDEN™,

a collaborative innovation management software platform, enabled integration and knowledge sharing between the different roadmaps.

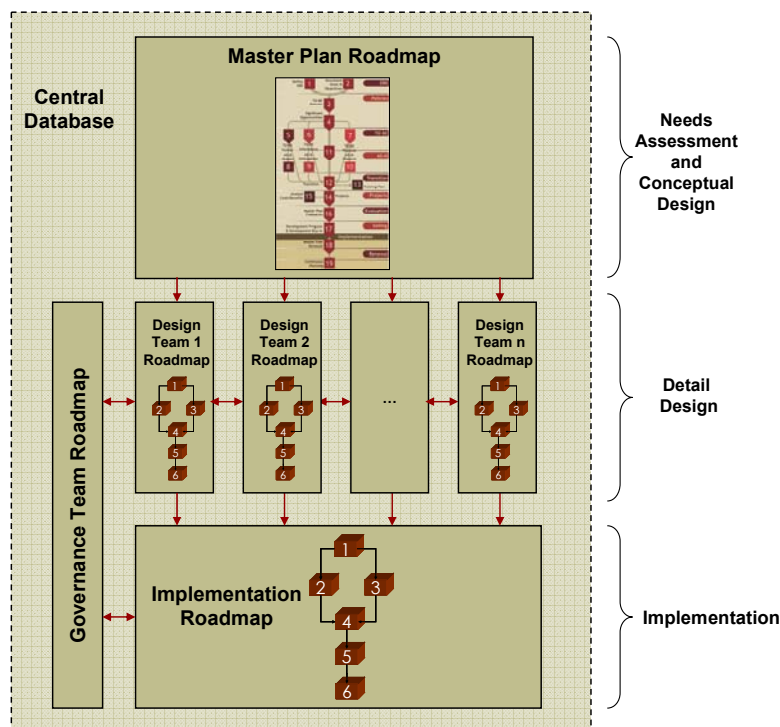
Benefits and gaps will be analysed in section 4.3.

5.2 Conceptual framework example

The second example illustrates how conceptual frameworks were used to plan an innovation project within another insurance company. This project was executed over a 9 month period starting in April 2004. The high degree of complexity contained in a contractual document (i.e. the Master Contract) – a sizable agreement between the client (i.e. the policyholder) and the insurance company (i.e. the insurer) – resulted in the situation where employees, clients and intermediaries found it extremely difficult to interpret, understand and apply the contents of this contract. The complexity of this contract further made it extremely difficult to update the contract with changes necessitated by changes to the product offering of the relevant insurance company. The contract further contained possible legal loopholes due to inconsistent updating in the past as well as ambiguous terminology and clauses, creating a possible legal risk to the insurer. The brief for this project was firstly to analyse and suggest ways to simplify this Master Contract (MC) (i.e. Phase 1 of the project) and subsequently looking at ways to reduce the complexity of the business as a whole (i.e. Phase 2 of the project). Reviewing the insurance company’s benefit structure was suggested as a starting point for reducing the complexity of the business.

Everything, except the implementation part of the Innovation Life Cycle process has been executed during this particular innovation project as the client implemented the innovation using internal resources.

Figure 11 Roadmap structure for design and implementation teams (see online version for colours)



5.2.1 Identification, assessment and planning of the innovation project

- (a) *Phase 1:* The initial project activities revolved around analysing the Master Contract and extracting key entities from its contents (e.g. types of policyholders, types of disability states, names of related documents, types of claims, types of benefits, etc.) and capturing these in a conceptual framework. All occurrences of these entities, in the content of the contract, were further linked to the entities in question. Subsequently, relations between the different entities were established by interpreting the content of the contract as well as by interviewing experts. The conceptual framework was then updated with these relations, resulting in a network of entities with their respective interdependencies, which was then used as a mechanism to get a shared understanding about the current contract as well as a means of analysing its content and structure.
- (b) *Phase 2:* After the suitable changes to the contract and relating entities were proposed, the next step was to investigate the possibilities around simplifying the business as a whole. This implied broadening the scope of the conceptual framework to include the entire organisation with the goal to understand the current situation to be able to identify suitable areas for simplification. Several documents were studied and experts interviewed to understand the value chain of the insurer. The conceptual framework was expanded throughout this process with information about, and relations between, significant stakeholders, processes, business rules, products, key documents, IT systems, benefits, etc. The expanded conceptual framework served as a model of the current organisation and was used to analyse the organisation for possible simplification areas after a common understanding was reached among the team members.

In summary, the conceptual framework was used to understand the domain in which the relevant innovation project was to be executed in.

5.2.2 Design and implementation

- (a) *Phase 1:* Once the significant parts of the Master Contract and its immediate surroundings were modelled in the conceptual framework, it was used to:
- 1 Identify duplicate terms for the same entity (e.g. accident policyholder and accident member) as candidates for simplification to reduce the complexity of the contract and increase the ease of understanding.
 - 2 Estimate the impact of removing problematic contract clauses (identified by experts as well as modellers) from the contract in order to decrease ambiguity and complexity. More specifically, the conceptual framework enabled one to focus on a given contractual clause and to see all other entities that relates to it (e.g. other clauses, benefits, claim requirements, etc.). This made the task of determining what other parts of the contract to consider, due to a change in a given clause of the contract, fairly easy.

- 3 Identify entities falling outside the scope of the contract, which might be impacted by any changes to the contract, that need to be investigated further (e.g. other documents, products, stakeholders, processes, business rules), etc.
 - 4 Identify a more suitable structure for the contract by grouping all closely related clauses together in order to minimise the number of cross-references as a means of increasing the ease interpreting the contents of the contract. This proposed change would not have been apparent without the aid of a conceptual framework.
- (b) *Phase 2:* Once the conceptual framework has been extended to include all significant parts of the entire organisation, it was used to:
- 1 Analyse the complexities of the organisation and identifying the most feasible improvement opportunity.
 - 2 Estimating and agreeing on the impact of the changes proposed on the organisation as a whole.

In summary, the conceptual framework was used to highlight and specify the relevant changes required to reach the project goals.

6 Synthesis

In the first example, several benefits were observed as result of using roadmaps as knowledge management tools to guide the innovation process:

- 1 Information and knowledge can easily be shared and used for collaboration, since it is captured within context in the roadmap structure. This improves both the time and effectiveness of the development and implementation of innovation.
- 2 Knowledge transfer between different teams in the life cycle phases of the innovation project is quicker and more effective.
- 3 Individual knowledge becomes group memory.
- 4 New team members can quickly be brought up to speed. All information on the project, additional information as well as information generated during the project, is stored in context by storing the information in the relevant step within the roadmap. The new member can, therefore, immediately see the whole outline of the project as well as all knowledge in context currently possessed in the project.
- 5 Development and implementation knowledge is captured for re-use in future improvement or innovation projects. This speeds up the initiation of future projects.

However, a difficulty experienced was the effort required to analyse and synthesise a vast amount of multidisciplinary knowledge captured in the roadmaps. Since conceptual framework modelling tools were not available at the start of the

project, it was difficult to fully understand the complexity and interrelationships of all aspects of the organisation and processes studied. If this had been available, it could have been used in the planning and initiation phases to increase the level of understanding and to speed up the identification and planning of specific innovation projects.

The most significant benefits using a conceptual framework that became apparent during the execution of the second project example are:

- 1 A conceptual framework serves as a mechanism to understand and share the intricate relations between the disparate entities of an entire organisation (e.g. understand relationships between different processes, IT systems, business rules and paragraphs of the complex contract document). Reaching a common understanding among the team members about the domain in which the innovation project question is to be executed is thus simplified using a conceptual framework.
- 2 It facilitates the process of analysing the domain in order to identify possible innovation opportunities.
- 3 Assessing the impact of proposed changes on the rest of the domain is simplified when using a conceptual framework.
- 4 The conceptual framework can incorporate views from different stakeholders leading to better buy-in into the innovation project.

However, during the execution of the second project example, the following noteworthy shortcomings and problems were identified:

- 1 The conceptual framework was not linked to a formal change process (i.e. the roadmapping process), making it difficult to track changes and the progress made.
- 2 The magnitude of user intervention required to create the relevant conceptual framework was significant.
- 3 It was difficult to validate the correctness of the resulting conceptual framework.
- 4 It may have been useful to have a time dimension to indicate the growth in the conceptual framework throughout the execution of the project.
- 5 It was difficult to identify the right level of detail for the conceptual framework.

These examples showed us that conceptual frameworks enable users to have a better understanding of the domain or environment, thereby making it easier to identify new opportunities for innovation. The conceptual framework also helps to identify and specify the roadmaps required to guide the innovation projects. Roadmaps guide the development and diffusion of the new knowledge and ensure that the knowledge is captured within context. It then helps to speed up future innovation projects having a structured and contextual access to the knowledge gained in the current innovation project.

7 Conclusion

The level of maturity of knowledge management tools has increased significantly in the past decade. While the tools previously required external expertise to help build and maintain a specific knowledge domain, it can now be built and maintained more dynamically. This is made possible by the development of new collaboration tools.

Roadmaps contribute by creating a common reference for project objectives. But users are still responsible for ensuring that the combination of knowledge objects captured is an acceptable quality. It is often not simple to assess and evaluate the vast amount of knowledge captured. Another tool is thus required to deal with this complexity. Conceptual frameworks constitute a navigable virtual network that helps to identify the possible relevant connections in the real environment, thereby making the vast amount of knowledge more accessible to the knowledge analyst within the context of his selected research domain, and in some cases helping to identify solutions for an innovation problem.

The combination of these two tools expands the feasibility and usability of a global and integrated knowledge network that would increase the innovative synergies in and between organisations. The different steps encountered by this evolution highlight an increasing level of management maturity. The modelling of domain expertise and project expertise, combined with the latest advances in informatics (processing power, storage and connectivity) opens opportunities to achieve a more advanced maturity level: an integrated network of organisations willing to collaborate by positioning their systems, processes and people in such a way as to allow for the transfer of information and knowledge between the organisations. With this, information and knowledge are automatically maintained by the natural activities of its users, while the information system enables useful access to relevant knowledge, thus enabling efficient collaboration and innovation.

Future research should explore how knowledge within integrated knowledge networks can be managed across the entities within the network in order to increase innovation levels. The use of roadmaps and conceptual frameworks should form the basis of this research. The application of conceptual frameworks is still immature, and research should be conducted on how best to construct, implement and maintain such a framework.

In order to successfully measure the value and ability of organisations within an integrated knowledge network to perform innovation projects, research should be conducted in measuring the maturity of organisations to execute innovation projects, and to determine the value of such innovation early on.

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Linking design and manufacturing domains via web-based and enterprise integration technologies

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Abstract: The manufacturing industry faces many challenges such as reducing time-to-market and cutting costs. In order to meet these increasing demands, effective methods are need to support the early product development stages by bridging the gap of communicating early design ideas and the evaluation of manufacturing performance. This paper introduces methods of linking design and manufacturing domains using disparate technologies. The combined technologies include knowledge management supporting for product lifecycle management systems, Enterprise Resource Planning (ERP) systems, aggregate process planning systems, workflow management and data exchange formats. A case study has been used to demonstrate the use of these technologies, illustrated by adding manufacturing knowledge to generate alternative early process plan which are in turn used by an ERP system to obtain and optimise a rough-cut capacity plan.

Keywords: PLM; product lifecycle management; ERP; enterprise resource planning; product development; conceptual design; knowledge management; enterprise integration.

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1 Introduction

One of the key industrial problems for modern manufacturers is the lack of collaboration during the early stages of product development. This problem is usually due to the following:

- 1 Lack of a technique for the rapid translation of early design ideas into an analysable form and
- 2 Lack of meaningful manufacturing knowledge in the feedback evaluation process

The industrial impact of the above problem is felt in many areas, such as vital decision-making especially in the areas of product configuration and the responsiveness to changing markets and meeting customer requirements such as *engineered-to-order*. Therefore, it is important to interact with the customer to meet product definition during the earliest concept stage of product development. Hence, it is imperative that the Original Equipment Manufacturers (OEM), suppliers, vendors and customers can interact effectively and generate a conceptual design that is manufacturable and cost-effective. The way to achieve this is by effective communication within the enterprise from the product design team and manufacturing operation.

With the advances in information and web-based technologies over the last decade, there is a shift of research towards focus on product development. Recently, a number of research projects have been undertaken to support collaborative and distributed solutions from the perspective of Computer-Aided Design (CAD), Product Lifecycle Management (PLM), workflow management, knowledge management and web-based technologies. The key results of these are summarised as follows.

Xiao et al. (2001) developed a Web-based Distributed Production Realization (Web-DPR) system as an infrastructure to support collaborative design and manufacturing. Based on the Java Remote Method Invocation (RMI) mechanism, agents and an event-based mechanism, the functional modules of the systems can be linked and co-ordinated effectively. However, the application is not specifically designed for conceptual design or for passing data on to process planning applications. Similarly, Qiang et al. (2001), developed a collaborative product design support environment based on the internet. The key aspect of that research is allow product designers to exchange and share product data and communicate with team members to modify geometry data on particular aspects of the design, and maintain operations consistency in all the distributed cooperative sites on a wide variety of platforms. A limitation of this approach is that the macro operations can only be replayed on workstations using the same CAD software. Similarly, Xie and Salvendy (2003) developed a mechanism to co-ordinate remote members in the process of a

collaborative project. Workers are able to actively obtain the constant feedback of the status and activities of members contributing to the whole set of collaborative tasks. For example, information about who the collaborators are, where they are now and what they are doing. The authors have noted the shortcomings of this prototype system being no version control or other security features. There are some further other disadvantages relevant to real-world application such as the inability to share data with other CAD users.

To address the above limitations, Xu and Liu (2003) developed an architecture utilising a web-enabled Product Data Management (PDM) system in a collaborative design environment. The system was implemented using Microsoft Visual Basic and runs in the Microsoft Windows environment and the internet to allow users on a wide variety of platforms to access the product data. The research, however, was focused on the detail stage of the design. The authors have noted that the implementation of the system is partial and further research is needed for transforming geometry schema into the object-oriented schema. Visual Basic executables rely upon run time libraries which need to be stored on the client machine which makes it inflexible.

Li et al. (2004a) developed a client/server framework to enable a dispersed team to accomplish a feature-based design task collaboratively. In this research, the establishment of the distributed design environment is based on RMI. The process of designing a part collaboratively in the environment is centrally server-based. The collaborative server can create and manage dynamic sessions which can be accessed by clients to provide a workspace to carry out collaborative design activities. Designers participating in the same session can share the same design model. The authors have noted that there are still some technical problems to be addressed. Firstly, the current information management on the server is a file system-based which can be replaced by a database system. Another issue is that the system lacked detailed visualisation information of mechanical parts in order to support web-based collaboration. However, Li et al. (2004b) have also developed an internet-enabled system based on Java, RMI and web technologies to support collaborative and concurrent engineering design by integrating three functional modules, namely co-design, web-based visualisation and manufacturing analysis. In the co-design module, designers are equipped with co-modelling and co-modification facilities to carry out a design task collaboratively. The web-based visualisation module provides a portal for users to view and analyse a design part conveniently. Manufacturing analysis module can be invoked by users to evaluate and optimise the manufacturing costs and the manufacturability of a design part. This system can be used for a geographically distributed design team to organise a 3D collaborative and concurrent engineering design.

The applications of workflow and knowledge management have been used to support a collaborative product development, for example, the most recent research are Madhusudan (2005) and Rodriguez and Al-Ashaab (2005). Madhusudan (2005) developed an Agent-based Process Coordination (APC) framework for distributed design process management. The approach is to embed autonomous agents in a workflow-based distributed systems infrastructure. The framework utilises a centralised decision-making and task sharing approach to support design activities. A design process plan is executed by a centralised coordination agent with the help of service agents. However, the research does not state how the data is to be shared across different applications in the downstream processes and whether the software tool works in a real-time collaborative environment. Rodriguez and Al-Ashaab (2005) proposed a knowledge-driven Collaborative Product Development (CPD) system architecture. The research is focused on the provision of real-time manufacturing knowledge to support geographically distributed companies in making engineering decisions. The sources of manufacturing knowledge are the manufacturing process, resource capabilities, company experience, technical documents and industrial heuristic knowledge. The architecture developed as modular-based and the manufacturing knowledge model and the product model are implemented as object-oriented databases. The information is accessed using a back-end connectivity CORBA (OMG, 2007). However, the authors have stated that there is no real-time visualisation of the geometry and, therefore, the design cannot be modified over the internet. Another shortcoming is that the research did not address the problem of how manufacturing knowledge can be represented in a common format to enable sharing in geographically distributed companies using different software packages.

Among the above authors, Huang et al. are particularly focused in collaborative product development. Huang et al. (2001) developed a web-based system to manage Engineering Changes (ECs) in a collaborative product development activity. ECs frequently happen during a design process, and managing the ECs in a web-based system can facilitate better information sharing, simultaneous data access and more prompt communications among team members. The system can play as a complementary tool to a PDM system to enhance its capability in the management of ECs. Meanwhile, Huang extended the web-based system to support product design review to support a design chain (Huang and Mak, 2000; Huang, 2002). The design review system functions as follows:

- Simulate an on-line central review meeting room equipped with a Virtual Reality Modelling Language (VRML) whiteboard for visualising an on-line design model.
- A review co-ordinator to provide a set of facilities for a project manager to plan the activities and resources involved in the review process.
- A Bill-of-Materials (BoM) explorer to store and share review comments and some relevant documents.

However, the above paradigm requires a series of repeatable request-download processes of static HyperText Mark-up

Language (HTML) pages that are executed locally. Under this paradigm, once the download process finished, the server loses control of the relevant HTML pages. Hence, this will cause undesirable results such as the up-to-date information for design changes may not be available to other clients in the collaborative product development activities.

Among all the research discussed, however, none of them particularly addressed collaborative product development and information distribution to support the early design stages with disparate technologies and software tools, which will increase the potential industrial benefits of front-end responsiveness, quality of design and production decisions. The combined disparate technologies include knowledge management using ontological technique supporting by PLM, Enterprise Resource Planning (ERP), aggregate manufacturing modelling, workflows management and eXtensible Markup Language (XML) data exchange format.

2 The proposed solutions

The aim of this paper is to present methods for the effective management of the internet-based process of communicating new product requirements and manufacturing performance evaluations. The demonstration of the case study will focus on the critical early stages of product development throughout the product life cycle using PLM, ERP and related web-based technologies. An integration architecture for product development has been developed to facilitate bridging the gap between the application of PLM, ERP, web-based technologies and manufacturing and design domains.

Solutions to these problems are proposed and described below. In order to meet the development in linking design and manufacturing domains, the novel aspects of the research work are:

- The ability to easily create, modify and utilise design and manufacturing knowledge during the early design phase.
- To create assembly plans for the components and evaluate the potential viability using assembly planning tool and interface with ERP tool.
- PLM which holds all design data and meta-data as well as enabling version control of design iterations and access to shared work area for the team members.
- Secure data communications technologies to allow data to flow between team members and the central repository using an activities co-ordination mechanism.

The next section focuses on the implementation issues of PLM, ERP and web-based technologies. The integration architecture forms the theoretical backbone and defines the role of the system in supporting product development in a collaborative and knowledge distributed environment. The integration architecture is designed to be used by product design, product development and manufacturing engineers to explore possible design alternatives in a web-based environment. The main

feature within the integration architecture is the introduction of an activities co-ordination mechanism to link design and manufacturing domains. In practice, the integration environment can be used in a collaborative manner by vendors, original OEMs and suppliers with deployment of different ERP and PLM/PDM systems.

3 The product development integration architecture

The proposed integration architecture is illustrated in Figure 1. The overall integration environment is categorised into *three layers*. The first layer is the enterprise systems which consist of the PLM/PDM and ERP technologies. The second layer is the communication and data exchange mechanism. The third layer consists of the Manufacturing and Design Domains.

The architecture uses PLM systems to address design interoperability. This solution provides the functionality of different designers at different locations to access the same design collaboratively. The architecture also supports STEP-based standards for geometric models. This standards-based collaboration can work in a global, distributed, and heterogeneous design environment. In addition, PLM offers *lifecycle management* and *versioning control* for the design and the ability to see the history or ‘evolution’ of a design through all its iterations. Thus, this allows geographically dispersed users to co-edit CAD geometry and related tasks dynamically.

3.1 The enterprise layer

The deployment of a PLM/PDM system provides an ‘integration wrapper’ for the entire integrated system. It supports an online distributed and collaborative environment

with specific functions including *product data/document management*, *versioning control*, *workflows* and *lifecycle management*. The term integration wrapper denotes the ability to ‘wrap data and knowledge’ from different domains into a common format, such as XML, so that a file can be shared within a distributed PLM environment and readily interpreted by using the terminology definitions of the ontology. The deployment of an open source ERP system is mainly used to generate capacity requirements planning based on the assembly and subassembly sequences of specific products.

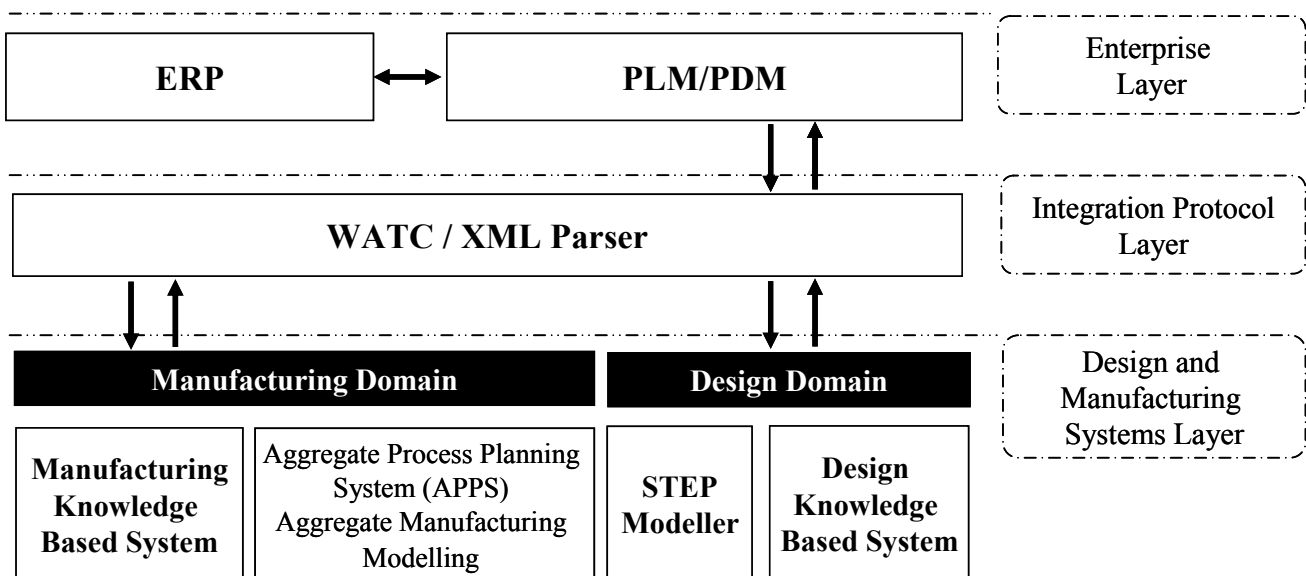
3.2 The integration protocol layer

An XML Parser is deployed as the interfacing technology between a PLM system and the Manufacturing and Design Domains for data interchange. This enables interchanging portions of XML documents while retaining the ability to parse them correctly and, as far as practicality is concerned, they can be formatted, edited, and processed in useful ways. The discussion of implementing the XML Parser is in Section 3.4.

3.3 The design and manufacturing systems layer

The manufacturing domain consists of an Aggregate Process Planning System (APPS) (Bramall et al., 2003) and manufacturing Knowledge-Based System (KBS) (Cheung et al., 2006). The design domain consists of a STEP Modeller and the Design KBS (Aziz et al., 2005). A CAD system Pro/Desktop is used as the solid modeller to display the image of the product through a PLM visualisation functionality. An Oracle database server is also deployed to handle requests for knowledge and model information as well as deploy PLM functionalities through the use of Java Database Connectivity (JDBC).

Figure 1 Overall system integration architecture in product development



3.4 Coordination of the activities within the integration architecture

The integration of distributed and time-dependent components requires a time synchronisation model. The time-based co-ordination element requires the recognition of the time-dependencies of activities within a distributed team that use the stored data and knowledge. In general, a PLM system comprises; a 'Document Manager' that contains a list of user defined *cabinets* to store data files, a 'Lifecycle' function that defines the timing of the development stages and a 'Workflow' function that determines what processes and interactions take place at each stage. Clearly, PLM functions can be used as a foundation for defining a time-based integration wrapper as a time synchronisation model.

3.4.1 Workflows Activity Task Controller (WATC)

A novel 'Workflows Activity Task Controller' (WATC) methodology has been defined to implement the *time-based integration wrapper* concept in the interactions between generic types of PLM, ERP, KBSs and Process Planning functions. The methodology has been formalised in UML as shown in Figure 3. WATC sequences early design activities including *concept definition*, *design development*, *manufacturing knowledge sharing* and *automated aggregate plan* generation. WATC currently supports the following five early design stages:

- 1 Receive/understand customer product request and formalise design specification.
- 2 Generation of conceptual design by the product development team.
- 3 Distributed review of the conceptual model and addition of manufacturing knowledge and constraints.
- 4 Deployment of capability analysis for the prioritisation of product development tasks.
- 5 Generation of aggregate process plans (routings) and integrated capacity planning.

The core technologies behind WATC are methods to control the interactions of a PLM system, a KBS and a Process Planning System. The implementation of WATC is centred on the lifecycle and workflow functionalities of the PLM.

The workflow starts with the customer's request for a new product or a change to an existing product as shown in Figure 2. All business processes are modelled graphically within the PLM system as flow charts. The initial stage is adding customer historical information such as previous product specifications, customer buying experience and relationships. This can be done by invoking a KBS. The KBS consists of two separate modules, one is for the design knowledge management system that captures information related to product design and design standards, and the other is for manufacturing knowledge management

to capture process and resource-related knowledge. The key stages of the workflow process are:

- 1 The primary action of the workflow is to activate the process by assigning a task to make a connection with the KBS. All the information or relevant knowledge is stored or retrieved via a Windchill PLM Cabinet function (PTC Windchill, 2002). The Windchill Cabinet function is used to store product centric information and provides a method of locating information within the PLM system.
- 2 The second stage of the workflow is to assign a concurrent task which involves notifying team members of the development team and issues requests to the appropriate personnel to enter conceptual design data.
- 3 The third stage of the workflow is to review the conceptual design.
- 4 The fourth stage is an XML Parser mechanism which supports the interaction of data reused of the APPS and PLM systems.
- 5 The final stage involves capacity planning and implementation.

3.4.2 The XML Parser mechanism

The XML Parser is responsible for extracting manufacturing knowledge from the XML-formatted knowledge file to be reused by the process planning engine in the APPS. With the attachment of updated historical information and manufacturing knowledge, a new product definition will be generated. The product definition will be delivered to the APPS to obtain preliminary process plans. The purpose of the APPS is to allow alternative process plans (or routings) for custom parts to be generated, evaluated and improved based upon estimated *manufacturability* before committing to a fully specified product model and supplier. The new process plans (routings) are then delivered to the PLM system for plan/review.

3.4.2.1 Methods of creating the XML Parser

The advantage of using an XML-formatted file is that there is a whole range of generic XML tools available to create an XML Parser for extracting the information and translating it into the required format of a proprietary tool to re-use. In this case, an XML Parser has been created for transferring the stored knowledge to the APPS. An XML Parser has been created based on the Java programming language. Figure 3 illustrates a UML activity diagram (Schmuller 1999) to represent the algorithm of a Java-based XML Parsers' internal methods that are used to read and extract the information (of data type string) and translate it into the format of a third party software system. The illustration represents two specific roles, the initial role is to *Prepare XML Metadata* and the second role is to *Extract XML Metadata*. Transition can take place from one role to another.

Figure 2 Time dependency scenario using WATC concept

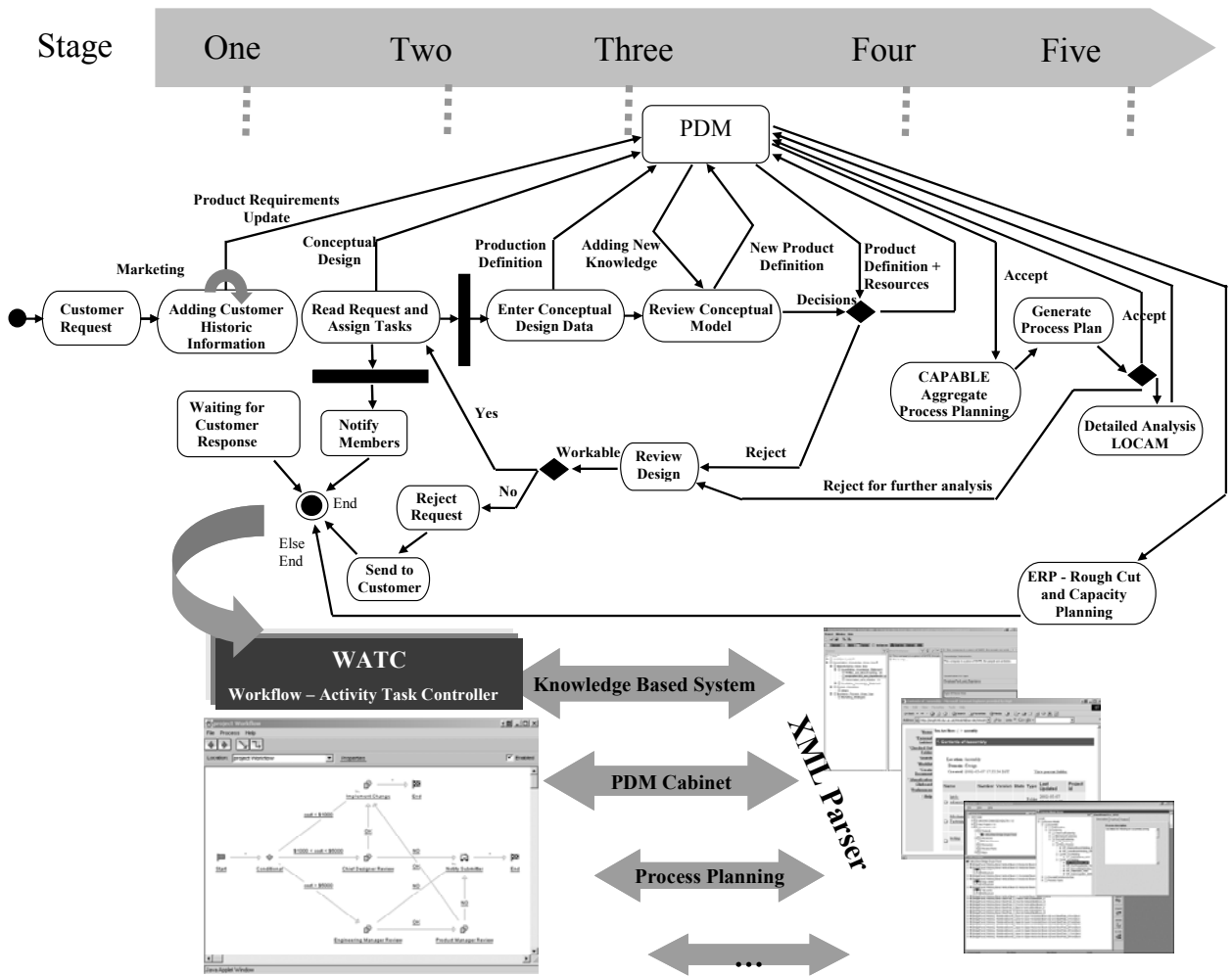
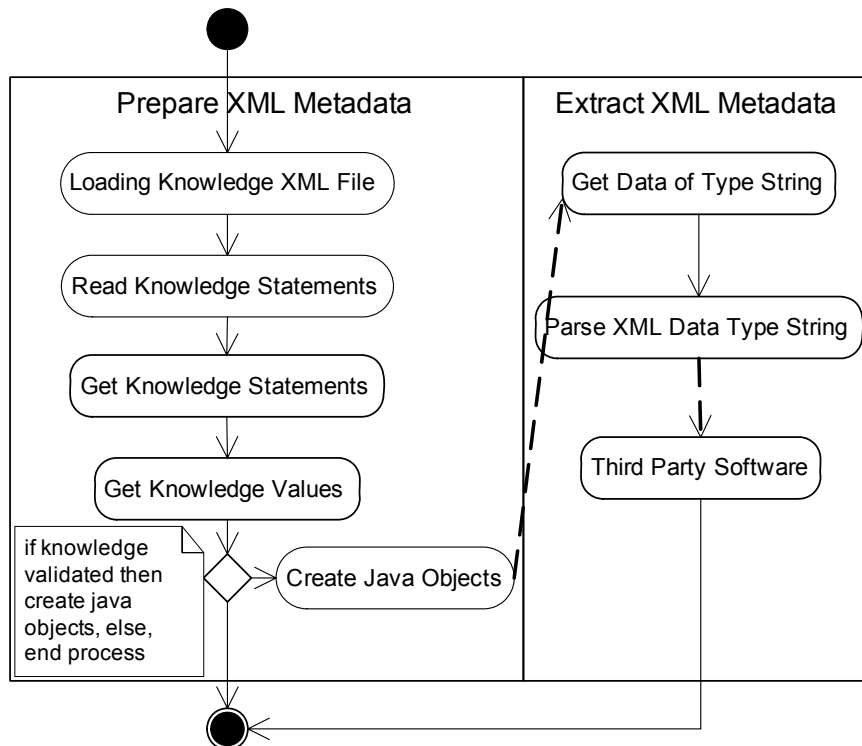


Figure 3 Algorithm of a Java-based XML Parsers' internal methods



4 Case study

4.1 Objectives and aims

The industrial collaborator, M&J Ltd is increasing their business internationally with distributed operations and supply networks. They aim to develop greater flexibility in reacting to customer requirements on a world-wide basis and are particularly interested in the integration of design with manufacturing operations through enterprise and web-based technologies. This will give them the ability to explore remote business opportunities and distributed sourcing options. The objective of the test is to demonstrate the various software components to bridge the gap of communicating early product ideas in the design domain and the manufacturing domain to support product development processes. The aim of the evaluation was to test:

- 1 The technical feasibility based upon the data supplied and collected from the industrial collaborator and
- 2 The WATC method to coordinate early design activities using PLM and ERP technologies, the organisational KBS and the APPS.

The exercise concerned the evaluation of a Bailey's single steel bridge panel at the conceptual design stage and how decision support can be enhanced.

4.2 Application of the Aggregate Process Planning System (APPS)

4.2.1 The product description

Figure 4(a) shows an early design configuration of a single steel bridge panel. The bridge panel was modelled using U-shaped steel beams and solid rectangular steel plates. The bridge panel was constructed from 14 steel beams (four horizontal, eight diagonal and two vertical), six steel plates and eight square slots. The overall dimension of the bridge is approximately 3 m by 2 m with an approximate weight of 130 kg. Assembling the bridge panel is a complex task. The number of welding processes required to assemble the panel requires more than 240 procedural steps. An example of the

type of weld is shown in Figure 4(b) illustrates the model of a bridge panel with Engineering Bill of Material (EBoM) configurations and the example product model modelled within the APPS. The product model represents a conceptual design stage of a single Bailey's steel bridge panel.

4.3 Factory model used in testing

The factory layout of M&J is made up by a series of cells and within every cell there is a dedicated workcentre. The type of cells and workcentre(s) indicate the type of machines and their operations. Figure 5 illustrates the factory design module as modelled in the APPS. It clearly shows the position of individual cells and associated machine types. Datasheets (see Table 1) for robotic handling and welding tools were used to specify process parameters for the robotic centres, giving a range of tools that would be able to perform all handling and welding operations.

4.4 Process model

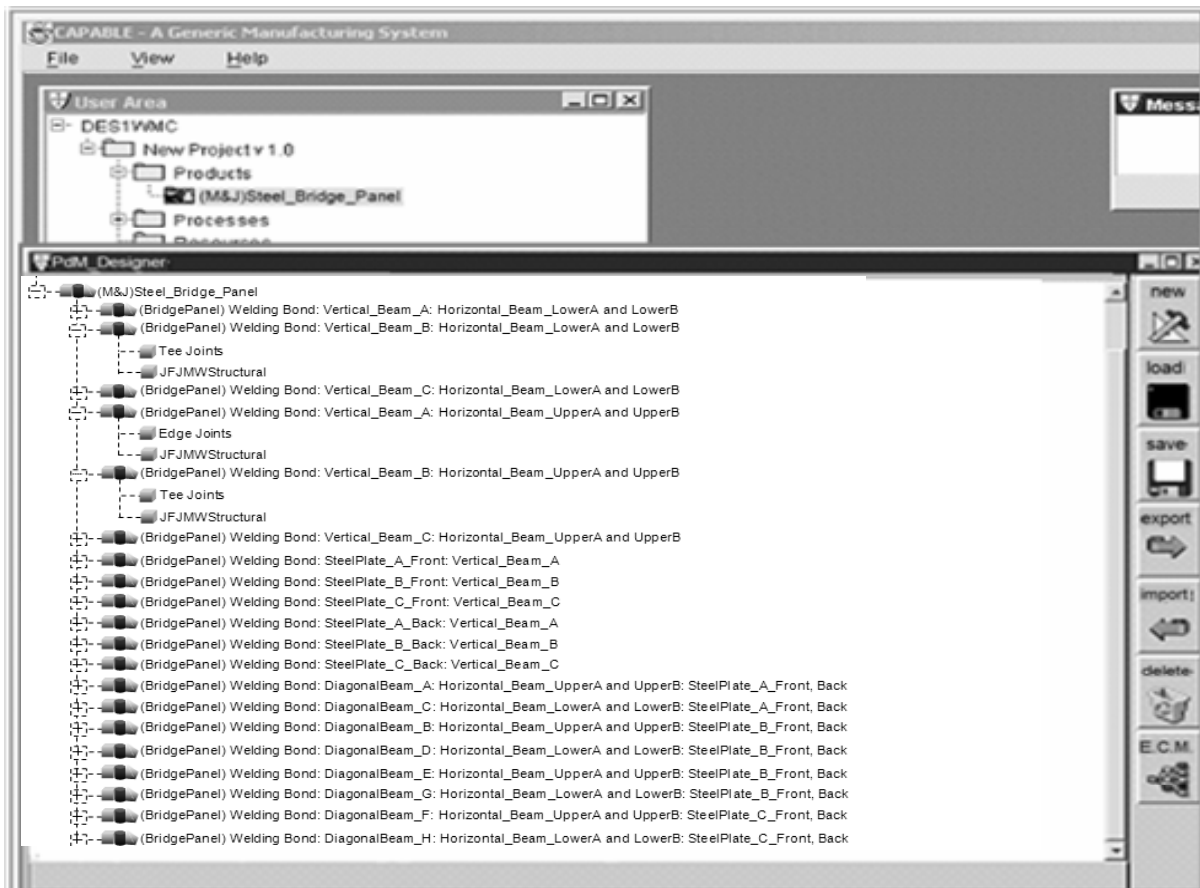
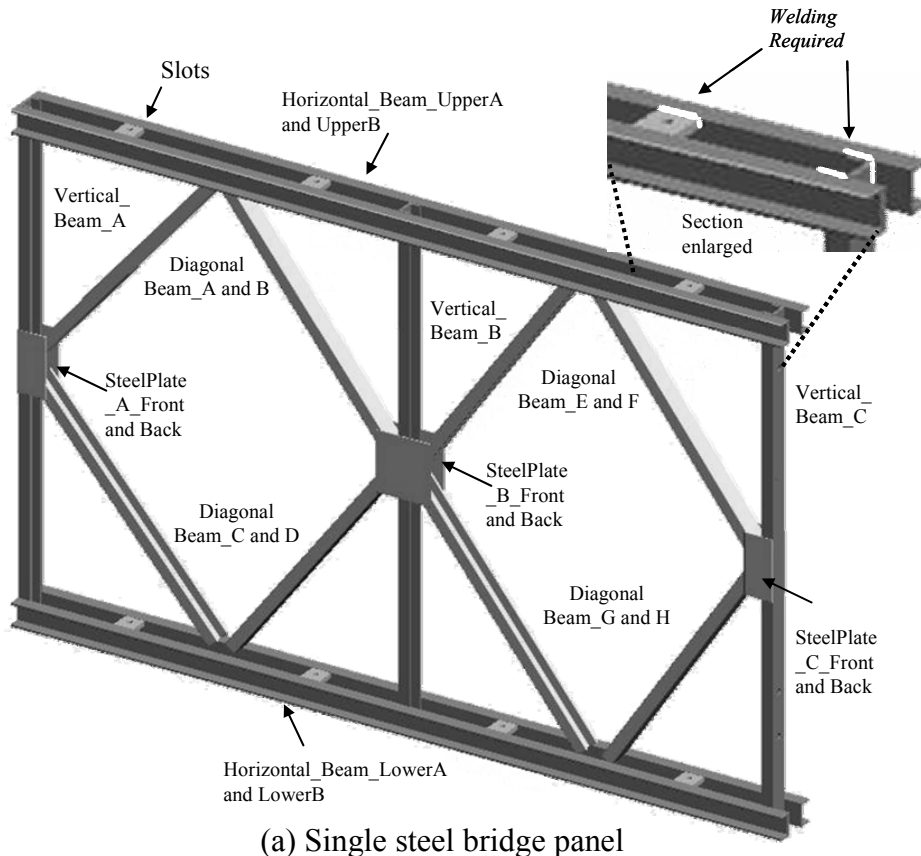
Process modelling is used to identify the type of process needed to assemble the bridge panel. The Process model provides specific methods which have been developed to calculate manufacturing time and production quality. Resource modelling is used to specify process parameters for the selected machining centres, i.e. to give a range of tools which will be able to perform all necessary operations associated with the product features. Figure 6 shows a user interface of the process model in the APPS. In order to assemble the bridge panel at M&J, other types of processes are also available within the system. These are:

- semi and fully automatic robotic welding,
- manual welding,
- drilling,
- surface coating,
- galvanising,
- immerse washing and inspection.

Table 1 Example resource model data

Resource name	Max. travel speed (mm/s)	Max. weld flow rate (mm ³ /s)	Max. feeding velocity (mm/s)	Max weld cord diameter (mm)	Max loading (kg)	Max arm length (mm)	Duration (Hrs)
'IRB 4400'	250	NA	72	NA	60	1950	NA
'IRB 1400'	250	NA	72	NA	5	1440	NA
'IRB 340'	100	NA	NA	NA	1	NA	NA
'IRB 6400PE'	250	3	72	14	120	2500	NA
'IRB 6400R'	250	3	72	14	500	2250	NA
Galvanising plant	NA	NA	NA	NA	NA	NA	24

Figure 4 Product model of a single steel bridge panel



(b) EBoM of Product configurations

Figure 5 Screenshot of the APPS factory model

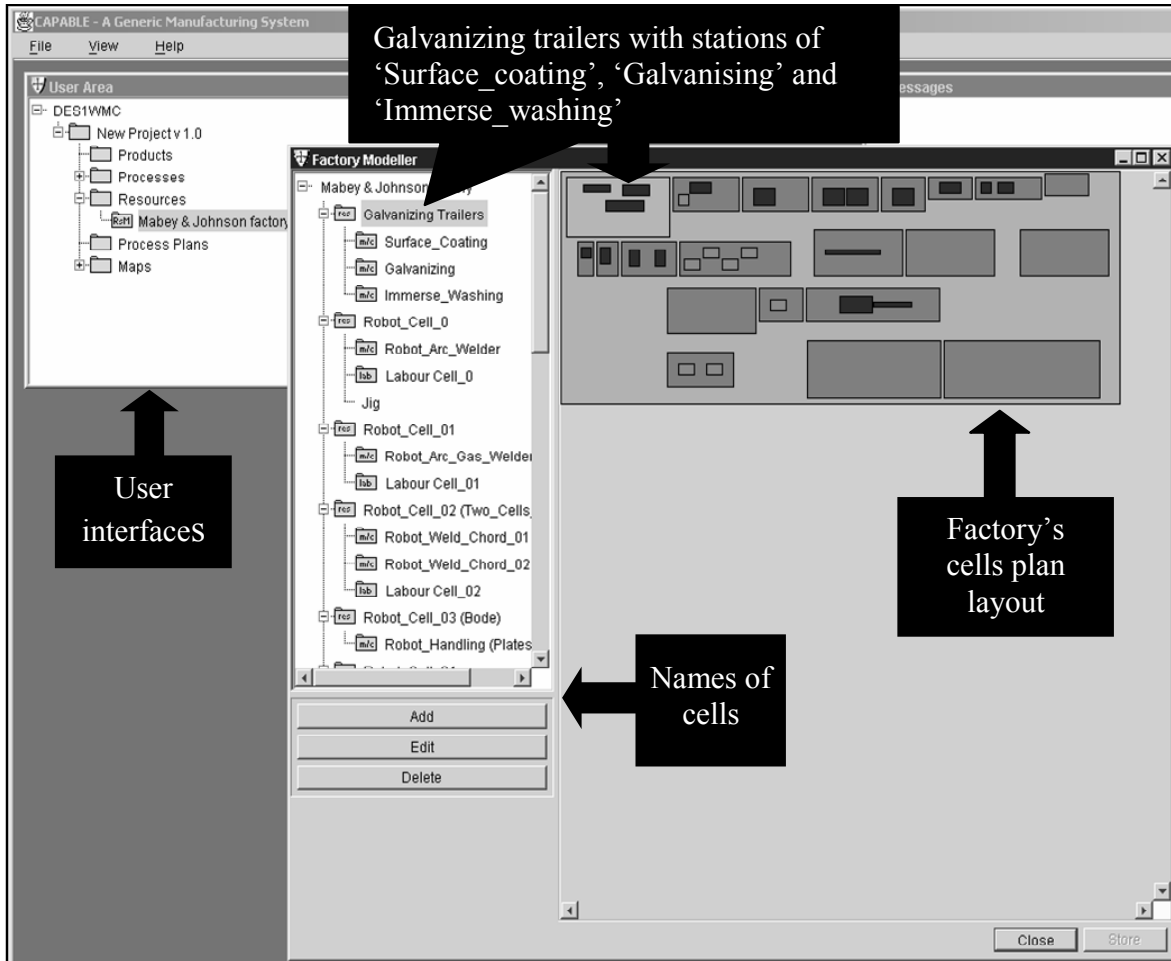
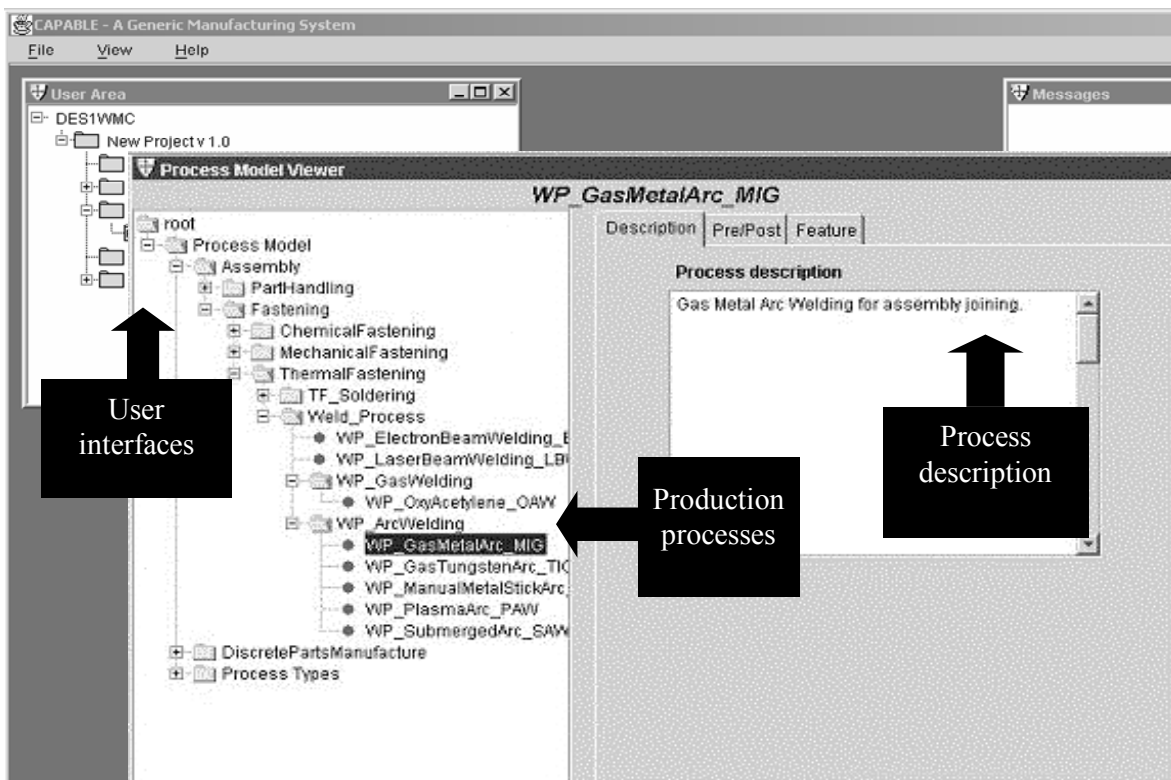


Figure 6 Screenshot of the APPS process model



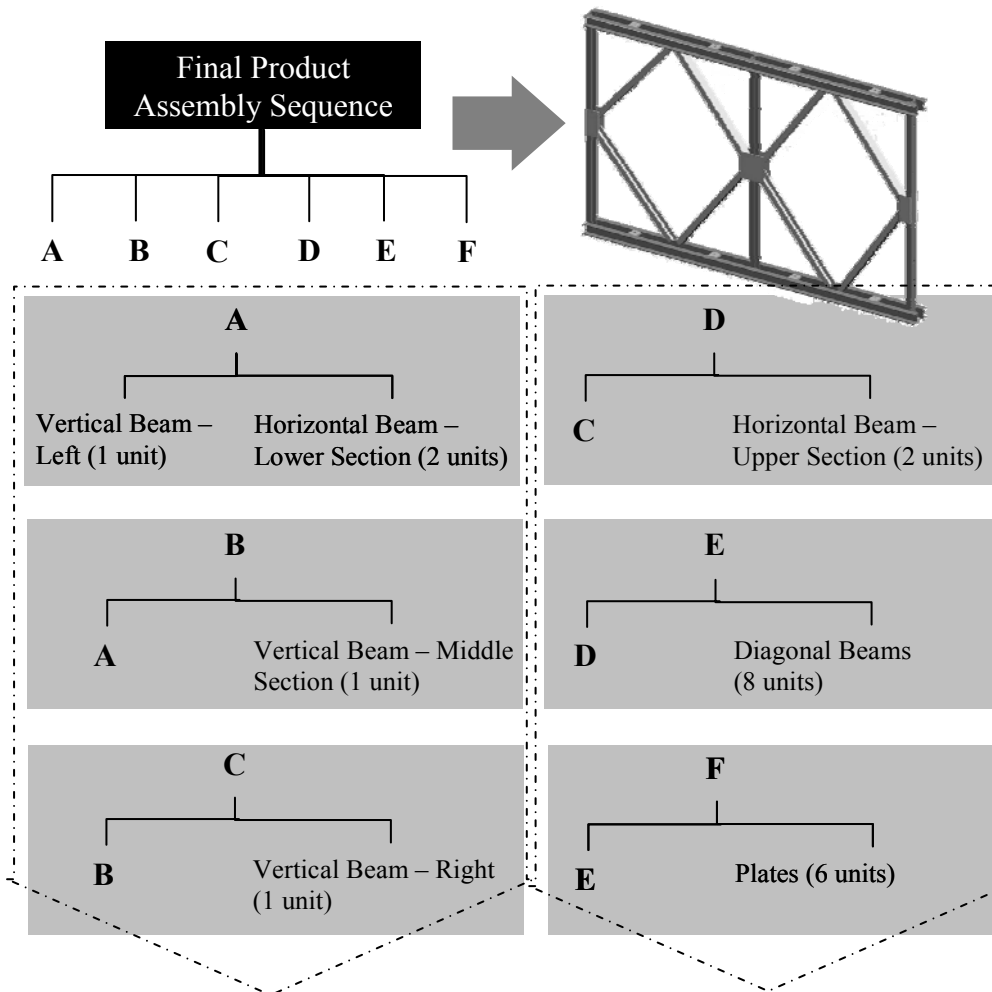
Furthermore, the company has also imposed Welding Process Specification, Just-in-time and Kanban techniques to improve the shop floor efficiency. Each of the processes and techniques require a high degree of *know-how* to operate successfully.

4.5 Aggregate process planning for a single bridge panel

The process plan represents a sequence of assembly and subassembly operations for the construction of a single

bridge panel. The steps of the assembly sequence of the final product is made up by a number of subassemblies A, B, C, D, E and F as represented in Figure 7. Each of the subassemblies is made up of a number of design feature units as indicated in the diagram. For instance, subassembly A and one unit of vertical beam produced subassembly B. Similarly, subassembly B and one unit of vertical beam produced subassembly C. Once the bill of material for the end product has been prepared, an aggregate process plan can be obtained via the APPS.

Figure 7 Assembly and subassembly sequence of a bridge panel



4.6 Manufacturing knowledge acquisition and reuse

4.6.1 Populating the manufacturing 'know-how' Knowledge-based system

It is assumed that knowledge acquisition is performed internally by the knowledge experts within M&J Ltd via interviews and paper-based information. There are two knowledge types: quantitative and qualitative. The knowledge types are further classified into *Written and Benchmarking, Observation and Intuition, Employee Tacit and Experience* and *Best Practice* as explained by Cheung et al. (2006). Figure 8 represents the Manufacturing Know-how KBS. The KBS consists of three parts: (1) the main body of the structure, (2) user input dialogue

and (3) the knowledge instances. The Figure illustrates an example of how instances related to a factory are populated and stored in the KBS.

One of the most important aspects of creating knowledge statements is setting the value of the *Probability Factor* (Cheung et al., 2006). For instance, *galvanising* is a simple but delicate process and is mostly manually operated which can involve up to six steps to produce the desired coating. Every galvanising 'dip' takes up to eight bridge panels at a time. *Dipping speed* varies upon the type of bridge panel and the number of panels going through the molten sink, thus, the *dipping speed* must be carefully controlled to avoid 'air trapped' when loading the panel into the molten sink (see Figure 8). If the *dipping speed* is

too high this may create a sudden explosion due to ‘air trapped’. Since *dipping speed* is so important the associated *Probability factor* constraint which defined by axioms is shown in Figure 9. Hence when the user chooses the value ‘always’, axioms tells the system how to interpret the

imports numerically. In this case, the highest possible value is ‘1’. This value will then to be used by the capability analysis method (Baker and Maropoulos, 1998). All of these experiences can be stored into the KBS as explicit manufacturing know-how.

Figure 8 Knowledge acquisition

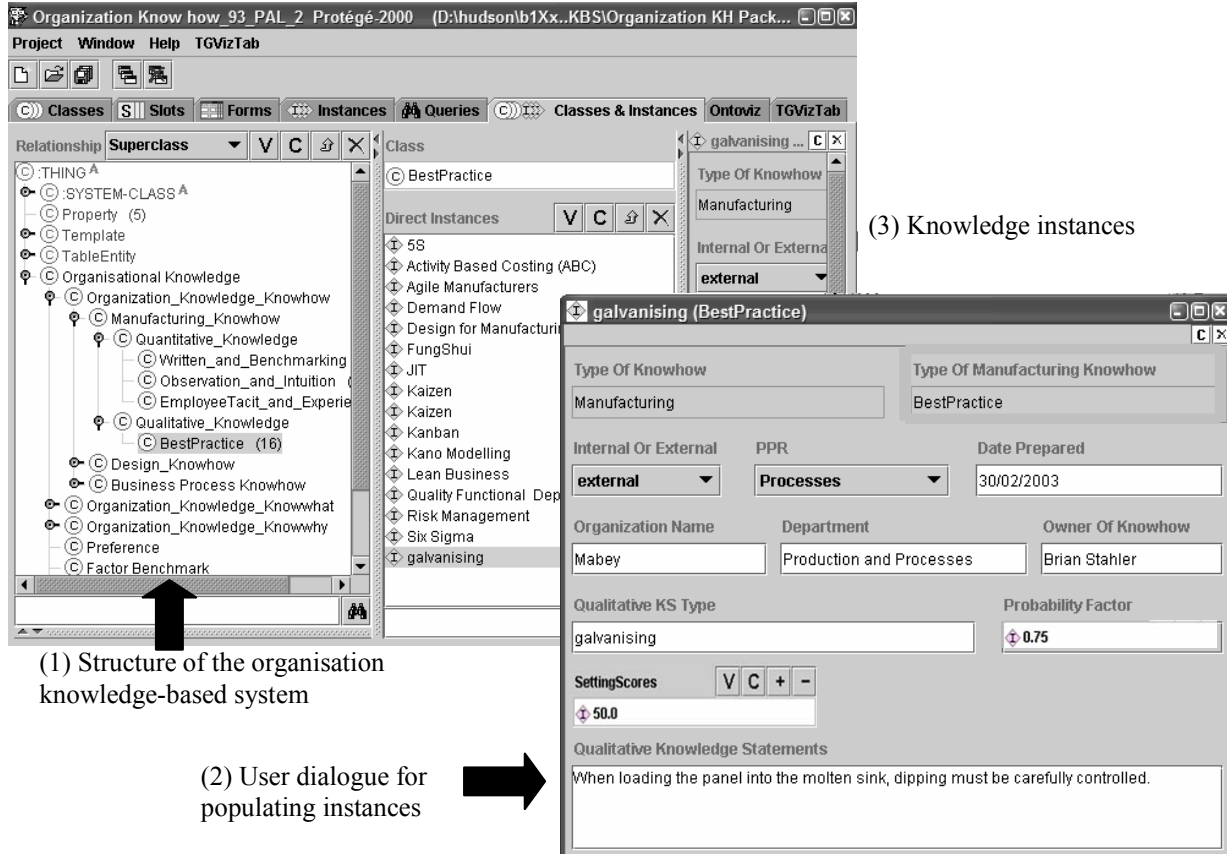


Figure 9 Example probability factors defined by axioms

```
(exists? Probability
  (and
    (< ('Always'? Probability) 1)
    (< ('Frequently'? Probability) 0.75)
    (= ('Never'? Probability) 0.0)
    (< ('Occasionally'? Probability) 0.25)
    (< ('Sometimes'? Probability) 0.5)
  )
)
```

Another example is the application of design know-how. Design knowledge, covering several processes and resources, was added into the ontology by the knowledge experts. Subsequently, using the APPS, a process plan was created using feature-to-process and process-to-resource mappings which involved the galvanising process. Taking into account the process parameters (the temperature fluctuation from ambient to 500°C) the following critical areas of knowledge were immediately identified and presented to the designer:

- Explosions *always* occur if *air trapped* is in the design, for example a closed tube.

- If *Weldments* are present, they should *always* be designed to avoid acid traps.
- *Flat panels should normally* be braced to minimise the risk of distortion.

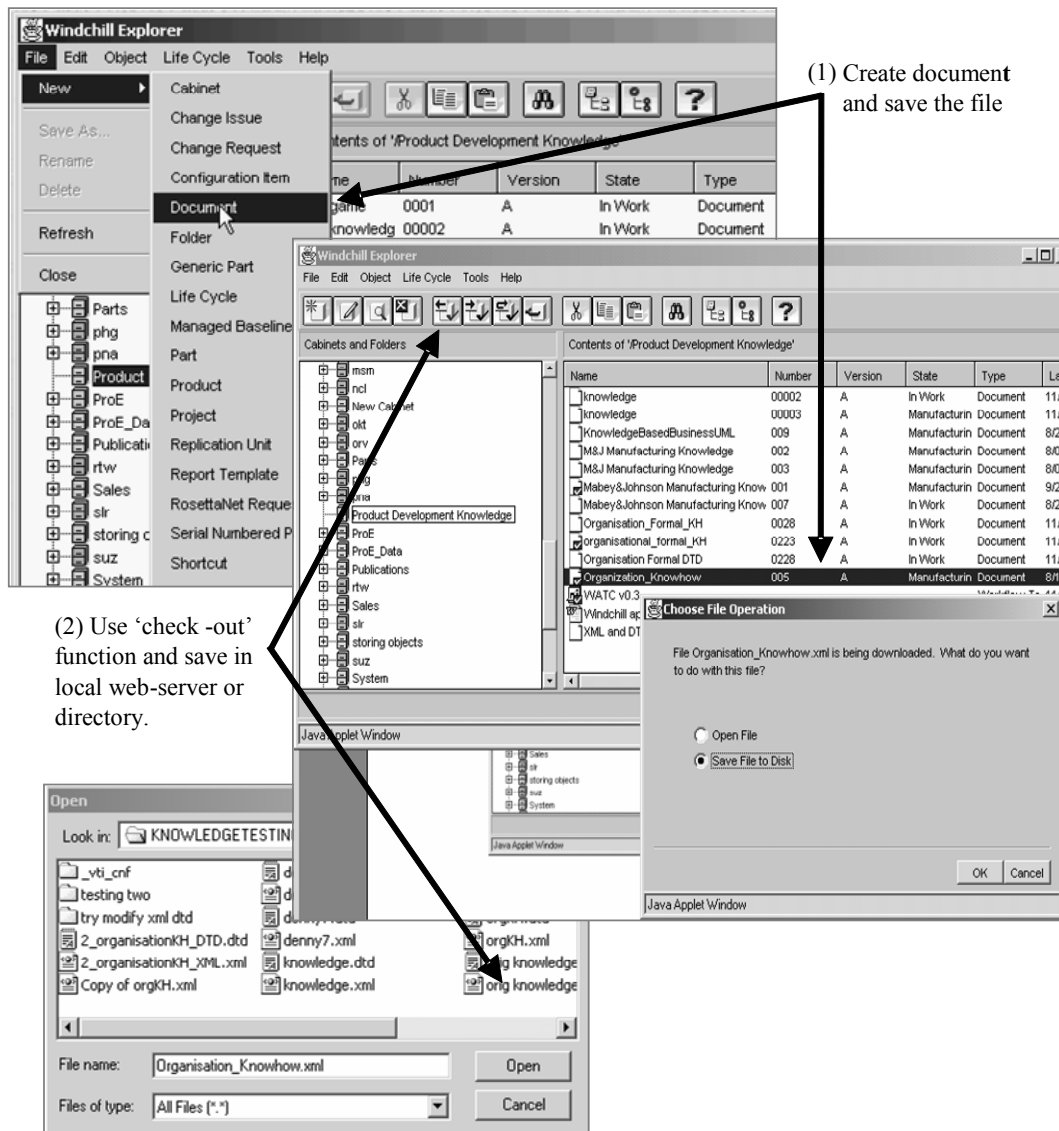
These are a few of the examples of using the KBS to capture the expertise to be reused and shared within the product development processes.

4.6.2 Usage of PLM system to store knowledge

Figure 10 illustrates a sequence of events of how a XML-based knowledge file being stored in a PLM system and subsequently to be downloaded by an external user. The diagram represents:

- 1 Having created the XML-based knowledge file, the next stage is to invoke the PLM system and use the ‘create document’ function to download the knowledge XML-based file into the PLM document storage cabinet.
- 2 Next is to use the XML document by invoking the PLM ‘check-out’ function which downloads the document into the user’s local file space.

Figure 10 Use of PLM in XML-based knowledge



4.6.3 XML Parser in knowledge re-use in process planning

This section describes the demonstration of how the application of the XML Parser supports a third party software system. The coordination of the activities is based on the method of WATC. The testing environment is illustrated in Figure 11, which depicts an example of web-based data interoperability between a KBS, a PLM system, the APPS and an ERP system. The example shows that the captured knowledge will be saved in a XML file and then placed into a Windchill PLM Cabinet. The diagram also illustrates the links of an XML-based manufacturing knowledge to be re-used by the APPS.

The links were established by the XML Parser and defined by *data-string-type* (extract XML Metadata). The *data-string-type* is the term used within the XML Parser to identify the *subject-type* in the XML-based knowledge document. Thus, this allows the extracted data to be transferred to the data models in the APPS. After obtaining an aggregate process plan for the conceptual design with the APPS, this will then transfer

into the PLM system and ready to be checked-out into the ERP system for capacity planning.

Figure 12 illustrates the knowledge statements related to a specific object termed Robot_Cell_0 which belongs to a station of a factory. As highlighted in the diagram, in order to refine a conceptual design:

- 1 from the APPS, a designer will invoke the XML Parser within the data model, for example the factory resource model,
- 2 the designer will select the XML-based knowledge file from the local directory which is already uploaded from the PLM cabinet and
- 3 the knowledge statements will then attach to a particular group of machines, which can be used for further analysis to enhance the planning process of a conceptual design. The example shown in Figure 12 indicates the resulting knowledge statements extracted to the APPS which relate to a factory (resource) model object 'Galvanising trailer' which belongs to a cell of 'M&J Ltd' factory.

Figure 11 Centralised testing in UML sequence diagrammatic representation

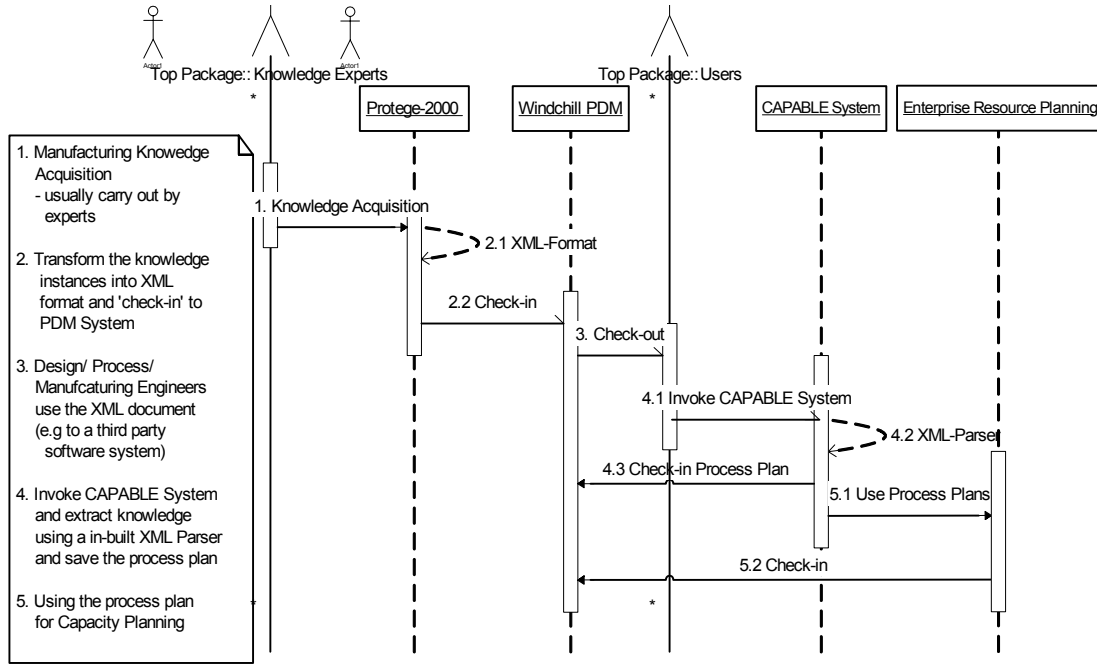
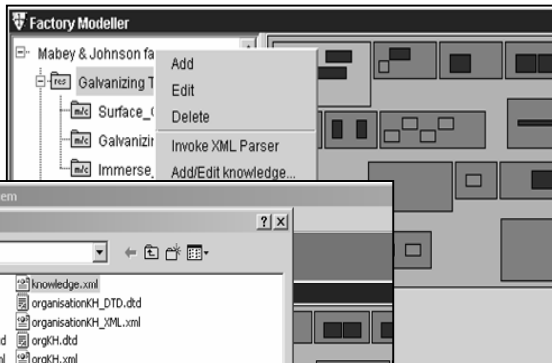
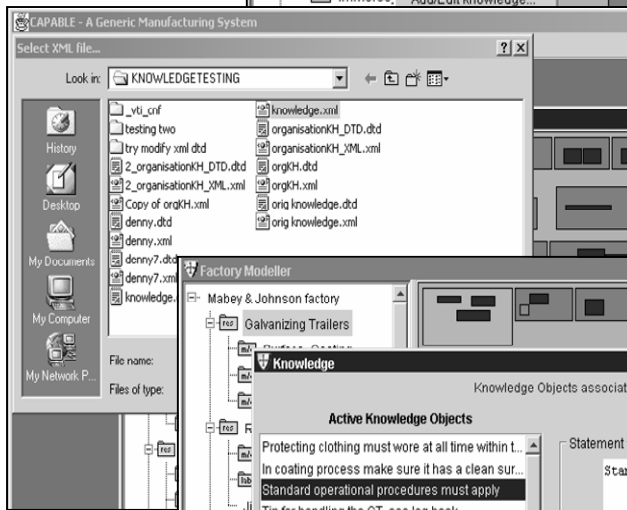


Figure 12 Example knowledge statements related to a specific object

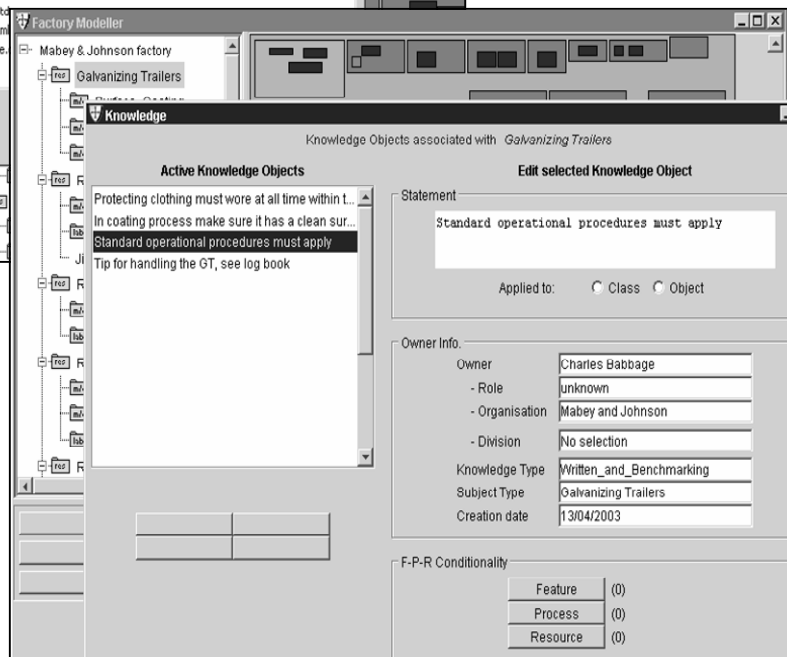
(1) Invoke XML Parser from a factory model



(2) Select the XML file



(3) Example of extracted knowledge statements into a factory model



The design engineer is then required to select the relevant knowledge to refine the design and subsequently run the APPS to obtain a preliminary process plan based upon these knowledge factors. If the plan requires review, the prioritised knowledge factors obtained from capability analysis, highlight the most appropriate areas of the process plan for improvement based upon the specific instances of knowledge factors used. If the process plan is acceptable, it is then delivered to the PLM system for plan/review, and subsequently is readied for implementation in an ERP system for capacity requirements planning.

An early process plan is generated by the APPS. However, in order for the ERP system to read and extract the right type of information, the process plan has been converted to a spreadsheet data formatted file. Based on this information the ERP system can estimate the resultant requirements at individual work centres as described in the next section.

4.7 ERP for capacity requirements planning and testing results

The ERP system used in this case study is called Compire. Since the system has many different functions available, the ERP system must be customised. For example, the correspondence functions which uses in the implementation are:

- (a) Import file loader
- (b) Resource
- (c) BOM drop
- (d) Product
- (e) Production
- (f) Asset

Import the spreadsheet file using the *Import File Loader* function. *Resource* function captures the relevant resource data, such as the machine and station types. *Product* function captures the requirement of product features. *BOM Drop* captures the assembly and process sequences. *Production* captures information related to the *Client (customer)* such as description of the product, production plan, line and date of movement. *Asset* is the final function used to capture detail views of the *resource* requirements such as the availability, location and delivery. Next, fill in all additional information, for example, in the *product* function. Information such as weight, height of the product feature, cost and so on.

The illustration shown in Table 2 indicates the Capacity requirements planning generated by the Compire system. The table illustrates the impact of the time-phased capacity information. The total workload of 1050 hours and its percentage allocations to each workstation over a 10 day period for 50 panels per day. One of the reasons to use a 10 day period is to show the periodic changes according to the manufacturer’s Master Production Schedule (MPS) requirements. The timing of workcentres varies, for instance, for the workstation *Galvanising* at time period 2, a capacity requirement was planned for 16.5 hours and *Immerse_Washing* was planned for 7.5 hours. This indicates that the total processing time for the 50 panels in *Galvanising* is 16.5 hours and 7.5 hours in *Immerse_Washing* respectively. Further particulars the table has indicated is the concern of long range capacity planning, thus, the system is able to generate and provide indications of capacity planning requirements for a longer period of time.

Table 2 CRP for a full panel

Workstations	Time Period										Total Hours	Workstations Percentage (%)	
	1	2	3	4	5	6	7	8	9	10			
Robot_Deck_01	0	0	0	0	0	0	0	0	0	0	0	0	0
Robot_Handling (Beams)	12	12	12	9.5	9.5	17	17	17	18.5	18.5	143	13.6	
Robot_Deck_02	0	0	0	0	0	0	0	0	0	0	0	0	
Robot_Handling (Plates)	6	6	6	9	9	9	9.5	9.5	9.5	9.5	83	7.9	
Robot_Weld_Chord_01	0	0	0	0	0	0	0	0	0	0	0	0.0	
Robot_Weld_Chord_02	0	0	0	0	0	0	0	0	0	0	0	0.0	
Robot_Arc_Gas_Welder	16	16	16	17.5	17.5	17.5	17	17	20	20	174.5	16.6	
Robot_Arc_Welder	16	16	16	17.5	17.5	17.5	17	17	20	20	174.5	16.6	
Surface_Coating	7	7	7	7.5	7.5	7.5	8	8	9	9	77.5	7.4	
Galvanizing	16.5	16.5	16.5	17.5	17.5	17.5	17	17	20	20	176	16.8	
Immerse_Washing	7.5	7.5	7.5	8.5	8.5	8.5	9	9	10	10	86	8.2	
Inspection	5	5	5	7.5	7.5	7.5	8.5	8.5	9.5	9.5	73.5	7.0	
Manual Drilling	0	0	0	0	0	0	0	0	0	0	0	0.0	
Panel_Drilling_1	5	5	5	6	6	6	7	7	7.5	7.5	62	5.9	
Manual Weld 01	0	0	0	0	0	0	0	0	0	0	0	0	
Total	91	91	91	101	101	108	110	110	124	124	1050	100	

5 Conclusions and future work

Within M&J Ltd, all technical knowledge is tacit and possessed by experts. Due to their increasing business practice with distributed operations and supply networks, it is important for them to be able to control and store this technical knowledge from the early design/concept evaluation stage which in turn could improve the responsiveness to customers. The case study was used to illustrate the concept of bridging the discontinuity in communicating early design concepts and manufacturability evaluations using a centralised network configuration. In essence, the case study has demonstrated the followings:

- Use of enterprise and web-based technologies and the application of an activities co-ordination mechanism which can enhance a distributed and collaborative environment to support the product development process.
- How manufacturing knowledge can be reused by the APPS through the application of an automatic data exchange mechanism.
- The performance of supporting the designers to refine a design at the conceptual stage by adding manufacturing knowledge into the APPS to generate alternative early process plan then use it in an ERP system to obtain and optimised a rough-cut capacity planning .

As a result, the methodology demonstrated in this research was used to capture, store and re-use this knowledge within the process of collaborative product development. Specifically:

- Early collaboration in product design using the WATC methodology can maximise the opportunity for optimising designs.
- With the increasing of knowledge in design and manufacturing capabilities, the application of organisational KBS coupled with the aggregate process planning method can be used to capture and maximise the amount of available information when designing customised products.
- The integration environment using enterprise technologies can enhance the speed of feedback and is used to support decision-making and enable the design to be right first time.

How much lead time can be reduced on new product introduction is difficult to measure at this stage as the methodology only tested the early stage of product development processes. Another assumption is that the case study was tested in a single user access environment. As for future work, (1) another case study should be carried out under several geographical locations, for example, with suppliers and subsidiary companies and, (2) the architecture should be extended to the supply chain area so that lead time of new product introduction can be evaluated.

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Customer requirements mapping method based on association rules mining for mass customisation

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Abstract: Customer requirements analysis is the key step for product variety design of mass customisation. Quality Function Deployment (QFD) is a widely used management technique for comprehending the 'Voice of the Customer' (VOC), however, QFD in excess depends on human subjective judgement during extracting customer requirements and determination of the importance weights of customer requirements. And also, QFD process and related problems are complicated. In this paper, based on generic data structure of product family (GBOM), association rules analysis is introduced to construct the classification mechanism between customer requirements and product architecture. The new method can map customer requirements to the items of product family architecture respectively, accomplish the mapping process from customer domain to physical domain directly, decrease mutual process between customer and designer, improve the product design quality, and thus furthest satisfy customer needs. Finally, an example of customer requirements mapping of the elevator cabin is used to illustrate the proposed method.

Keywords: association rules analysis; requirements mapping; classification mechanism; GBOM; mass customisation.

Reference to this paper should be made as follows: Xia, S-S. and Wang, L-Y. (2010) 'Customer requirements mapping method based on association rules mining for mass customisation', *Int. J. Computer Applications in Technology*, Vol. 37, Nos. 3/4, pp.198–203.

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1 Introduction

With the increasing competition in the global market and individual customer needs, the manufacturing companies have to devote much attention to Mass Customisation (MC) to increase customer value (Pine, 1993). MC is defined as 'producing goods and services to meet individual customer's needs with near mass production efficiency' (Child et al., 1991; Tseng and Jiao, 1996). MC is currently attracting a lot of attention from researchers and industry (Jiao and Tseng, 1999).

It is impossible for manufacturing companies to provide infinite product offerings in order to satisfy customer individual needs. Otherwise it will inevitably lead to high complexity and costs in product fulfilment (Simpson, 2004). Moreover, large numbers of products available lead customer to lose their head, and thus they could not make a final choice. Therefore, the manufacturing industry has been

facing the challenge of determine how to offer 'right' product variety to the target market (Aron et al., 2006; Zhang and Jiao, 2007). This is the essence of MC.

Customer requirements analysis is the key step for product variety design of MC. Quality Function Deployment (QFD) is a widely used management technique for comprehending the 'Voice of the Customer' (VOC) and enabling a translation of the customer requirements into the appropriate product designs or engineering characteristics (Akao, 1990). However, QFD in excess depends on human subject judgement during extracting customer requirements and determination the importance weights of customer requirements. Due to the imprecision and ambiguousness of customer requirements and the limitation of technical personnel preferences, the requirements extracted are always not the actual customer needs (Martin, 1996; Karsak, 2004). Many latter approaches (Elrod et al., 1992; Fung et al., 1998; Kwong and Bai, 2002; Liu and Shih, 2005) try to reduce

the shortcomings of human subjective judgement involved in transforming the VOC to product specifications, but these approaches only partly improve the process of QFD. Moreover, most approaches assume product development starts from a clean sheet of paper. In practice, most new products evolve from existing products (Tarasewich and Nair, 2001; Jiao and Zhang, 2005).

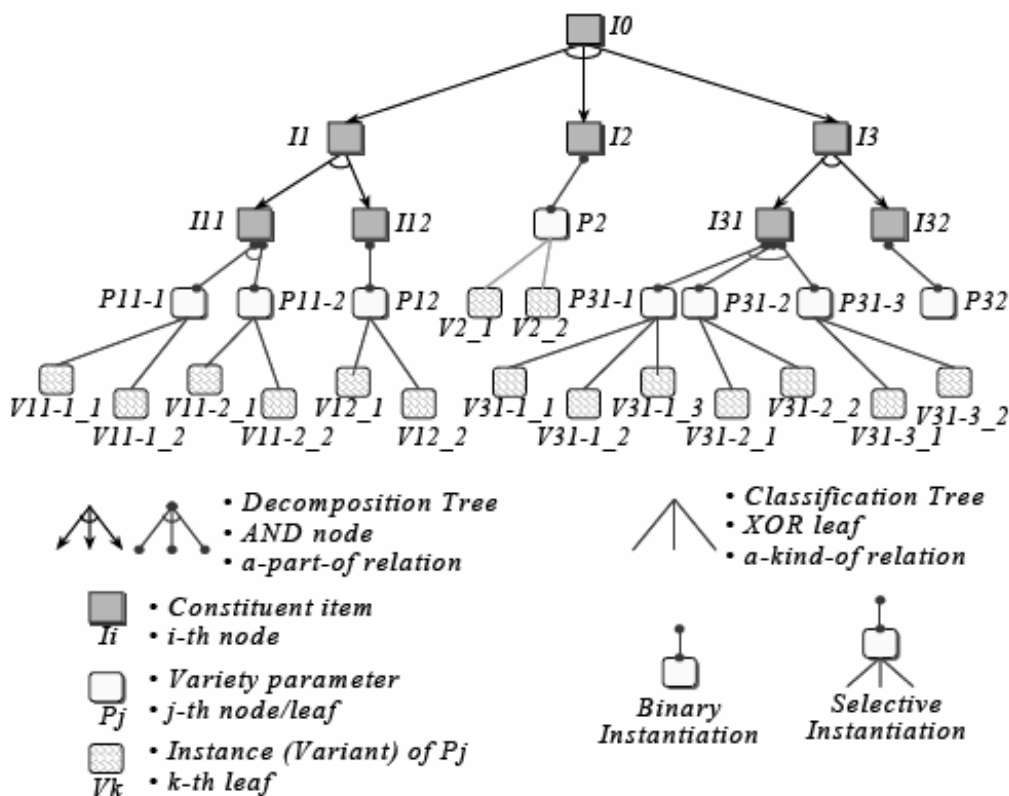
Our work proposes a novel customer requirements mapping method by constructing a classification mechanism between customer requirements and product architecture. The relationship between customer requirements and the items of product family architecture is found using association rules mining based on the data extracting from the company’s sales records and product portfolio. The results are put into a rules knowledge base. The new customer requirements are mapping to requirement parameters in rules knowledge base, and then are translated to product family structure parameters accordingly.

2 Background

2.1 Generic structure for product family

In order to satisfy customers’ needs for increasing variety, MC companies have to increase the product variety. This variety leads to difficulty of managing product variants. The traditional approach to variant handling is to treat every variant as a separate product by specifying a unique BOM for each variant. But in MC production, design and maintenance of such a large number of complex data structures are difficult. To overcome these limitations, a Generic BOM (GBOM) concept has been developed (Hegge and Wortmann, 1991; Van Veen, 1992). The GBOM provides a means of describing, with a limited amount of data, a large number of variants within a product family. Underlying the GBOM is a generic variety structure for characterising variety of product family, as illustrated in Figure 1.

Figure 1 GBOM for MC



GBOM is a combined decomposition/classification tree. The tree is described as a hierarchy containing constituent items $\{I_i\}$ at different levels of abstraction, where $\{I_i\}$ can be either abstract or physical entities. There is a set of attributes, defined as variety parameters, $\{P_j\}$, which associated with each I_i . Like attribute variables, parameters can be inherited by child node(s) from a parent node. Different instances of a particular P_j , e.g. $\{V_k\}$, embody the diversity resembled by, and perceived from, product variants (Tseng and Jiao, 2001).

2.2 Association rules mining

Association rules mining aims to find interesting or correlation rules that satisfied minimum support and minimum confidence requirements from a large set of data items. Therefore, this research employs association rules mining to constructing a classification mechanism between customer requirements and product architecture.

Agrawal et al. (1993, 1996) formalised the problem of finding association rules. Let I be a set of items and D be a database of transactions, each of which includes a set of

items. An association rule is an implication of the form: $X \Rightarrow Y$, where $X \subseteq I$, $Y \subseteq I$ and $X \cap Y = \emptyset$. X is the antecedent (body) and Y the consequent (head) of the rule.

Two measures, *support* and *confidence*, are used to indicate the quality of an association rule. The support of a rule is the percentage of transactions that contain both X and Y , which indicates how frequently that rule applies to the data, whereas the confidence of a rule is the fraction of transactions that contain X , that also contain Y , which is a measure of the reliability of an association rule. To select interesting rules from the set of all possible rules, a *minimum support* and a *minimum confidence* are fixed.

The most famous algorithms for association rules induction is the Apriori algorithm (Agrawal et al., 1993; Agrawal et al., 1996). Apriori algorithm is composed of the following two steps: In the first step, the frequent itemsets are discovered. These are sets of items that have at least the given minimum support threshold. In the second step, association rules are generated from the frequent itemsets found in the first step. The first step is the more important, because it affecting the performance of mining process. In order to make it efficient, the Apriori algorithm exploits the simple observation that no superset of an infrequent itemset can be frequent.

3 Methodology for customer requirement mapping process

3.1 Classification mechanism

Usually, customer requirements are imprecise and ambiguous, such as, the light should be bright, the colour need nice-looking, etc. Meanwhile, due to the different methods of customer expressing their real needs, customer requirements are multifarious and hard to deal with. In this research, we characterise customer requirements and product structure parameters by sets, which can be easily employed to data mining process.

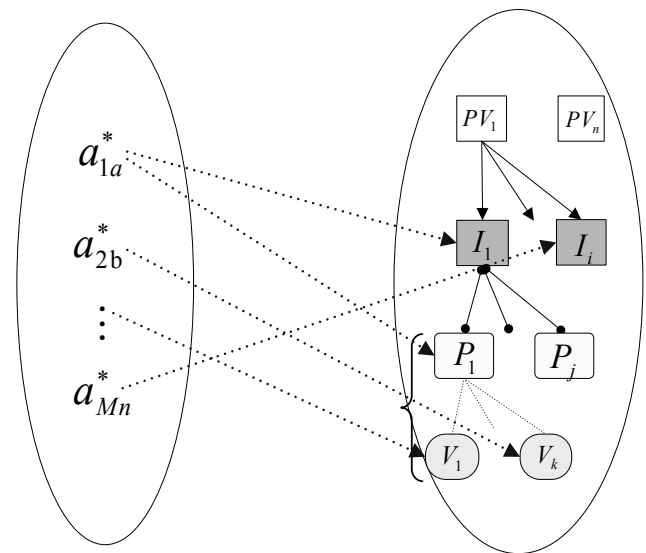
Customer requirements can be described as a set of attributes, $CA \equiv \{a_1, a_2, \dots, a_M\}$, where M denotes the number of customer requirements attributes (Jiao and Zhang, 2005). Each attribute has a set of options, instance sets, $a_i \equiv \{a_{i1}^*, a_{i2}^*, \dots, a_{in_i}^*\}$ where n_i denotes the i th option of the n th attribute. Suppose all customer comprise a set $C \{c_1, c_2, \dots, c_k\}$, where K is the number of customer, then, the set of all customer requirements attributes is $CA^* \equiv \{\overline{a_1}, \overline{a_2}, \dots, \overline{a_k}\}$ where $\overline{a_i}$ is corresponding to customer c_i requirements. For example, $\overline{a_k} \equiv \{a_{12}^*, a_{21}^*, \dots, a_{M3}^*\}$ where a_{12}^* denotes the second option of attribute a_1 as desired by customer c_k , a_{21}^* the first option of attribute a_2 , and a_{M3}^* the third option of attribute a_M .

In the same way, product structure parameters comprise a set, $PS \equiv \{s_1, s_2, \dots, s_N\}$, where N is the number of product structure parameters. Each parameter has a set of options, instance sets, $s_p \equiv \{s_{p1}^*, s_{p2}^*, \dots, s_{pt_p}^*\}$, where t_p denotes the p th instance of the t th parameters. Suppose all product variants of a product family comprise a set $PV \equiv \{pv_1, pv_2, \dots, pv_l\}$,

where L is the number of product variants, then, the set of all structure parameters of product variants is $PS^* \equiv \{\overline{s_1}, \overline{s_2}, \dots, \overline{s_l}\}$, where $\overline{s_j}$ is structure parameters option. For example, $\overline{s_i} \equiv \{s_{13}^*, s_{22}^*, \dots, s_{N1}^*\}$, where s_{13}^* denotes the third instance of parameter s_1 , s_{22}^* the second instance of parameter s_2 , and s_{N1}^* the first instance of parameter s_N .

Therefore, in order to find the relationship between customer requirements and product structure, the work need find the relationship between $\overline{a_k}$ and $\overline{s_l}$, in the form of $\langle \overline{a_k}, \overline{s_l} \rangle$, where $\overline{a_k}$ is the item in the set of customer requirement attributes and $\overline{s_l}$ is the item in the set of product structure parameters. Figure 2 shows the mechanism of finding the relationship between customer requirement items and product structure items.

Figure 2 Classification mechanism



Based on the company's sales records and product portfolio, we can extract transaction data related to which customer was met with which product variant. The target data is organised into a proper transaction database for data mining after pre-processing, such as data cleaning, removal of noises, handling of missing data, etc.

3.2 Determination of the importance weights of customer requirements

The importance of customer requirement items is different. Therefore, determination of the importance weights of customer requirements is essential. Prioritising customer requirements could be viewed as a complex multi-criteria decision making problem. Considering the vagueness and imprecision in the importance weights assessment, a fuzzy AHP (Analytic Hierarchy Process) approach is employed (Wong and Bai, 2002).

In order to present the vagueness, 1 to 9 are used to represent subjective pairwise comparisons of customer requirements. A fuzzy number is a special fuzzy set $M = \{r, \mu_M(r)\}, r \in R$, where r takes the real value, $R: -\infty < r < +\infty$, $\mu_M(r)$ is a continuous mapping from R to closed interval $[0,1]$. A triangular fuzzy number denotes as $N = (x, y, z)$, where $x \leq y \leq z$, has the following function:

$$\mu_N(r) = \begin{cases} 0 & r < x \\ \frac{r-x}{y-x} & x \leq r \leq y \\ \frac{z-r}{z-y} & y \leq r \leq z \\ 0 & r > z \end{cases}$$

And then, set the interval of confidences level $\alpha \in [0,1]$, the triangular fuzzy number can be presented as:

$$N_\alpha = [x^\alpha, z^\alpha] = [(y-x)\alpha + x, -(z-y)\alpha + z]$$

3.3 Mapping process

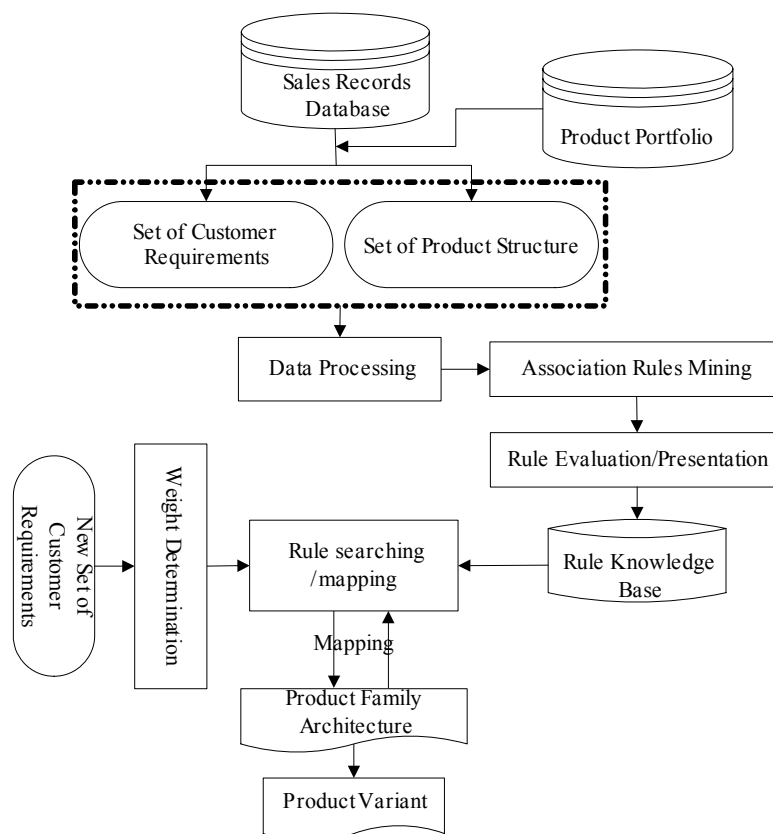
After using the Apriori algorithm, find all association rules of the form ‘**IF** requirement attribute A, and requirement attribute B ... requirement attribute M **THEN** structure parameter N’, which are satisfied *minimum support* and *minimum confidence*. A rule extraction regulation is employed, which assures the consequent of all rules put out is only one structure parameter. All the target results are put in knowledge base. The mapping process is searching the ‘right’ association rules based on the items in the set of

new customer requirement attributes, and then finding the most appropriate structure parameters to satisfy customer needs respectively. Each of the steps of the mapping process is discussed as follows:

- Step 1:* Initialise the first item in the set of new customer requirement attributes as the keyword, search those rules in the classification knowledge base, which antecedents is corresponding to the keyword.
- Step 2:* If the rule found in Step 1 is unique, then put out the consequent of this rule, i.e. structure parameter, and go to Step 6, otherwise, go to next.
- Step 3:* If the rules are not unique, then compare the support and confidence of these rules, put out the consequent of rule which has the largest support and confidence, and go to Step 6, otherwise go to next.
- Step 4:* If those rules have the same support and confidence, then compare the weights of requirement attributes, put out the rule which has the largest requirement weight, go to Step 6.
- Step 5:* If there is no rule which antecedent is corresponding to the keyword, then initialise the antecedent nearest to the former keyword as the new keyword, and go to Step 2.
- Step 6:* Initialise the remainder items as keywords to carry on mapping process, as far as the total items in the set of new customer requirement attributes are completed.

Figure 3 illustrates the architecture of methodology for customer requirements translation process.

Figure 3 Architecture for customer requirement translation process



4 Case study

4.1 Customer requirement attributes

The elevator cabin is a highly customised component of elevator product family. Elevator cabin consists of ceiling, walls, floor, handrail, door, lantern, aerator, button panel and so on. Examples of the related requirement attributes or options are listed in Table 1.

4.2 Classification mechanism

Extraction data from transaction database, examples of the mining association rules results listed in Table 2 after presentation. For example, the first rule notes that 90% are satisfied by the cabin dimension $H*W*L$: $2300 \times 1600 \times 1400$ (mm) when their requirement item is a ‘big cabin’. All the rules are put in knowledge base after evaluation for the translation process.

Table 2 Examples of classification knowledge

ID	Rules		Support	Confidence
	antecedent(a_{nh}^*)	consequent (s_{nh}^*)		
1	Big cabin	$H*W*L$: $2300 \times 1600 \times 1400$ (mm)	0.525	0.900
2	Big cabin	$H*W*L$: $2000 \times 1400 \times 1500$ (mm)	0.345	0.750
3	Luxury decoration bright illumination	Decorative material: stainless steel A	0.250	0.650
4	Luxury decoration low price	Decorative material: stainless steel B	0.250	0.650
5	Thick floor	5 (mm)	0.845	0.900
6	Bright illumination	Illuminating equipment A	0.740	0.980

4.3 Mapping process

A set of customer requirement attributes is $CA \equiv \{\text{big cabin, luxury decoration, bright illumination, thick floor, aerator needless, low price}\}$. By using the AHP approach, the importance weights of customer requirements are computed as [0.242, 0.141, 0.136, 0.131, 0.092, 0.258]. Followed the mapping process as described in part III, the cabin structure parameters are determined. The details are as follows:

Determination of cabin dimension: Initialise the first item in the set of new customer requirement attributes, i.e. big cabin, as the keyword, search those rules in the classification knowledge base, which antecedents is corresponding to ‘big cabin’. Two rules are found, $H*W*L$: $2300 \times 1600 \times 1400$ (mm) with support 0.525, confidence 0.900, and $H*W*L$: $2000 \times 1400 \times 1500$ (mm) with support 0.345, confidence 0.750. The support and confidence of the first rule is bigger than the second one, therefore, the cabin dimension is determined as ‘ $H*W*L$: $2300 \times 1600 \times 1400$ (mm)’.

Determination of decorative material: There are two rules found corresponding to ‘luxury decoration’: ‘luxury decoration and bright illumination \Rightarrow Decorative material: stainless steel A’ and ‘luxury decoration and low price \Rightarrow Decorative material: stainless steel B’ with the same support and confidence, 0.250, 0.650 respectively. It is paradoxical; therefore, comparing the importance weight of customer requirements is necessary. The importance weight

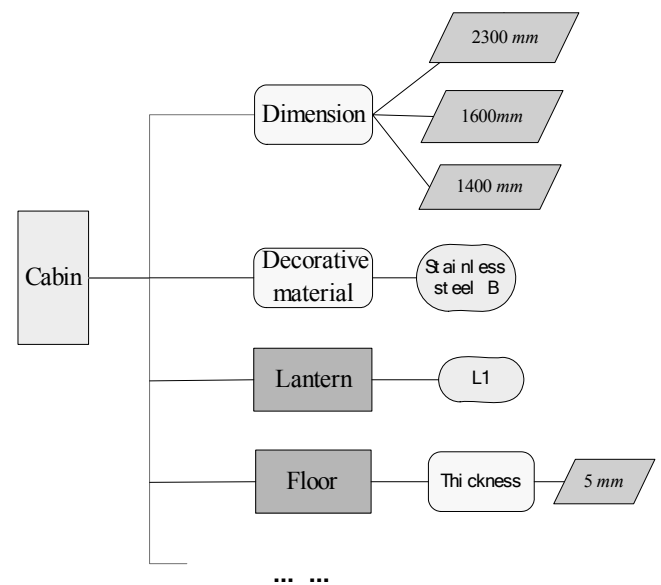
Table 1 Examples of customer requirement attributes

Set of customer requirements attributes (CA^*)	Set of attribute instance (a_i)	Description
Cabin dimension	$a_{11}^* a_{12}^* a_{13}^*$	Big, common small
Decorative material	$a_{21}^* a_{22}^* a_{23}^*$	Luxury, common, coarse
Lantern	$a_{31}^* a_{32}^*$	Bright, soft
Floor thickness	$a_{41}^* a_{42}^*$	Thick, common
Aerator	$a_{51}^* a_{52}^*$	Breezy, needless
Total price	$a_{61}^* a_{62}^* a_{63}^*$	High, common, low

of luxury decoration is 0.141 and low price is 0.258, therefore, the decorative material is stainless steel B.

Continue the mapping process, all the cabin structure parameters can be determined, example of the cabin GBOM is illustrated as Figure 4.

Figure 4 Example structure of product variant for customer requirements after translation



5 Conclusion and future work

Comprehending the 'VOC' is the key step for product variety design of MC in today's extremely competitive environment. In this paper, a novel customer requirements translation method by constructing a classification mechanism between customer requirements and product architecture was presented. In the methodology, association rules mining was employed to find the relationship between customer requirements and the items of product family architecture. And a fuzzy AHP approach was introduced to compute the importance weights of customer requirements. This method can decrease mutual process between customer and designer, improve the product design quality, and thus further satisfy customer needs.

An example of customer requirements translation of the elevator cabin is used to illustrate the proposed method. The overall results show that the using data mining to translate customer requirements is an effective approach.

In fact, translation of customer requirement is a complex and systemic problem, and our work is a primitive model. The future work will focus on other problems such as configuration constraint to improve the method approved in this paper.

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Reliability evaluation of conceptual colour design based on rough sets

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Abstract: Conceptual Colour Design (CCD) is a key step in product innovation. And to identify whether colours meet market demands is crucial for making right conceptual design. Thus a new reliability evaluation method of CCD is proposed in this paper. Firstly, a pure reliability evaluation model is presented according to the Euclidean distance between colour design ideas and market demand. Secondly, RS theory is introduced into calculating weights of influencing factors of colour market demand. The process of constructing decision table of colour RS and extracting weights is presented in detail. Thirdly, an integrated reliability model considering the Euclidean distance and weights of influencing factors is given. Finally, a CCD case of dress is analysed using this method. The results show the evaluation method is practical and effective.

Keywords: conceptual design; colour design; reliability evaluation; rough sets.

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1 Introduction

Conceptual Colour Design (CCD) is an early step in product colour design. CCD usually refers to selecting colours according to market demand (Luo, 2006). The detailed colour design will be processed according to the colours selected. It is predictable that a cyclone in Texas would be brought by a butterfly's flying in Brazil, which is the famous 'Butterfly Phenomenon' from Laurens' report. Similar phenomenon has been found in product development, i.e. a little discrepancy in Conceptual Design (CD) can lead the anaphase design away from original requirement. It is well said that a miss is as good as a mile. Obviously, CCD is very significant for improving product enchantment in market competition.

In recent years, many studies have been presented on conceptual product design (Gao and Li, 2007) and pre-market forecasting (Urban et al., 1996). However, there is a shortage of theory or tools for CCD. Industrial designers and artists select colours almost according to their experiences while inspirations come. Whether the colours selected answer for market demand remains to be proved. Therefore, it is necessary to evaluate the reliability of CCD using computer aided design tools before further detail design.

The reliability of CCD can be defined as follow. Given that λ is the difference between colours presented by designer and the market demand from consumers, CCD reliability is formularised as

$$\xi = 1 - \lambda, \quad (1)$$

where ξ is the reliability value, and $\lambda \in [0,1]$ is the Euclidean distance between colour design ideas and market demand. Obviously, the value of ξ will be high when design ideas satisfy consumer demand, or else the value will be low.

From the perspective of cognitive science, the information of design ideas and colour market demand are both considered as knowledge. CCD reliability evaluation requires that the CAD system is not only developed with abundant colour interrelated knowledge, but also able to extract useful information from existing knowledge. Now there are many knowledge representation methods, for example logic model, framework, semantic networks, production rules, the state space and artificial network (Zha et al., 2004). However, the factors influencing colour market demand are incomplete, uncertain and vague. The methods mentioned above are unable to extract implication knowledge or to create new knowledge from ambiguous knowledge.

Rough Set (RS) theory, originated by Z. Pawlak in 1982, is a formal mathematical theory modelling knowledge in terms of equivalence relations (Francis and Shen, 2002). The main advantage of RS theory is that it does not need any preliminary or additional information about data (like probability in probability theory, grade of membership in fuzzy set theory, etc.). RS theory supports a series of knowledge engineering, such as data preparation, data reduction, rule generation and data-dependent access. RS theory has been applied in a number of areas, mostly in processing incomplete and ambiguous knowledge (Francis and Shen, 2002).

Thus, an evaluating method of CCD reliability based on RS theory is proposed in this paper. RS is applied in extracting the weights (i.e. attributes importance in decision table)

of the influencing factors of colour market demand. Attributes importance provides a reliable basis for the quantitative evaluation of CCD reliability in this paper.

2 Evaluating CCD reliability based on RS

2.1 Basic definitions of RS

Only the introductory part of RSs is reviewed here, as it is sufficient for showing how to evaluate the reliability of CCD.

A colour market demand information system S consisting of four parts is defined as

$$S = \langle U, R, V, f \rangle,$$

where U is a non-empty, finite set of objects, i.e. $U = \{x_1, x_2, \dots, x_i, \dots, x_n\}$, where x_i is an object;

R is the collection of attributes, we have $R = C \cup D$ and $C \cap D = \emptyset$, where C is a non-empty, finite set of condition attributes including culture, nationality, season, region, industry, and so on; and D is a non-empty set of decision attributes which usually refer to the popular degree of colour objects;

V is the union of attribute domains, i.e. $V = \bigcup_{r \in R} V_r$,

where $V_r = [-1, 1]$ is a finite attribute domain, and every element of V_r is a value of the attribute r ; and f is an information function such that $f(x_i, r) \in V_r$ for every $r \in R$ and $x_i \in U$.

The object x_i has some necessary attribute information in the domain U . Generally, the objects can be classified using this attribute information. If two elements have the same attribute information, we would not able to divide them precisely. Then, we call the relationship between them an equivalence relation or indiscernibility relation. The definition of the indiscernibility relation can be written as follows.

Given an information system $S = \langle U, R, V, f \rangle$ and $x_i, x_j \in U$; when $f(x_i, r) = f(x_j, r)$, i.e. $V_i = V_j$, we say x_i and x_j are indiscernible, and say $(x_i x_j)$ is a duality indiscernibility relation about the element r , the indiscernibility relation is written as $\text{IND}(r)$. Thus the equivalence relation set cluster consisting of all indiscernibility relations about attribute R is written as $\text{IND}(R) = \bigcap_{r \in R} \text{IND}(\{r\})$. It also can be written as

follows:

$$\begin{aligned} U / \text{IND}(R) &= U / R \\ &= \{(x_i, x_j) \mid x_i \in U \wedge x_j \in U \wedge \forall r \in R \wedge f(x_i, r) = f(x_j, r)\} \\ &= \{f(x_j, r)\} \end{aligned} \quad (2)$$

In addition, the RSs approach to data analysis hinges on two basic concepts, namely the lower approximation set $B_-(X)$ and the upper approximation set $B^-(X)$. They can also be presented using the Y_i basic sets of equivalence relation set cluster as below:

$$B^-(X) = \bigcup \{Y_i \mid Y_i \in U / B \wedge Y_i \cap X \neq \emptyset\}, \quad (3)$$

$$B_-(X) = \cup\{Y_i | Y_i \in U / B \wedge Y_i \subseteq X\}, \tag{4}$$

where, we have $POS_B(X) = B_-(X)$ which is called positive region of X with B , and $NEG_B(X) = U \setminus B_-(X)$ is called negative region of X with B .

To sum up, for every subset $X \subseteq U$, if X can be differentiated precisely with attribute R , we say that X is a precision set, otherwise call X a RS. And all RSs satisfy the inequality

$$B_-(X) \neq B^-(X). \tag{5}$$

2.2 Decision table of colour RS

Decision table is a kind of special and important knowledge expression system in RS theory (Masahiro and Takuya, 2007). It is good at expressing the decision-making (the behaviour, operation, reasoning, control) how to proceed when certain conditions are met.

Decision table of colour RS can be described with the information system $S = \langle U, R, V, f \rangle$ defined in the Section 2.1. Obviously, objects, attribute and descriptor are the three basic elements of representing decision table. And decision table is a two-dimensional sheet, where rows are

object's attribute information while columns are object's marker. Each row contains the information describing the object character, and the information about the object types (Table 1).

Generally some designers usually present colour ideas with semantic interpretation of colour emotion (Ou et al., 2004) while others are accustomed to select colours from colour palette directly. There are mapping functions between colours and colour emotions. We have established a system for the mapping between colours and the multi-dimension colour emotions (Quan et al., 2006). In order to satisfy both needs with computer-aided CCD system, we add a column of hexadecimal sign of RGB colour objects in the decision table. System users will see the colour palette and colour emotion semantic scales at the same time. RGB colour model consisting of three decimal variables, i.e. $R \in [0, 255]$, $G \in [0, 255]$ and $B \in [0, 255]$, is hard to used in the decision table directly. The hexadecimal sign corresponding to RGB model is convenient for coding and searching operation in the decision table. For example, the dark-blue colour with RGB model is written as: $R = 8$, $G = 100$, $B = 255$, when converted to 32 bit hexadecimal mode it is written as 0x000864FF.

Table 1 The decision table of colour RS

U (colour objects domain)	Hexadecimal sign of RGB colour objects	C (Condition attribute)							D (Decision attribute)
		Semantic interpretation of colour emotion			Season	Region	Industry	Other condition	Popular degree
		Cool-warm (c1)	Light-heavy (c2)	Soft-hard (c3)					
x1	0x00270636	-0.9	0.6	-0.6	spring	Xi'an	dress	.....	0.2
x2	0x000001A0	-0.3	-0.3	0.6	summer	Xi'an	dress	.....	0.4
x3	0x00FFBBAA	0.6	-0.3	-0.3	spring	Xi'an	dress	.....	0.7
x4	0x00FFBA92	0.3	-0.6	0.3	autumn	Xi'an	dress	.....	0.5
x5	0x00FFF6CF	0.3	0.6	0.6	winter	Xi'an	dress	.....	0.6
x6	0x00FFD6D9	0.6	-0.3	0.3	summer	Xi'an	dress	.....	0.4
x7	0x00E8B1BC	-0.3	-0.6	0.3	summer	Xi'an	dress	.....	0.9
x8	0x00FFA6A9	0.9	-0.3	0.6	winter	Xi'an	dress	.....	0.7
.....	.....	.....	.....	.....	.....	Xi'an	dress	.....	.....

Natural language is a significant way to express ideas from deep brain. In the field of industrial design, researches in product semantics intend to understand how we as human beings interpret the appearance (e.g. colour and shape), the use and the context of a product (Krippendorff and Butter, 1984). Semantic interpretation with natural language is frequently used by designers and artists to express colour design ideas (Shang and Ming, 2000). Furthermore, semantic interpretation of colour emotion is the embodiment of influencing factors of colour market demand. Thus semantic interpretation of colour emotion is considered as important condition attribute in the decision table. The most significant semantic interpretations of colour emotion are cool-warm, light-heavy and soft-hard (Ou et al., 2004). The Semantic

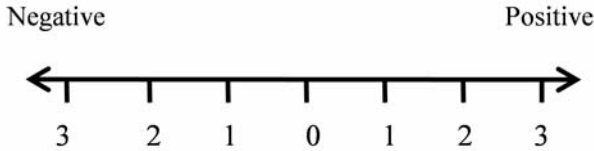
Differential (SD) method (Krippendorff and Butter, 1984) measures people's reactions to stimulus words and concepts in terms of ratings on bipolar scales defined with contrasting adjectives at each end (Figure 1).

Usually, the position marked 0 is labelled 'neutral', the 1 positions are labelled 'slightly', the 2 positions 'quite', and the three positions 'extremely'. Accordingly, the semantic pairs are usually described using SD as a fuzzy set $\{-0.9, -0.6, -0.3, 0.0, 0.3, 0.6, 0.9\}$ corresponding to semantic intensity (slightly through extremely) and direction (e.g. negative vs. positive) in the decision table (Table 1).

It is known to all that fashion colour plays a powerful guiding role in the consumer market. Generally, fashion colour changes cyclically under the influencing factors

including region, culture, industry and climate (Moore and Cassill, 2001). In this paper, fashion colour is used for evaluating the reliability of colour design ideas, the decision table of colour RS is filled with the dress fashion colour record data through 2001 to 2006 years in Xian city of China, a little part of the record is shown in Table 1. In this case, the popular degree value, i.e. the decision attribute, is a relative per centum from market research.

Figure 1 Semantic differential scale



2.3 Algorithm of extracting attributes important

In many past researches of evaluation method, weight value of the influencing factors always was given by experts according subjective experiment and knowledge (Francis and Shen, 2002). In this paper, the weight value of influencing factors of colour market demand will be extracted objectively from the statistical record of fashion colour.

In Table 1, every condition attribute value domain is $\{-0.9, -0.6, -0.3, 0.0, 0.3, 0.6, 0.9\}$. The condition attribute set $C = \{c_1, c_2, c_3\}$ is used for showing how to extract weight value in this paper. According to equation (2), if the U displayed is differentiated by the ‘cool-warm’ condition attribute c_1 , we get the equivalence relation set cluster is given as $U/c_1 = \{\{x_1\}, \{x_2\}, \{x_3, x_6\}, \{x_4, x_5\}, \{x_7\}, \{x_8\}\}$.

Similarly, we can get the integration equivalence relation set cluster differentiated by c_1 and c_2 as below $U/(c_1, c_2) = \{\{x_1\}, \{x_2\}, \{x_3, x_6\}, \{x_4\}, \{x_5\}, \{x_7\}, \{x_8\}\}$.

Given an object set cluster $F = \{X_1, X_2, \dots, X_n\}$ of the information system S, and $U = \bigcup_{i=1}^n X_i$. Let B is a subset of the attribute set, then classification quality is written as

$$r_B(F) = \frac{\sum_{i=1}^n |B_-(X_i)|}{|U|} \tag{6}$$

or,

$$r_B(F) = \frac{\text{CARD}(\text{POS}_B(F))}{\text{CARD}(U)}, \tag{7}$$

where the symbol ‘|·|’ and the function CARD are both used for calculating the element number of a set cluster.

Given the set cluster F fetched with decision attribute D, the weight of attribute subset C’ for the attribute set C is defined as

$$w_{C'} = r_C(F) - r_{C \setminus C'}(F) \tag{8}$$

where $r_C(F)$ is the classification quality of the attribute C; $r_{C \setminus C'}(F)$ is the classification quality of the attribute C without C’.

This formula describes how much change of the classification quality will be taken by deleting the subset C’, i.e. the amount of the element number of $\text{POS}_{C'}(F)$. And he change is bigger the attribute is more important.

As it is, the summation of all the weight values is not a constant. In order to apply weight value for the evaluation of CCD, a unifying equation is given as

$$W_i = \frac{w_i}{\sum_{i=1}^n w_i} \tag{9}$$

According to the definition of CCD reliability, the integrated reliability equation is written as

$$\xi = 1 - \sqrt{\sum_{i=1}^n W_i \left(\frac{t_i - t'_i}{T_i}\right)^2} \tag{10}$$

where ξ is CCD reliability value; W_i is the weight value of the c_i attribute, $i = 1, 2, \dots, n$. $t_i - t'_i / T_i$ is the unified Euclidean distance of every attribute between the selected colour and the market demand, where t_i is the attribute value of a selected colour, t'_i is an attribute value of the goal market fashion colour, T is the domain value of the c_i attribute.

2.4 A case of evaluating CCD reliability

Market demand is always the most significant criterion of evaluating the reliability of the CCD. A dress colour market research for the 2007 spring was performed in the 2006 winter, in Xian, China. The colour demand questionnaire used in market research is shown in Figure 2. The market research data has been processed through particular statistical analysis. The statistical result, i.e. the colour market demand, is described as ‘quite warm, quite light and quite soft’. The quantificational fuzzy set corresponding to the market demand is given as $\Omega = \{0.6, -0.6, -0.6\}$. Where the set Ω domain is $[-0.9, 0.9]$, and the domain value $T = 1.8$.

Figure 2 Colour demand questionnaire

The data shown in Table 1 is used in this case. We have the object domain U, the decision attribute D, and the condition attribute set $X = \{c_1, c_2, c_3\}$.

Suppose the colour design idea given by designer expresses a feeling of ‘slightly cool, quite light and quite soft’. The colour selected can be described by the attribute set X .

According to equation (2), it is easy to get equivalence relation set clusters as follows:

$$\begin{aligned}
 F = U/D &= \{\{x_1\}, \{x_2, x_6\}, \{x_3, x_8\}, \{x_4\}, \{x_5\}, \{x_7\}\}, \\
 U/(c_1, c_2) &= \{\{x_1\}, \{x_2\}, \{x_3, x_6\}, \{x_4\}, \{x_5\}, \{x_7\}, \{x_8\}\}, \\
 U/(c_1, c_3) &= \{\{x_1\}, \{x_2\}, \{x_3\}, \{x_4\}, \{x_5\}, \{x_6\}, \{x_7\}, \{x_8\}\}, \\
 U/(c_2, c_3) &= \{\{x_1\}, \{x_2, x_8\}, \{x_3\}, \{x_4, x_7\}, \{x_5\}, \{x_6\}\}, \\
 U/(c_1, c_2, c_3) &= \{\{x_1\}, \{x_2\}, \{x_3\}, \{x_4\}, \{x_5\}, \{x_6\}, \{x_7\}, \{x_8\}\}.
 \end{aligned}$$

Using equations (3) and (4), we can get the approximation sets as:

$$\begin{aligned}
 POS_C(F) &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8\}, \\
 POS_{C \setminus c_1}(F) &= \{x_1, x_3, x_5, x_6\}, \\
 POS_{C \setminus c_2}(F) &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8\}, \\
 POS_{C \setminus c_3}(F) &= \{x_1, x_2, x_4, x_5, x_7, x_8\}.
 \end{aligned}$$

According to equations (6) and (7), the classification qualities are written as:

$$\begin{aligned}
 r_C(F) &= 8/8 = 1, \\
 r_{C \setminus c_1}(F) &= 4/8 = 0.5, \\
 r_{C \setminus c_2}(F) &= 8/8 = 1, \\
 r_{C \setminus c_3}(F) &= 6/8 = 0.75.
 \end{aligned}$$

Then, every attribute importance is extracted according to equation (8) as follows:

$$w_1 = 0.5, w_2 = 0, w_3 = 0.25.$$

According to equation (9), the unified weight values can be written as

$$W_1 = 0.67, W_2 = 0, W_3 = 0.33.$$

Finally, CCD reliability value is obtained from equation (10).

$$\xi = 1 - \sqrt{0.67 \times \left(\frac{-0.3 - 0.6}{1.8}\right)^2 + 0 \times \left(\frac{-0.6 + 0.6}{1.8}\right)^2 + 0.33 \times \left(\frac{-0.6 + 0.6}{1.8}\right)^2} = 0.59$$

In addition, seven CDs are also have been evaluated using this method. The results are shown in Table 2.

Table 2 The reliability evaluation results of CCD

S. No.	Description of CCD	Reliability
1	Slightly cool, extremely light, quite soft	0.59
2	Slightly cool, quite heavy, quite soft	0.59
3	Quite warm, quite light, slightly hard	0.62
4	Quite warm, quite heavy, quite soft	1.00
5	Extremely warm, quite heavy, extremely hard	0.50
6	Neutral, slightly light, quite soft	0.73
7	Extremely cool, quite light, extremely hard	0.17

Obviously, the test results above show that the weight of the attribute ‘cool-warm’ is the biggest one while the weight of the attribute ‘light-heavy’ is the smallest one. The former has a great effect on CCD reliability, and the latter has no effect because its value is zero.

To sum up, this evaluation method based on RS can represent CCD reliability objectively and quantificationally, which is convenient for selecting conceptual colours by designer and intending intelligent design system. In addition, the important precondition is that the colour market demand and the colour popular history records used for evaluating are reliable.

3 Conclusion

CD is considered as the most critical stage in product development. A CD begins with market demand and ends with product concepts description. The main focus of the CCD is to select primary and secondary colours for product. However, CCD usually is carried through subjectively by designers. It is unknown whether the colours selected by designer will meet the market demand.

In this paper, a reliability evaluation method based on RS for CCD is proposed. A reliability evaluation model is built according to the weighted difference between colour design ideas and colour market demand. Colour market demand can be acquired through market research. Influencing factors of market demand are processed using decision table of colour RS. The weights of influencing factors are extracted by RS algorithm. The reliability evaluation model is tested with a CCD of dress. The results show that the method based on RS can evaluate reliability of CCD objectively and quantificationally, which is propitious to make good winning in product development.

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Fine grain associative feature reasoning in collaborative engineering

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Abstract: This paper explores the vast domain of systematic collaborative engineering with reference to product lifecycle management approach from the angle of feature-level collaboration among partners. A new method of fine grain feature association modelling and reasoning is proposed. The original contribution is on the explicit modelling and reasoning of collaborative feature relations within a dynamic context. A case study has been carried out to illustrate the interweaving feature relations in collaborative oil-rig space management and the effective application of such relations modelled in design solution optimisation.

Keywords: fine-grain associations; feature-based collaboration; collaborative engineering; CAD/CAM; intelligent design.

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1 Introduction

Product lifecycle management has been an active research domain in recent years but its scientific framework and key supporting theories are still evolving with different schools of thoughts. Many researchers and developers extended design and manufacturing information systems to cover the full spectrum of product lifecycles. Such effort can be represented by some commercial software packages, such as Teamcenter (Siemens AG, 2007), Windchill (PTC.com, 2007), etc.

Saaksvuori and Immonen (2005) have systematically described this approach. Although such systems and studies have advanced engineering system integration coverage to a broad business management domain supported with databases and network technologies, the key challenging problems, such as semantic interoperability, detailed engineering constraint management, effective and efficient change management, still left unresolved. This paper looks into these challenges from a totally different angle. Instead of building an engineering information system by integrating different application systems

piece by piece, a complete and open product lifecycle repository system supporting multiple applications, systems and stages is proposed (Ma et al., 2007a). The key contribution of this method to the field of research is the unlimited information grain size of application integration. The characteristics created with such fine grain system integration are the full support of associative features within and across different applications or lifecycle stages; constraints can be flexibly created and managed. In turn, the product model can be seamlessly integrated with engineering process model in a smart modelling manner. Then detailed business and engineering intelligence could be embedded into the system's integrated product and process model. Eventually, pervasive and intelligent collaborative engineering can be enabled.

2 Literature review

Concurrent engineering promotes engineering considerations about all lifecycle issues in parallel across different stages (Prasad, 1997). The traditional sequential mode of product development has been changed into an iterative and evolutionary mode. Product development becomes evolution of design and manufacturing processes via tight application integration and parallel engineering. At the same time, collaborative engineering approach has grown significantly to support distributed, multi-discipline and multi-organisation teams during the product development processes. This approach is motivated by the globalisation of economy and boosted by the development of the internet (Wang et al., 2002; Fuh and Li, 2005; Yang and Zhang, 2006). In general, systematic product and process modelling methods developed are useful for both concurrent and collaborative engineering. In fact, these two business approaches have been blended into a global business management trend and create a more system oriented concurrent and collaborative approach. Concurrent and collaborative engineering deals with either separate or integrated applications via associations. To support such inter-weaving, integrated, and complex engineering systems, informatics modelling plays an essential role.

When studying individual engineering areas, such as design, manufacturing and management processes, Knowledge-Based Engineering (KBE) is a common practice in many CAx systems to support decision making, such as functional design and process planning, etc. (Zha et al., 2001; Tor et al., 2002; Park, 2003).

Fundamentally, system integration is a problem of information sharing and management. As to the contents of information, it can be largely classified into product-related data and process-related data. Within the domain of product-related data, two categories exist, i.e. geometric and non-geometric. Traditionally, application integration was based on the geometric data sharing. For example, integrations between product design and tooling design, reverse engineering, rapid prototyping, computerised numerical machining control, coordinate measuring machine, mesh generation for CAE, virtual reality systems, etc. have been widely studied (Kramer et al., 2001; Deng et al., 2002). STEP and IGES standards have been developed for this purpose. However, they are aimed

to achieve the required interoperability mainly for geometric information. To allow early design anticipation and later change management across the product lifecycle stages, ever more close value chains are being formed in modern collaborative engineering, and then non-geometric information are shared and used while the intellectual properties must be surely warranted. Such industrial applications demand a systematic approach to enable the interoperability for managing not only product or process geometric entities but also their related constraints and semantics. The authors propose a unified associative feature-based approach.

3 Theoretical exploration

3.1 From feature templates to associative features

The concept of features is flexible and can be used in many aspects of mechanical engineering. There are various definitions about features for different application domains. Representatives of feature definitions include a region of interest in a part model (Wilson and Pratt, 1988), any geometric form or entity that is used in reasoning in one or more design or manufacturing activities (Cunningham et al., 1996), generic shapes associated to certain properties or attributes and knowledge useful in reasoning about the product (Shah, 1991), regions of an object that are meaningful for a specific activity or application (Vandenbrande and Requicha, 1993), a set of form elements with a functional meaning in a given application context that allows an association between shape and functionality (Martino et al., 1998), a representation of shape aspects of a product that can be mapped to a generic shape and are functionally significant for some product lifecycle phase (Bidarra and Bronsvort, 2000), etc. These definitions reveal that features have two fundamental characteristics: being related to product information in a higher level than geometric and topological entities; and representing engineering semantics.

However, in the current CAD/CAM technology, features are generally parametric patterns of 'basic unit of knowledge'. Features are defined in a 'fixed' pattern that can be defined with a group of 'fixed' constraints. A new concept, named 'associative feature' was introduced (Ma and Tong, 2003) suggesting a new method of feature modelling where a type of continuously changing features can be defined in object-oriented manner, and the feature properties and behaviours evolve as the associative feature evolves. As stated in Ma and Tong (2003) that associative features should have the following key characteristics: (1) built-in associative links to its related geometric entities; (2) self-validation for the consistency of its entities, attributes, constraints, etc.; (3) methods available for constructing, storing, indexing, editing and destroying its instances; (4) methods that can be expanded to interface with query and execution mechanisms for high-level knowledge processes; (5) methods to interface with other engineering application tools. The conceptual representation of associative feature is very much related to the definitions of 'generic feature' and 'generic constraint' as described by Ma et al. (2007a).

It is a theoretical advancement to suggest that features are kept valid and associated throughout a product lifecycle instead of within just one stage or one application of the lifecycle, such as detailed product design. A well-defined feature object type (or a class) has to be developed to cover the various stages of lifecycles of different mechanical components in a very generic yet abstracted form. More recently, the concept of associative assembly features (Ma et al., 2007b) has extended the 'breadth' of *associative features* to cover assembly patterns with good scalability across components or assembly members. The successful implementation proves that associative features can be applied to serve as the intermediate layer of information representation to interface the tedious CAD geometry and the related attribute creation and manipulation methods with high-level knowledge management and engineering. Associative feature approach can effectively enhance traditional feature-based technology in three aspects: design change management by features, semantic modelling for engineering rules and engineering models' reuse. Then, it is clear that the next natural research work of this technology is to develop the generic mechanisms of capturing, storing and retrieving engineering knowledge with the support of associative features because if the effort is successful, a full cluster of associative features can be *persistently modelled* to support product lifecycle management. To achieve this goal, more effective interoperability among computer systems is essential.

3.2 Existing standards supporting interoperability

Interoperability can be described as the exchangeability and usability of data types and related information between two or among more systems or components. Interoperability among engineering software tools is in high demand due to globalisation and value chain integration. In the past, interoperability has always been a 'problem' because data formats and their embedded data structures (schemas) become a means of protection of commercial interests. To date, interoperability has only been achieved at the data level. IGES and STEP-based interoperability depends upon geometry modelling standardisation. Mere geometric entities are converted from one format to another based on the common B-Rep and CSG frameworks. For example, STEP has obvious limitations on semantics and high-level entity types such as user-defined features and constraints. If a parametric part is created in Pro-E with features, such as counter-bore holes, chamfers, or boss cylinders, after being exported into a STEP file and imported into UGS NX, the model becomes a fixed solid block. The observation from the informatics point of view can reveal that the information grain size is at the 'file level' when data exchanges take place. In addition, the contents of the files are partially translated due to the inconsistent definitions of semantic entities.

3.3 Engineering intent representation and management

Theoretically, all CAx applications should operate on a common set of data so that the product engineering and management can be effective and efficient to manage changes

required. However, as reviewed above, in reality, different applications have difficulties in sharing a consistent product model space because of their different semantic representations and derived variations.

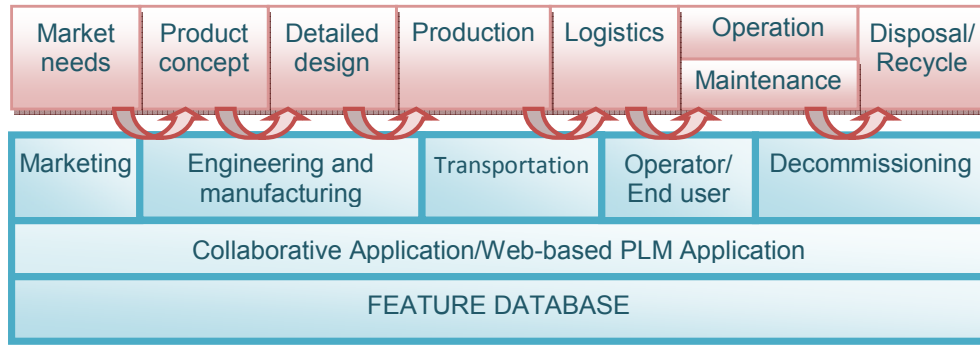
The representation and processing methods for engineering intent depends on the collective grouping of constraints and the reasoning or optimisation methods. Many decisions made in the product development and manufacturing processes are supported by engineering principles, concepts, and rules. However, engineering intent, such as 'know-how', has been only implicitly embedded in product data relations. So far, very limited works are done in constraint management that is associated to engineering intent. The lack of intent representation has affected the product validation processes. Developing a unified and associative collaborative engineering platform is a challenge in engineering informatics.

When engineering intent is represented explicitly by the collective groups of constraints and entities, due to the continuing involvement and changes along the product lifecycle, such constraints have to be maintained systematically to keep its validity. This requirement involves data consistency and validation checking methods. It can be appreciated that for a product, there is a master product model. All other related models, such as analysis models, manufacturing models, tooling models, quality models, and even the MRP and ERP models, are either directly based on or associated to the master model. Figure 1 gives an information structure that shows the coverage of an ideal PLM system and the supporting sub-systems according to the authors. Engineering intent expressed by well-defined relations can be explicitly represented and managed via database technology. In general, there exists a continued flow of engineering or business intent throughout the stages of a product lifecycle. When the application scope is scaled from a small enterprise to a bigger one, or even to a full-scale OEM like Boeing and GM, the configurations of products and lifecycles to be managed could become tremendously important and very complicated. Then there is an issue of scalability too.

3.4 Fine grain interoperability and associations

In recent years, the concept of 'open' data formats or source codes is gaining acceptance due to customer demands for collaboration in the global arena. Data-oriented functions, such as creating a solid in CAD systems, have become a common expectation. Currently, the interoperability among different systems is confined by the accessible neutral-information grain size. In order to facilitate engineering collaboration, therefore, the research of interoperability at the level of semantic knowledge becomes imperative. This topic covers the informatics modelling for semantic information sharing, mapping, manipulation, conversion and knowledge-based reasoning and automation (Bronsvort and Noort, 2004; Gao et al., 2004; Pratt and Srinivasan, 2005). To solve this problem, a scheme like 'the valuing system' of 'trading currencies' in a large market is needed. For higher level semantic information association and sharing, a common and flexible standardised scheme is required but not yet available (Kim et al., 2006; Ou-Yang and Chang, 2006; Ouertani and Gzara, 2007).

Figure 1 Information model structure for a fine grain feature-based collaborative engineering (see online version for colours)



The authors champion associative, fine-grain feature-based modelling approach. Fine grain associations refer to the relations created or used for certain engineering purpose among engineering entities without the limitation of access, even to entities below 3D solid or part level. It is tied closely to the associative feature concept that has been introduced by the authors in early publications (Ma and Tong, 2003). To generalise the effort, the engineering intent has to be explicitly modelled and ‘materialised’ in the form of engineering associative features which consist of lower level entities, constraints and reasoning methods. In other words, generic engineering intent can be modelled in the form of a set of *live objects* according to the principles of software informatics while the collective properties and behaviour can be dynamically created and managed by creating the associated objects across different grain sizes, keeping the relations persistently, managing their applied methods, and evolving their statuses or stages. Then many dynamic changing scenarios with the effective context support can be illustrated. By managing these scenarios, intelligent design and manufacturing can be achieved.

Towards to this direction, a preliminary case study on the space management of pipelines in oil-rig construction industry is demonstrated. The above theoretical points are further explained with the example.

4 Case study

This study focuses on ‘pipeline feature’ modelling supported with fine-grain ‘context’ extraction and optimisation of space management in oil-rig design. It is an extension to a student’s research project of parametric computer-aided design with Solidworks. Due to the limitation of resources, the project did not involve multiple CAD systems. The prototype system can generate an oil-rig model with the programming toolkit. Associative context space has been modelled via C++ programming and dynamically derived via CAD API functions. The research element in this project is how space management can be automatically and intelligently optimised via the associative feature object methods and an algorithm interacting with the surrounding context. Then pipeline planning and preliminary 3D layout management are tested interactively with the support of a grid-based optimisation

algorithm. The key research impact is on the method for associative design feature modelling, generation and management with constraints. Each instance of the associative pipeline feature can be automatically created, analysed and semi-automatically optimised in stages with the developed program. According to the authors’ knowledge, no similar previous work has been reported.

Similar to the cooling channel modelling reported in early publication (Ma and Tong, 2003), the pipeline of an installed oil-rig system is modelled as a functioning object with the following characteristics: (1) The pipeline is modelled in a continuously evolving associative feature with flexible behaviours defined with well-defined constraints. The essential member entities are the connection segments and attached interfacing mechanical elements that form a connected ‘path’ from a start position to the destination position. This path is modelled as a set of connected line and arc segment in 3D space. Each segment has the starting point and vector, ending point and vector, as well as the connectivity constraints. Such constraints are added along the process of concept development by the designers interactively. When a pipeline is initially designed, a simplified pattern is automatically generated with the built-in constraints of segment connectivity, inlet and outlet ending flange geometry, and initial given raw material lengths. (2) Within a given space envelope interested, the existing parts or systems are searched and extracted for verification. (3) Some engineering rules are built into the design algorithm by specifying optimisation constraints, e.g. ‘the minimum crossing space between pipelines has to be more than x meters’, ‘the use of lower space is prioritised for the ease of maintenance’, ‘reserving maximum space for operational use’, etc.

To represent the space occupation and for the ease of space analysis, a 3D space-grid method to model the interested space environment is developed. To simply explain the concept, a 2D concept is shown in Figure 2. The grid elements are represented by a binary array and the availability is simply represented by ‘True’ or ‘False’ Boolean value. The grid size can be adjusted according to the required resolution or the scale of the interested space. The grids are also very easy to be indexed and analysed to derive the available space clouds, with the detailed distribution and topological neighbourhood search. With a reference coordinate system, the minimum or maximum

space locations can be easily determined via a few simple iterative functions. Then it can be built into the software to search for the possible paths that a pipeline can be installed with the minimum space due to engineering requirement. For illustration purpose, again, a 2D path via available grids is shown in Figure 3. Clearly, more often than not, there are many solutions, and optimisation based on the selection criteria is necessary. First, characteristic attributes or

properties of the pipeline paths have to be modelled and analysed. Then the ‘associative pipeline’ feature object class can be developed. While different solutions determined by an algorithm automatically are feasible objects, or ‘options’ for the designers to select interactively, based on merits of different solutions, the contents of the pipeline are captured gradually such that the object instance becomes more and more materialised or ‘solidified’.

Figure 2 2D schematic representation of space occupation and the path patterns (see online version for colours)

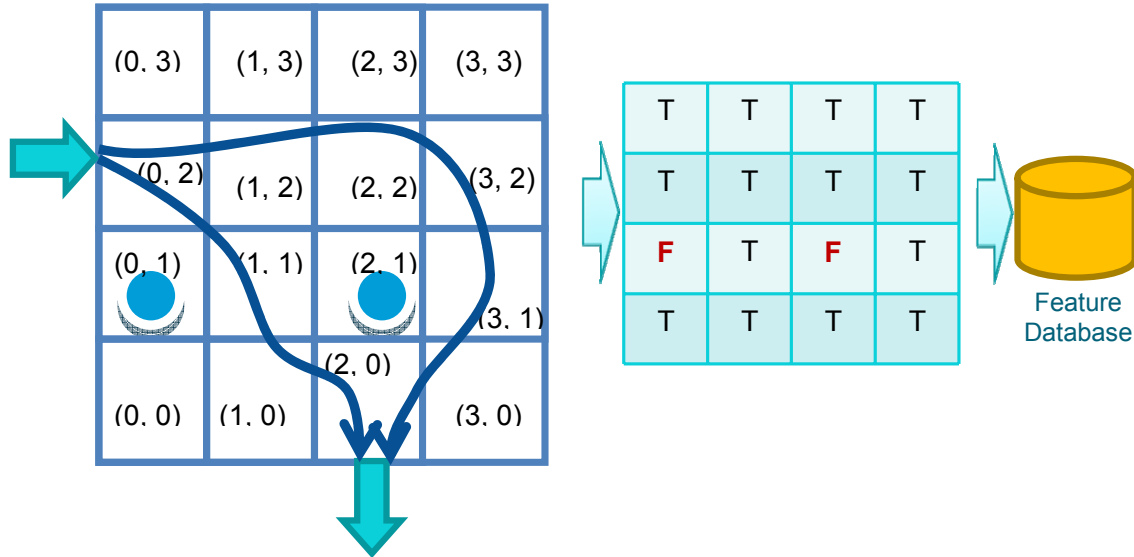
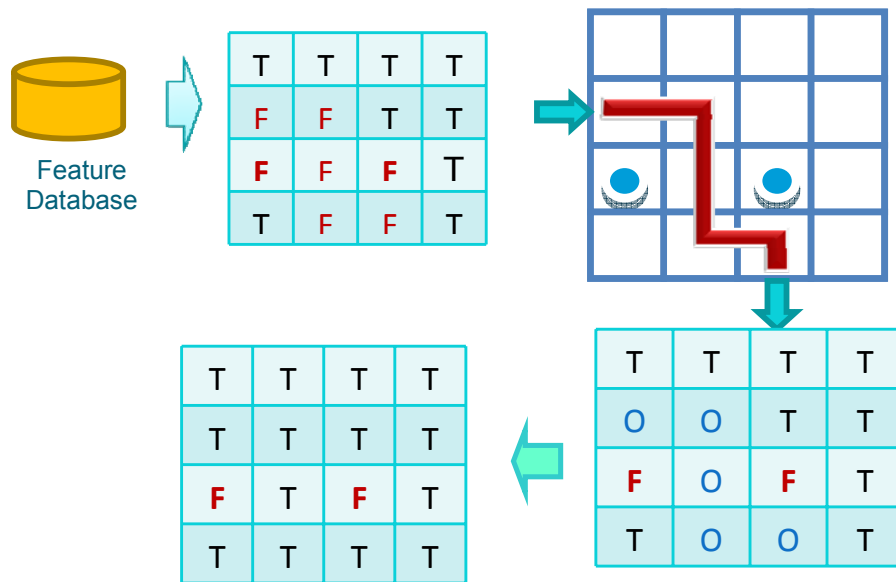


Figure 3 Simplified pipeline path searching method in 2D illustration (see online version for colours)



By adding one more dimension in the searching and optimisation algorithm, as shown in Figure 4, the concept of pipeline feature has been extended into 3D pattern with associated parameters, characteristic attributes, built in constraints and the intelligent generation and editing methods. As to the surrounding context environment, the design space can be initialised as shown in Figure 5.

The surrounding geometry elements, such as neighbouring faces of the interested space, are identified after cycling the entire product model with a few searching and analysis routines such that only the relevant entities are clustered into the neighbouring entity list. Then their volumetric portions which fall in the interested space scope are extracted. Note that *fine grain* access to context space geometric elements is required.

Like the 2D grids used to represent certain areas, 3D volumetric ‘grids’ are generated throughout the space of the context environment and classified as either ‘occupied’ or ‘available’ ones. By running the optimisation routines, a ‘best’ concept of pipeline layout can be determined and then the full solid representation in the form of solid pipes (including flanges and connection interfaces if necessary but not shown here) are generated automatically. In similar manner, a new piece of equipment can be evaluated to fit into a space predefined and its location and orientation are optimised if feasible. Such space management algorithm can be repeated again and again whenever a new pipeline or a piece of equipment is to be inserted according to some built-in space management strategies. Since most of the on-board equipment items are purchased and installed by the collaborating partners and subject to replacement by other competitive suppliers, this case study is representative in real collaborative engineering situations as the authors observed in Keppel Offshore & Marine Ltd in Singapore.

Figure 4 An example pipeline path in three orthogonal views (see online version for colours)

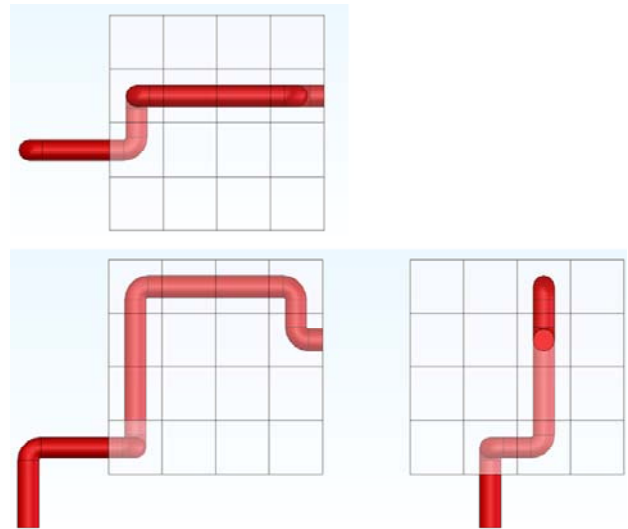
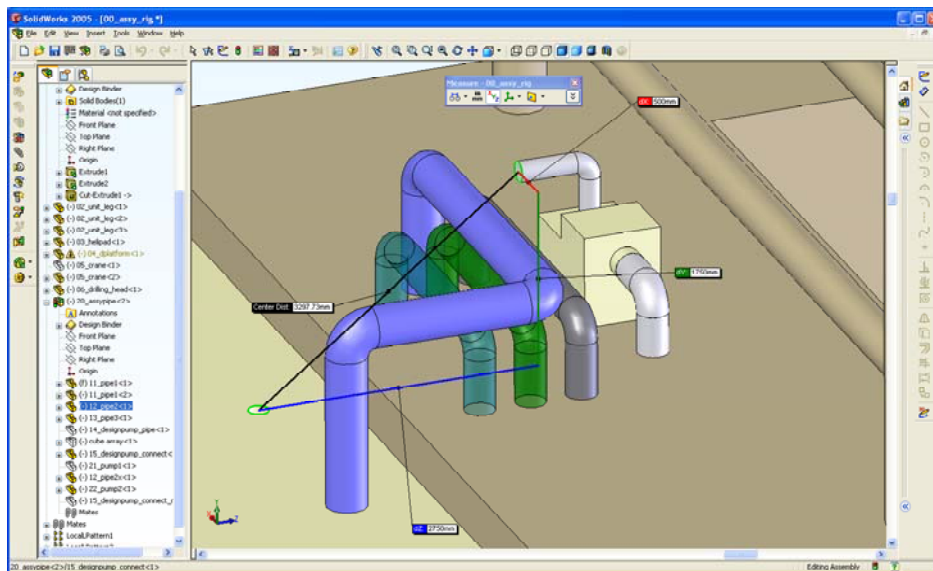


Figure 5 Initial space state for the design of pipeline path (see online version for colours)



There could be different space management searching conditions and the process can be interactively controlled by the designer or automated either partially or fully depending on the trade off of productivity and the flexibility of design practice. For example, the pipeline inlet and outlet positions can be both predefined, unlimited, or limited by some orientations or positional allowances. In Figure 6, a candidate solution is generated. However, the pipeline has been put *under* the existing pipelines and it is then rejected by the designer due to its difficulty of by-passing in construction or future maintenance. Figure 7 offers an accepted pipeline path design. The authors are aware of that there are commercial solutions available for the generation of pipelines or cables trays, etc. However, the main point of this paper is to highlight the context reasoning requirement and the algorithm working with associative features and fine grain access to the context geometries as shown in this case study.

Figure 6 A candidate path solution (see online version for colours)

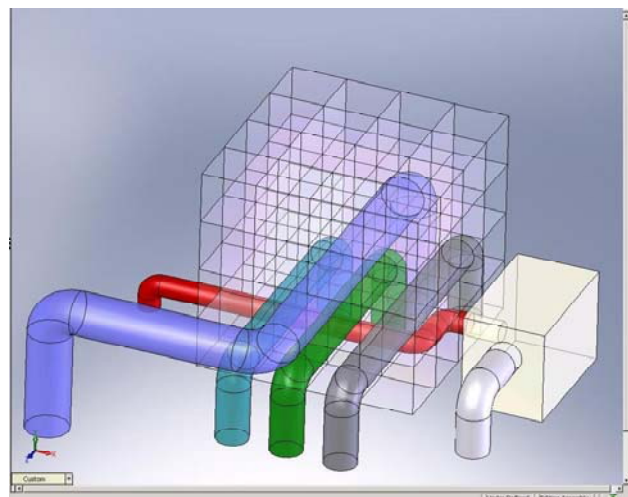
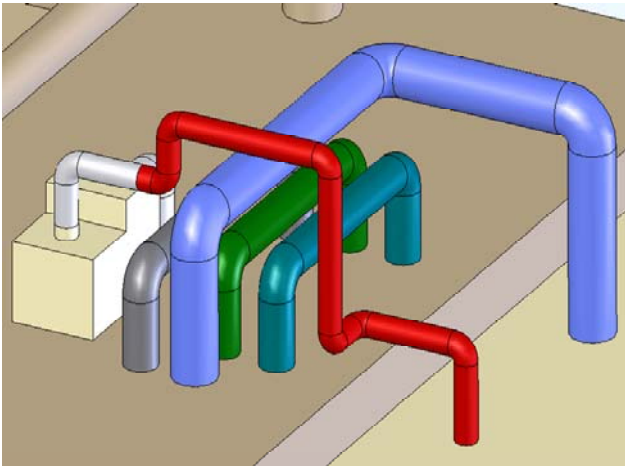


Figure 7 One of the acceptable pipeline paths generated (see online version for colours)



5 Conclusions

Engineering activities evolve gradually from conceptual level to detailed level; from abstract to complete forms; from unknown to known; and from prototypes to matured products and processes. Engineering activities are associated by shared engineering knowledge and methods with the support of reasoning and decision making from the user or its agents. Traditional engineering IT solutions with the legacy of 3D CAD/CAM systems have encountered explosive data volume and complicated data consistency problems for system integration. Although Product Data Management (PDM) systems have been developed to track engineering drawings and product model integrity, but their information grain size is at the 3D solid part level. Such information grain size does not address detailed semantic relations during the design and manufacturing processes and hence PDM systems end up into managing huge product databases without effective methods to manage intricate engineering knowledge and methods.

This paper emphasises the associative feature modeling in engineering informatics. Context-based and fine grain information access is essential for supporting intelligent and dynamic design and manufacturing processes. A fine grain associative feature application scenario has been illustrated by an example prototype program developed to design oil-rag models via certain automated API applications. Effective pipeline feature definition, generation and editing interfaces as well as the program algorithms are discussed. The novelty of this research is that the associative feature scheme is able to support fine-grain feature-level associations and propagation of modifications across product lifecycle stages with the precondition that a unified product modelling database is in place. Associative features provide an intermediate information layer to bridge the gap between engineering knowledge and product geometry. They are also used to maintain geometric and non-geometric relations across product models. The feasibility of the proposed scheme is demonstrated with the prototype system and a case study.

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Research on design structure matrix and its applications in product development and innovation: an overview

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Abstract: Firms rely on new product development to succeed in competitive global markets. Competition forces these firms to launch more innovation products in shorter periods of time. However, owing to complexity of product development and innovation, it is difficult to model product development process with traditional modelling tools, such as directed graph, Petri-Nets and so on. Design Structure Matrix (DSM) has attracted extensive attention among scholars due to its visual and compact matrix expression format. This paper first reviews four types of DSMs and their applications in engineering; and then, several algorithms (i.e. partitioning, tearing, banding, clustering) are introduced in brief; after that, the applications of DSM in concurrent engineering, virtual enterprise and other fields are introduced. In addition, hybrid model of four DSM types as well as numerical DSM (NDSM) and its applications are discussed. Finally, the limitations and expansions of DSM are made as the promising area for further research.

Keywords: DSM; design structure matrix; product development and innovation; information flow; project management.

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1 Introduction

People's demands for product quality increase with advance in science and technology. How to launch new products quickly to satisfy customisation requirements is becoming a crucial factor for enterprises to attract consumers and then to possess more share, which not only asks them to develop

new products in shorter time, but also recovers all costs in shorter time in order to support further research in new product development and innovation. Therefore, the capability of new product development and innovation has become a key measure to determine whether enterprises can survive and develop in the new century (Zhang, 2000; Xu, 2005).

As a popular representation and analysis for system modelling, the Design Structure Matrix (DSM) (Steward, 1981) provides a simple, compact and visual representation of a complex system that supports an innovative solution to the decomposition and integration problems (Huang et al., 2008). It had been widely applied as the basis of product development, project scheduling and costing. Since the 1990s, with rapid development of computer science and information technology, DSMs have been applied in the building construction (Austin et al., 1996, Austin et al., 2000; Yang et al., 2005; Liu et al., 2006b; Wan et al., 2006), semiconductor (Osborne, 1993; Eppinger, 2001), automotive (Sequeira, 1991; Smith and Eppinger, 1997a, Smith and Eppinger, 1997b; Maimström et al., 1999), photographic (Ulrich and Eppinger, 2000), aerospace (Browning, 1996, Browning, 1998; Andersson, 1999; Danilovic, 1999; Clarkson and Hamilton, 2000; Ahmadi et al., 2001), telecom (Pinkett, 1998), small-scale manufacturing (Dong et al., 1996; Lewis and Liu, 1997), factory equipment (Hameri et al., 1999) and other fields.

According to information management problem and resource allocation problem existing in product development and innovation, in this paper, we will explore principles and applications of DSM in order to help improve the competence of enterprises in product development and innovation, reduce development time and cost, as well as enhance the competitiveness of products.

2 Design structure matrix

In general, a simple DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format. Specifically, in DSM, each row and its corresponding column are identified with the identical labels. Along each row, the marks indicate what other elements the element in that row depends on. A certain column indicates what other elements the element in that row provides to. Diagonal elements do not convey any meaning at this point. Thus, in Figure 1, element *A* provides something to elements *B*, *D* and *E*, and it also depends on something from elements *C* and *E*.

Figure 1 A simple example of DSM

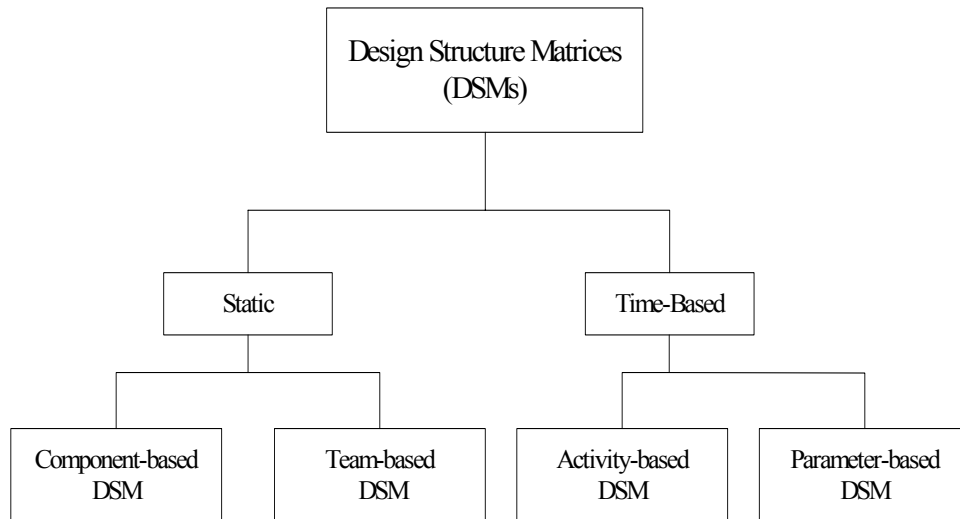
	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>
element <i>A</i>	<i>A</i>		<i>x</i>		<i>x</i>
element <i>B</i>	<i>x</i>	<i>B</i>	<i>x</i>	<i>x</i>	
element <i>C</i>			<i>C</i>	<i>x</i>	
element <i>D</i>	<i>x</i>	<i>x</i>		<i>D</i>	
element <i>E</i>	<i>x</i>			<i>x</i>	<i>E</i>

2.1 DSM categories

Browning (2001) thought that there are two categories of DSMs: static and time-based. Static DSMs represent system elements existing simultaneously. Static DSMs are usually analysed with clustering algorithms. In time-based DSMs, the ordering of the rows and columns signifies a flow through time which is typically analysed using sequencing algorithms. Currently, there are four DSM types useful to product developer, project managers, system engineer and so on.

- 1 *Component-based or architecture DSM*: used for modelling system architectures based on components or subsystems and their relationships. For example, Liu et al. (2006c) used component-based DSM to reveal and explore the development process of piston connecting rod components; Liu et al. (2006a) applied it to engine design of a certain motorcycle and used Genetic Algorithm (GA) to realise clustering of the product architecture, which simplified the complexity of design process and at the same time, enhanced the speed of product development and achieved a preferable result.
- 2 *Team-based or organisation DSM*: used for modelling organisation structures based on people or groups and their interactions. For example, Eppinger (2001) used a team-based DSM to analyse an automobile engine development organisation. They captured the frequency and direction of information flow between the product development teams so as to improve development process.
- 3 *Activity-based or schedule DSM*: used for modelling processes and activity networks based on activities and their information flow and other dependencies. The activity-based DSM is especially useful for highlighting iteration and coupled activities in a design process, so it applied much widely. For example, Zhang et al. (2004) used an activity-based DSM to study the development process of crane jib in order to realise optimisation and reorganisation of design process. Partitioning and tearing algorithms were used to resequence the rows and columns of the DSM in order to obtain the optimal execution ordering, lessen production pressures and heighten economic benefits of enterprises as well.
- 4 *Parameter-based DSM*: used for modelling low-level relationships between design decisions and parameters, systems of equations, subroutine parameter exchanges, etc. The purpose of building and analysing a parameter-based DSM is to reduce process duration and to minimise quality loss (Krishnan et al., 1997b) – the overconstraining of downstream options by upstream decision. For example, Black (1990) applied a parameter-based DSM to automobile brake system design. This work enabled designers to investigate the best initial point for iterated design and helped the company develop a systematic approach to low-level design process planning. In addition, this method is also applied to other automobile industries (Cesiel, 1993; Dong, 1999), airplane engine design (Mascoli, 1999), software development (Roger and Salas, 1999) and building engineering (Pektas and Pultar, 2006), etc.

Figure 2 shows each application classified as either static or time based. Table 1 contrasts the four DSM applications in a succinct format. From Table 1, we can see that there are two ways of integration analysis: sequencing and clustering, where sequencing consists of partitioning, tearing, and banding and is usually applied to time-based DSMs, while clustering is applied to static DSMs. Accordingly, in the next section, we will discuss four types of DSM algorithms.

Figure 2 DSM taxonomy (Browning, 2001)**Table 1** Summary of DSM type characteristics (Browning, 2001)

<i>DSM type</i>	<i>Representation</i>	<i>Applications</i>	<i>Integration analysis via</i>
<i>Component-based DSM</i>	Components in a product architecture and their relationships	System architecting, engineering, design, etc.	Clustering
<i>Team-based DSM</i>	Individuals, groups or teams in an organisation and their relationships	Organisation design, interface management, application of appropriate integrative mechanisms	Clustering
<i>Activity-based DSM</i>	Activities in a process and their inputs and outputs	Project scheduling, activity sequencing, cycle time reduction, risk reduction, etc.	Sequencing
<i>Parameter-based DSM</i>	Parameters to determine a design and their relationships	Low-level process sequencing and integration	Sequencing

2.2 DSM algorithms

As an excellent modelling tool in engineering practice, besides having much powerful capability to describe complex product development process, DSM can use different algorithms (i.e. partitioning, tearing, banding and clustering) to improve the planning, execution, and management of complex product development project. In the following sections, we will introduce these four algorithms one by one.

2.2.1 DSM partitioning

Partitioning is the process of manipulating the DSM rows and columns such that the new DSM arrangement does not contain any feedback marks; thus, transforming the DSM into a lower triangular form. However, for most complex projects, it is hardly possible that simple row and column manipulation can realise a lower triangular form. As a consequence, the aim changes from eliminating the feedback marks to moving them as close as possible to the diagonal. In doing so, fewer system elements will be involved in the iteration cycle resulting in a faster development process. There are several approaches used in DSM partitioning. At present, partitioning methods such as the reachability matrix method (Ledet and Himmelblau, 1970) and triangularisation algorithm (Kusiak et al., 1994) are used much widely.

2.2.2 DSM tearing

Partitioning can transform DSM into a lower triangular form to avoid large-scale iterations, whereas, the loop of information flow for design process is not broken. In order to eliminate these closed information dependency loops, tearing is used to choose the feedback marks so that if we removed them from the matrix, it will give rise to a lower triangular format. The marks that are removed from the matrix are called 'tears'. Now, tearing algorithm is still a hot issue in academia. In various literatures about tearing, most use 'explicit' approaches which are the comprehensive evaluation based on intensity-dependent between elements in nature, viz. the element which has maximum output intensities to downstream as well as minimum input intensities to upstream will be torn firstly (Xiao et al., 2006). For example, Xiao et al. (2007b) used Grey Relational Intensity (GRI) and Analytical Hierarchy Process (AHP) to quantify interaction between elements so as to search for the optimal tearing ordering; Zhou et al. (2003) adopted fuzzy sort algorithm for process reengineering and sequence of injection product; Kusiak and Wang (1993) proposed the highest intercrossed frequency principle to find out the optimal tearing ordering. However, these 'explicit' approaches are highly dependent on problem characteristic and expert experience. In addition, National Aeronautics and Space Administration (NASA) promulgated decision-making

tool – Design Manager’s Aid for Intelligent Decomposition (DeMAID) based on GA in 1989. This tool introduces an ‘implicit’ tearing algorithm. It doesn’t point out the index about information content in advance, but in subsequent iteration process, it can find out the optimal execution ordering of coupling elements through evaluating fitness function. The difficulty in using this approach lies in two aspects: one is how to structure suitable fitness function; the other is how to confirm coupling intensities between activities (Finger and Dixon, 1989a; Finger and Dixon, 1989b). Note that in practice, some weaker relationships may be eliminated by tearing, but some are not. Therefore, in general, evaluation operation should be performed after tearing in order to determine whether to cause rework of some activities in coupled sets (Jin and Li, 2000).

2.2.3 DSM banding

Banding is the addition of alternating light and dark bands to a DSM to show independent (i.e. parallel or concurrent) activities (Mei, 2003). The collections of bands or levels within a DSM constitute the critical path of the project. Furthermore, one element within each band is the bottleneck activity. Thus, fewer bands are preferred since they improve the concurrency of the project. Note that in the banding procedure, feedback marks are not considered.

2.2.4 DSM clustering

In partitioning, the main goal is to move the feedback marks from above the diagonal to below the diagonal as much as possible. However, when the DSM elements are design components or teams within a complex project, the objective is different from that of partitioning algorithms. The new objective becomes finding subsets of DSM element (i.e. clusters) that are mutually exclusive or minimally interacting. This process is referred to as clustering. In other words, these clusters should contain most, if not all, of interactions internally and the interactions or links between separate clusters is eliminated or at least minimised (Fernandez, 1998; Sharman and Yassine, 2004).

Traditional clustering algorithms include similar coefficient method, sorting method and path searching method and so on. However, in the case of the number and the size of the clusters are not known in advance, the above clustering approaches fail to solve these problems (Chen and Yang, 2007). So, many scholars have proposed other algorithms to realise clustering in these conditions. The most representative work has been done by Fernandez (1998) and Thebeau (2001) who introduced the notion of a ‘coordination cost function’ to evaluate different clustering arrangements within the DSM. For more complex scheduling problem, when the number and the size of matrix are much larger, the calculation workloads increase by exponential level. Due to these reasons, others resorted to intelligent computation approaches to solve clustering problems. For example, Liu et al. (2006a) addressed a clustering algorithm based on GA; Xiao et al. (2007a) proposed a coupling function planning based on immune clustering recognition approach. All these were useful complementarities for clustering problem and also achieved better result.

Nevertheless, due to satisfying certain conditions and relative complexity to build these intelligent algorithm models, ‘coordination cost function’ is usually adopted to find the optimal clusters in the case of relatively simple clustering planning problems.

3 Applications of DSM in product development and innovation

In this section, we will discuss the applications of DSM in product development and innovation. Firstly, the relationships between the four types of DSMs are analysed. Secondly, Numerical Design Structure Matrix (NDSM) is explored. Subsequently, applications of DSM in Concurrent Engineering (CE) are discussed. Fourthly, we study the applications of DSM in Virtual Enterprise (VE). At last, we also investigate some other applications of DSM in product development and innovation.

3.1 Relationships between the four types of DSMs and their applications

Firstly, on the one hand, component-based DSM describes product architecture. On the other hand, team-based DSM describes organisational structure. Because organisational elements are typically assigned to develop various product components, the product architecture has a large influence on the appropriate structure of the product development organisation (Seliger et al., 1997). Moreover, better understanding the relationships between product architectures and organisation structures is a key factor to achieve success in product design. Component-based and team-based DSMs are proved helpful in comparing and contrasting alternative product and organisation configurations.

Secondly, since the structure of a product includes functions, components, interfaces, modularisation, etc., it determines the process design structure (Nightingale, 2000). Comparing a component-based DSM to an activity-based or parameter-based DSM would help to find relationships between product structure and design development activities as well as provide an important guarantee to realise design objective.

Thirdly, activity-based DSM describes high-level design development process which generally includes analyses, tests, reviews, etc. Using partitioning and tearing, it is easy to find out redundant information. Parameter-based DSM describes low-level design development process which just considers design process of dimension, material, tolerance and other part parameters. Parameter-based DSM is used for identifying unaware of the couplings and feedbacks between parameters. Although these two DSM types differ in the level of analysis and the scope of their representation, they are not independent on each other. This is because all the development processes consist of decomposition processes from high-level stage to low-level stage, and the result of every stage will affect the whole product quality and cost. Therefore, only if composing activity-based with parameter-based DSM together, design process can become more reasonable and credible.

Lastly, although these four DSM types differ in modelling, they also describe different aspects of design process. So, hybrid models are created. Eppinger et al. (1994) have found in automotive industries that activity-based DSM and parameter-based DSM are somewhat insufficient. The former ignored too many important technical details, while the latter lacked the overall context. They thought that using a hybrid model, the coupling between activities became exposed in sufficient details to consider redefining activities by regrouping parameters into new activities; Guo et al. (2006) presented an approach of process modelling based on Design Structure Matrix Family (DSMF). They also built a tree structure to outspread a design process. In doing so, the process was decomposed to activity level, component level and parameter level by a top-down method, where activity level, component level and parameter level were corresponding to activity-based, component-based and parameter-based DSM, respectively. Comparing to DSM, DSMF described information dependency relationships between different levels which facilitate to lessen the complexity of process planning. However, the approach ignored design conflicts occurring in development process and did not offer the detailed design process of complex products. As a result, integration of DSMF with other technologies is necessary. For instance, use theory of inventive problem solving (TRIZ) to solve design conflicts or contractions of product development (Tan, 2003); use Case-Based Reasoning (CBR) approach to achieve product design process for innovation (Wang et al., 2007). In Section 4, we will further discuss the integration of DSM with other technologies. Furthermore, note that in the process of building DSM, precision of information inputs and outputs should be needed and deviation caused by human factors should be avoided by iterative modifications.

3.2 Numerical Design Structure Matrix (NDSM) and its applications

Original binary DSM is populated with 'ones' and 'zeros' or 'X' marks and empty cells. This single attribution was used to convey relationships between different system elements; namely, the 'existence' attributes which signifies the existences or absence of a dependency between the different elements. Compared to binary DSM, NDSM could contain a multitude of attributes that provide more detailed information on the relationships between the different system elements. An improved description of these relationships provides a better understanding of the system and allows for the development of more complex and practical partitioning and tearing algorithms. For example, consider the case where activity *B* depends on information from activity *A*. However, if this information is predictable or have little impact on activity *B*, then the information dependency could be eliminated. Binary DSM lacks the richness of such an argument.

According to the representation and analysis of the problem, the number of NDSM has certain attributes. Some typical applications of NDSM are introduced as follows:

- 1 *Dependency strength*: This number can be used to reflect the dependency strength between activities. As an example, Steward (1981) used a number between 1 and 9 to describe the dependency between automotive parts. Chen and Lin (2003) used a number between 0 and 9 (including integer and decimal) to show the dependency between activities of an engineering design of a chemical processing system. Usually, the larger the number is the stronger dependence it represents. So, the matrix can be partitioned by minimising the sum of the dependency strengths above the diagonal. This process is repeated until all feedback marks disappear. Note that level number can be made depending on the engineers' judgement.
- 2 *Variability of information exchanged* (Carrascosa, 1998): A variability measure can be devised to reflect the uncertainty in the information exchanged between activities. This measure can be characteristic by two variables, e.g. upstream information evolution and downstream information sensibility (Krishnan et al., 1997a). The notion of upstream evolution refers to the rate at which the exchanged information reaches its final form. Evolution generated information is fast when the information gets close to its final form rapidly. While, the evolution is said to be slow if finalising product information early in the upstream process is either impossible or involves a huge quality penalty for the upstream phase. The downstream sensitivity measures the duration of downstream work required to accommodate changes in the upstream information. Downstream phases are highly sensitive when the phase are so closely coupled that the downstream work required to incorporate even small changes in the upstream information is large. Krishnan (1996) took the base panel of an automobile as an example and observed evolution and sensibility of all of parts in order to use overlapping model to reduce development time.
- 3 *Probability of repetition*: It shows the probability of one activity causing rework in another. Smith and Eppinger (1997b) used probability matrix of repetition to build Markov Chain model in order to analyse the pure sequential iteration and calculate the total time of this process.
- 4 *Amount of rework*: this can be visualised as the fraction of original work that has to be repeated should iteration occur. It is generally represented by the number between 0 and 1. Browning and Eppinger (2002) used the amount of rework to set up Work Transformation Matrix (WTM) and combined statistic approach to achieve the distribution curves of development time and cost so as to manage and estimate the development activities.

However, the researches on NDSM focus on describing the relationships between different elements using the integers between 1 and 9 or the decimals between 0 and 1. In many engineering applications, sometimes there exist negative

relationships between elements. For example, in activity-based DSM, consider the case where the execution of activity *A* blocks the accomplishment of activity *B*. Then, there exists negative dependency relationship between *A* and *B*. Moreover, in parameter-based DSM, the values of all parameters have their own ranges and most of them interact and inter-constrain. Therefore, the negative values can exactly represent these relationships. For instance, consider three interdependent parameters of refrigerator including compressor power, refrigerator volume and the lowest refrigerator temperature. When the refrigerator volume is certain, the larger the compressor power is the lower the refrigerator temperature is. There exists positive relationship between them. When the compressor power is certain, the larger the refrigerator volume is the higher the refrigerator temperature is. There exists negative relationship between them. Use ‘●’ to indicate positive relationships and ‘×’ to indicate negative ones. The symbol ‘●●’ or ‘××’ signifies the stronger dependency and Figure 3 shows these relationships. Besides, when the compressor power is certain, the effect of the refrigerator volume on the lowest refrigerator temperature is different to the effect of the lowest refrigerator temperature on the refrigerator volume. So, they should take different values. In addition, negative values can also represent other implications. For example, they may represent the overlapping between two activities and the absolute values of them reflect overlapping time of two activities (Chu et al., 2006). Due to existing negative relationships, great effects will take place not only on product planning but also on organisation building. As a result, the further research should consider when negative relationships exist in matrix elements, how to manage and schedule development process, as well as explore the effects on convergence to design process, the quality of products, cost and others.

3.3 Applications of DSM in CE

A traditional product development process adopts sequential way. In this way, usually departments act more or less independently, not knowing the demands and the capabilities of each other. With insufficient communication with other engineers and manufacturing functions, design engineers may design a product that will lead to severe problems during manufacturing and assembly operations. In order to render the product manufacturability, feedback and communication between manufacturing and design groups are very extensive and time consuming due to the nature of the sequential design procedure. On the contrary, CE is a philosophy that has emerged in the last decade in response to growing pressures to reduce costs and lead times while improving product quality. CE is defined as a systematic approach to parallel development of all product lifecycle activities, from initial conception through design, planning, production and disposal. The overall CE rests on a powerful principle that promotes the incorporation of downstream concerns into the upstream phases of a development process. Chapman and Hyland (2004) pointed that CE is thought to represent a long-lasting paradigm for product innovation management. However, many companies still face enormous challenges when implementing and managing CE practices. This is mainly owing to the complexity of product development and innovation and serious lack of corresponding CE models and tools. Yassine and Braha (2003) presented four underlying CE principles, viz. ‘iteration problem’, ‘overlapping problem’, ‘decomposition and integration problem’ and ‘convergence problem’, and then used DSM to analyse these four problems, but they didn’t discuss the relationships between the four problems.

Generally, overlapping is an approach adopted to reduce development time. In overlapping process, the downstream activity begins earlier by using preliminary information from upstream and downstream iterations occur due to incompleteness of information transfer. For example, Krishnan et al. (1996, 1997a) illustrated the overlapping model with industrial applications involving the development of automobile doors and developed the notions of evolution and sensitivity. Loch and Terwiesch (1998) studied the function of uncertainty on the product development process and built uncertainty overlapping model. Xiao and Si (2003) presented a new process model of development with uncertainty, borrowing ideas from the uncertainty model and iterative overlapping model proposed by Loch and Terwiesch, and Krishnan respectively, to realise reduction on the time. But all these models only consider two activities overlapping. Xu and Yan (2006) presented a time computing model for the overlapping and iteration between design activities in concurrent development. They divided the activity sets into coupling and non-coupling activity blocks based on DSM. According to the direction of information flow, rework time of each activity caused by overlapping is calculated in turn. However, the uncertainty of information transfer is not considered. In general, the common implementation steps

Figure 3 DSM with negative dependency strength

	compressor power	refrigerator volume	the lowest refrigerator temperature
compressor power		●	●
refrigerator volume	●		×
the lowest refrigerator temperature	●	××	

of overlapping model should be as follows: (1) define the complex product development project including contents, scope, and objective, etc. And decompose the complex product development project into some sub-activities based on Quality Function Deployment (QFD) and built the DSM model used to describe relationships of information inputs and outputs between activities; (2) use partitioning and banding algorithms to find parallel, sequential or coupling relations; (3) establish the overlapping model and calculate total time for development process; (4) consider time-cost trade-offs in overlapping product development and test the created project planning. Note that the difficulty in building overlapping model lies in how to determine the downstream rework caused by uncertainty and incompleteness of upstream information. Moreover, adopting overlapping approach usually compresses time at the expense of consuming more resources. Consequently, how to build suitable overlapping model under limited resource constraints needs further study.

Coupling between activities is the main factor causing the complexity of design process in product development and innovation. It simultaneously incurs iterations of activities. Osborne (1993) found that iteration account for between one third and two-thirds of total development time for projects at a major semiconductor producer. Osborne also found that unpredictable iteration is the main cause of variability in the lead time of projects at this firm. It goes without saying that iteration problem seriously affects the application of CE. So, Smith and Eppinger built two different iteration models based on DSM, called a sequential iteration model (Smith and Eppinger, 1997b) and a parallel model (Smith and Eppinger, 1997a), respectively. The sequential model where coupled design activities are executed one after the other is modelled as a Markov chain and can be used to compute lead time and to identify an optimal sequence of the activities to minimise iteration time. The parallel model where the coupled design activities are all executed in parallel and iteration is governed by a linear rework rules is modelled as WTM and used to identify the iteration drivers and the nature as well as rate of convergence of the process. However, the sequential iteration model uses probabilities of rework and assumes constant activity execution time at every iteration stage to analyse the iteration process. It also attempts to reorder activities to reduce time, which may not always be possible (Eppinger et al., 1997). Furthermore, how to determine probabilities of rework is very difficult. On the contrary, the parallel iteration model analyses the eigenstructure of the design system and identifies iteration drivers, but assumes complete parallelism in activity execution. Some shortcomings existing in it are as follows: (1) the values taken in WTM are lack of objectivity; (2) the number of iteration is infinite in design process, which is not reasonable (Sun et al., 1999; Jin and Li, 2000). We consider there are two key elements to determine the design time required for each of design iteration. The first element is the learning effect which affects the amount of time needed at each iteration as well as the number of design iteration. The second one is the degree to which the activity depends on the other activities. So, the amount of rework should be nonlinear at different iteration stage. In addition, we also introduce a notion of 'available

information evolution' to describe the degree to which activities have accumulated available information. When it reaches a certain threshold value and the quality of product is no longer improved in following iterations, we think no more iterations happens. In doing so, infinite iteration process is avoided. Note that owing to the constraints from staffs, materials and equipments in product development and innovation, complete parallelism iteration is impossible, hence, how to find out the optimal multi-phase WTM (Smith and Eppinger, 1998) execution scheme needs exploring under resource constraints.

CE is a process in which appropriate disciplines are committed to work interactively to conceive, develop, and implement product programs that meet pre-determined objectives. CE is the term applied to the engineering design philosophy of cross-function cooperation in order to create product which are better, cheaper, and more quickly brought to market. However, as no single team has the expertise to tackle the whole development process, the decomposition of complex development process is necessary and local development teams are created to be in charge of developing simple subsystems in order to reduce the technical complexity of development and innovation. Moreover, a system development teams are built to coordinate these local teams. They manage the whole development process and identify those inadvertent feedbacks. A component-based DSM and a team-based DSM appropriately describe these two aspects for product development and innovation process: on the one hand, a component-based DSM can be created for the physical interactions between the components to represent the structure of the system decomposition and integration problem; on the other hand, a team-based DSM is used to create the communications between the different development teams including local and system teams in order to better map people and teams, and decide who should be on the team to address the system problems (Yassine and Braha, 2003). Recently, the creation of cross-function teams is a hot issue, but most researchers built development teams only according to designers' comprehensive qualification, interest, time constraint and other factors (Zhou et al., 2003; Ren and Fang, 2005). They tore the inner connections between development teams and design activities, especially those development processes which have large-scale and strong couplings. As a result, how to set up suitable development teams to realise the CE philosophy of replacing large loops with small ones is a promising area for further research.

In addition, due to the iteration phenomena existing in overlapping and coupling activities, exploring when the iteration no longer occurs in design activities is needed. This is called 'convergence problem'. Smith and Eppinger (1997a) analysed the eigenstructure of the design and identified iteration drivers using WTM, but they did not point out the essential nature of causing divergence or slow convergence in product development and innovation. Yassine et al. (2003) found that it is design churn defined as a scenario where the total number of problems being solved does not reduce monotonically as the project evolves over time that made it hard to measure actual development

progress and ultimately difficult to judge whether the project is on schedule or slipping. Furthermore, the authors revealed several main sources of churn and provided three mitigation strategies to combat design process churn, divergence, or slow convergence. They also thought that how to find the information hidden in product development and how to deal with feedback are crucial to mitigate design churn. However, they did not consider the effect of cost and resource allocation on design churn. Thus, this is a promising area for further research.

In fact, 'iteration problem', 'overlapping problem', 'decomposition and integration problem' and 'convergence problem' existing simultaneously in CE interact. For example, overlapping model is used to reduce development time, whereas, in practice, not all of downstream activities can overlap with their upstream ones. In this situation, we are able to decompose some complex activities into small, simple and irrelevant sub-activities and pick out one or more to attempt to overlap but others still perform by a conditional sequential way (Chen and Xiao, 2008). Therefore, appropriate decomposition and integration of activities is useful for building overlapping model. Generally, disposal of coupling is the key element affecting product development and innovation process. Owing to the incompleteness of information transfer, the iteration of design process is an unavoidable phenomenon and the convergence of iteration for design activities should be considered. In order to lessen the number of iterations, replacing large loops with small ones in design process is necessary using decomposition and integration of design activities. It is obvious that a successful CE strategy lies in accurately dealing with these four problems.

3.4 Applications of DSM in VE

With the arrival of the 21st century, market competition is becoming global and intensive, and the business environment is changing quickly and greatly. Therefore, it is a pressing mission to master the demand information and to quickly make decisions in order to provide satisfactory production and service (Xu et al., 2002). Modern enterprises are impelled to seek new paradigms and VE brings about. It means that several legally independent enterprises joint together to co-operate for a particular mission. By combining their areas of particular expertise with the complementary expertise of other partner companies, it is possible to prosper and respond to the new market requirements (Mikhailov, 2002). However, owing to most of partner companies located in various areas and operated by different patterns, how to coordinate activity scheduling, information transferring and resource sharing between them is a bottleneck to constrain the development of VE. Chen and Wang (2003) proposed a framework for complex product concurrent development in a VE and analysed iterations involved in product developments by DSM and extended WTM. Then GA is adopted to solve the optimal schedule of development activities. As a matter of fact, there exists complementary relationship between VE and DSM. On the one hand, although VE names 'virtual', they are composed of different organisational entities. These entities do not belong to certain integral and internal entity. Consequently,

this organisation form exceeds the constraints of geographical locations and organisational boundaries existing in common enterprises and also greatly extends the functions of them so that they can quickly respond to changes of markets and seize opportunities. On the other hand, being a useful modelling tool for product development and innovation, DSM has a powerful ability to tackle all kinds of complex design activities. The chief of VE can use DSM and incorporate the ability of every enterprise in order to realise reasonable activity scheduling and resource configuration. Furthermore, combining the advantages of these two approaches is more beneficial to achieve time compression, improve product quality and enhance enterprise competition power. Therefore, as a future development direction, combining VE with DSM will play a key role in product development and innovation.

3.5 Applications of DSM in other fields

Besides applications in CE and VE, there are many other applications of DSM in product development and innovation, such as product architect (Sharman and Yassine, 2004; Sosa, 2008), configuration (Helo, 2006; Sharif and Kayis, 2007), modularity (Sered and Reich, 2006; Bjornfot and Stehn, 2007), organisation optimisation (Batollas and Yassine, 2006; Wei, 2007), activities sequencing (Maheswari et al., 2006; Chen and Huang, 2007) and so on. All these applications are helpful to reduce new product time-to-market, lessen its cost, and improve its quality. However, as a information flow model, DSM has its own characteristics (e.g. size, sparseness and sequencing object) which would cause serious problems. For example, when it is critical to perform project activities in an appropriate sequence in product design, how to find an optimised sequence for a set of design activities is very difficult. To cope with the deficiency, many researchers investigate the use of intelligent algorithms such as genetic algorithm (Meier et al., 2007), simulated annealing (Abdelsalam and Bao, 2007) and others. Nevertheless, under different environments, not all of intelligent algorithms can find an optimal solution. Therefore, the further research should be focused on how to select appropriate algorithm to solve hard DSM problems. In addition, each product development project is usually unique in nature in practice (Kusiak et al., 1995). It often encounters situations where the duration of particular activities cannot be given precisely at the project initialisation stage. Moreover, resources including human resources, funds and equipments needed are often uncertain. All these things indicate that product development process is executed under uncertain environments. As a consequence, DSM combined with risk management methods should be introduced in development product and innovation, which is another study orientation of further researches.

4 Limitations and expansions of DSM

As a rule, product development contains at least five different domains: the product system; the process system; the system organising the people into departments, teams, groups, etc.; the system of tools, information technology-solutions, and

equipment they used to do the work; and the system of goals, objectives, requirements, and constraints pertaining to all the systems (Danilovic and Browning, 2007). Each of these five systems is composed of elements with relationships and thus can be discussed in terms of its structure, network and architecture. Moreover, each of the five systems is related to the others. Each system both enables and constrains the others. Since DSM only focuses on information dependency relationships in a certain domain, it cannot reflect information that needs to be exchanged, not only within each domain but also across domains. In addition, owing to uncertainty of market changes and technology conflicts existing in product development and innovation process, DSM is limited to solve these problems. As other approaches, such as Quality Function Deployment (QFD), Axiomatic Design (AD), Domain Mapping Matrix (DMM), Systematic Inventive Thinking (SIT), TRIZ and CBR, can be used to map between two different domains and also adopt a matrix format, it is possible to integrate DSM with them.

Chen et al. (2004) found that the difficulties in constructing a reliable NDSM prevented wider applications of DSM. So, they proposed an approach to quantify the dependency between design activities by making full use of the information contained in QFD matrix and realised the information mapping and transferring across different domains. However, the goal of the authors is to set up a reliable NDSM, and they were lack of systematic viewpoint to consider the whole development process and ignored effect of other factors such as cost and resource. Tang et al. (2007) presented an idea that AD and DSM can co-evolve step-by-step during the product design process. But in this paper, the authors only discussed the information mapping between function requirements and design parameters, and determined the key performance parameters with subjectivity. Cao et al. (2006) introduced a structural analytical approach to deal with coupled design appeared in design with AD based on the partitioning and tearing of DSM. Nevertheless, they did not consider technology conflicts existing in design process. Hu et al. (2006) proposed an open modular product design methodology based on structure-mapping approach and DSM to improve innovation speed and technology level of plastic injector producers. It is a typical hybrid application of AD and DSM in industry. Danilovic and Sandkull (2005) introduced a DSM and DMM approach that enables the identification of interdependencies and relations in a multi-project environment. This approach enables clarifications of assumptions, the tractability of dependencies, and explores the information needed within and between different departments, projects and people. This creates a transparency and enables the synchronisation of action through transformation of information and exploration of assumptions within and between domains. However, this approach is only a good idea but lack of detailed industrial application.

In a word, on account of the complexity and the uncertainty in product development and innovation process, only adopting a single approach is difficult to satisfy customer requirements, thus, efficient integration of these approached mentioned

above is necessary. For example, use QFD to abstract customer requirements so as to determine design scheme and use independency axiom and information axiom in AD to estimate the alternative schemes in a conceptual design stage; adopt CBR to search for the most similar case to create a detailed design plan and then recur to TRIZ or SIT to improve it in a detail design stage. In addition, combining DSM with DMM can analyse the information that needs to be exchanged or transferred, not only within one domain but also across domains. In doing so, product development and innovation process can be accelerated. It is obvious that integration of these approaches in product development and innovation will make new products have powerful competitive advantages.

5 Conclusions

DSM provides a compact and visual description for complex product design and management. It also provides an assistance to capture the information between engineering design and organisation structure and is convenient for communication among teams or people. Through simple matrix transformation, called partitioning or clustering, system structure can be resequenced. In many situations, DSM can also provide a systematical approach to enhance the understanding for process and simultaneously promote improvement and innovation for the performance of systems.

In recent years, many scholars devote themselves to the research of DSM. Some useful DSM software tools have been developed and applied to the new product development and innovation in Ford and Boeing companies successfully. Development cost and time have reduced rapidly which brought huge economic benefits. Therefore, with continuous advance in it, DSM must become an efficient tool for product development and innovation.

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Synchronisation of heterogeneous design models of manufactured products by the formulation of business knowledge

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Abstract: Product design development needs collaboration between different designers. A product is co-modelled by a team of designers at geographically distributed locations using a set of heterogeneous business tools such as Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems. However, existing collaborative environment support only a limited set of specific business tools. This paper presents an approach to enhance collaboration between experts using heterogeneous CAD/CAM models by the formulation of business knowledge throughout a Model-Driven Architecture (MDA) approach. An MDA-based solution is proposed to deal with the issues identified in developing such collaborative framework. We present a meta-modelling architecture to synchronise heterogeneous models whereby business models at different levels of abstraction can be synchronised. One issue is to measure the potential of such an approach in non-software engineering field. A case study is applied to Esprit™ CAM tool enabling Esprit™ to interoperate with the SolidWorks™ CAD tool throughout the Product Process Organisation (PPO) collaborative environment.

Keywords: collaborative design; CAD/CAM interoperability; business knowledge; model synchronisation; product modelling; MDA; model-driven architecture; data exchange; integrated design.

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1 Introduction

During product development, many experts are involved to participate to the definition of the product. These experts work with respect to their own knowledge and know-how assisted by expert tools.

Usually they collaborate inside synchronous or asynchronous phases. Synchronous phases correspond to meeting (co-localised or remote meetings) where experts negotiate the main product evolution respect to their business analysis which was developed during asynchronous phases. The heterogeneity of business tools implies different file formats and data representation which must be harmonised to ensure the coherence of the

design. The ability to share business models is important during product design and manufacturing. In mechanical engineering, designers often use Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software. Integration of CAD and CAM data tools into the design processes faces a number of challenges. One of the most significant challenges is the synchronisation of business views across the wide range of commercial CAD/CAM tools. This synchronisation remains informal because of the lack of links between expert assistance tools. However, because they collaborate to the same product definition, experts develop some specific knowledge to share their own view with others.

In this paper, we study how we can formalise this kind of knowledge, and how this formalisation can be used to assist synchronisation.

This paper demonstrates on a simple case study how such a synchronisation should work between information issued from CAD/CAM software. The proposed approach is based on the Model-Driven Architecture (MDA) (OMG, 2003). The MDA [main support for the Model-Driven Engineering (MDE)] is used to show how expert's knowledge is employed to support linking requirements (design artefacts and manufacturing constraints relationships) in a manner that allows interoperability between CAD/CAM software.

This paper is organised as follows. Section 2 presents related research in interoperability among CAD/CAM systems. Section 3 presents MDA technologies as a support to expert's knowledge formulation. With a collaborative design scenario Section 4 highlights the problem of interoperability with heterogeneous tools in the product manufacturing field. Section 5 presents the collaborative environment Product Process Organisation (PPO) (Girard et al., 2002; Robin and Girard, 2006) as a space to share experts' formalised knowledge. Finally, Section 6 gives the conclusions and directions for future research.

2 Interoperability in CAD/CAM context

CAD software is usually used to build a reference model of the product. Usually, the product model includes 3D geometric representation but also production attributes such as material properties, surface treatment, manufacturing processes and part numbering. The sum of this information represents the 'Product Model'. The analysis of the manufacturing of the product is accomplished by CAM software. Today CAM software manages and control banks of robotic milling machines, lathes, welding machines, and other tools, moving the product from machine to machine as each step in the manufacturing process is completed.

The design and manufacturing of a complex product typically involves more than one designer who are generally geographically distributed and use heterogeneous tools dedicated to their expertise involving efforts to exchange data between CAD/CAM systems: CAD/CAM systems are still developed to work in isolated environment and usually are not able to communicate with each other.

In a CAD/CAM context, there are three methods to ease data exchange: the use of integrated CAD/CAM software modules from the same vendor, the use of standard data exchange format such as Initial Graphics Exchange Specification (IGES) and STandard for the Exchange of Product (STEP), and specific proprietary data exchange format:

- *Integrated Software Modules:* The integrated CAD/CAM system provides a seamless link between the integrated systems. However, the customer is generally tied to a single vendor and may have to compromise on the available features in one part of the system in order to have the desired features of the other part. Newer developments

from other vendors that may improve the efficiency of production are difficult or impossible to integrate, limiting the user's adaptability.

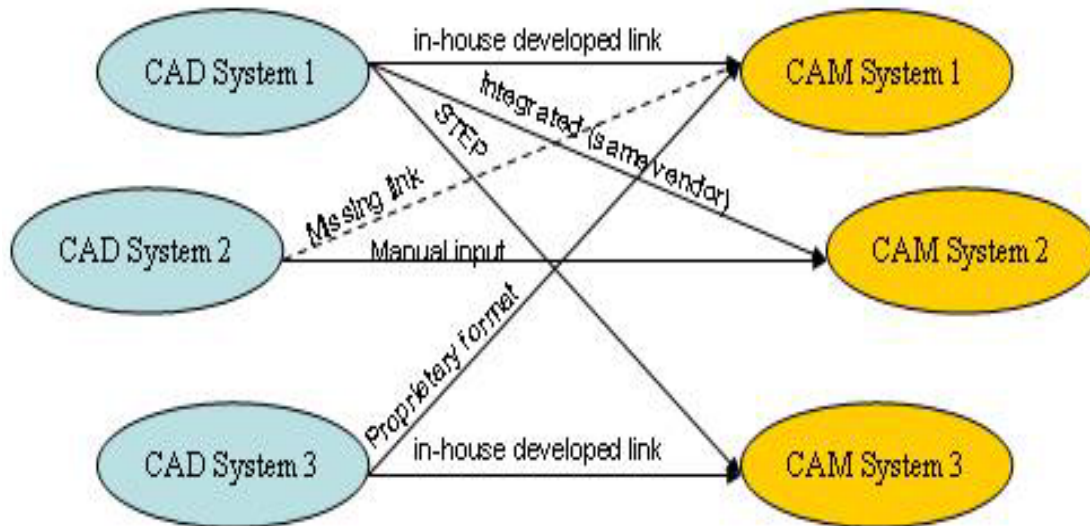
- *Standard Data Format:* Many 'standard' formats for data exchange already exist. Standards such as STEP model data may be capable of transferring all necessary production information for a part. A prerequisite is of course that both the CAD and CAM systems support the same data format and that the corresponding drivers are up to date respect to the standard versions. This must be kept in mind when upgrading one or both systems. However, an important limitation of standard data-exchange formats is that they do not provide data management capabilities. Without data management, the exchanged data represents a snapshot in time, and subsequent changes to the product model must be manually monitored and exchanged again. Moreover, standards do not formalise every concepts used in business applications, especially when innovative processes are under consideration.
- *Specific Data Format:* A custom interface may use a specific data format or a customised version of a standard data format to transfer data between two specific systems. This method has the disadvantage of the previous methods (the customer remains tied to specific vendors) but has the benefits of an integrated link between the systems.

Figure 1 summarises different data exchanges methods. Connection between one or more CAD systems to many different CAM systems using the types of links described above is achieved. Often connections between CAD and CAM systems are iterative, requiring additional data conversions and a high degree of manual input (Xu et al., 2002).

Interoperability among CAD/CAM systems is a well-known problem in product design and development (Bianconi et al., 2006). At present geometrical data exchange among different software packages is usually carried out through neutral file formats (IGES or STEP) or through proprietary formats.

In the case of data exchanges between CAD systems, designers share geometrical data throughout standards. Currently, the features (modelling operations and functions) cannot be captured. The feature tree representing a trace of *design intent* is then lost.

Current researches focused on the development of systems for the exchange of procedural models (Bianconi et al., 2006). A procedural representation is defined in terms of entities and functions that may be reconstructed in different environments without any loss of information. Much research is focused on procedural and feature-based models definition (Bianconi, 2005) by the specification of feature ontology (a set of objects, concepts and rules), and the specification of a unique identification of the same geometrical/topological entities (persistent naming/naming mapping). The definition of suitable feature ontology and the problem of consistent naming or naming mapping appear predominant. Interesting approaches are being developed by various research groups; however, a comprehensive and unifying solution is yet to come.

Figure 1 CAD-CAM connection (see online version for colours)

Some researches focused on developing a web services-based platform for exchange of procedural CAD models between heterogeneous CAD systems (Chen et al., 2005). The platform is based on Neutral Modelling Commands and the APIs of CAD systems. Web services technique is used to construct a standard interface for the procedural CAD model exchange platform.

The review of interface-based systems shows that, during the last years, new interesting approaches have emerged: among them the Object Management Group (OMG)-CAD services, was developed. CAD services (Russell et al., 2002) is an ongoing process carried on by the OMG. The CAD services interface standard is an effort to provide uniform, simple, distributed services that enable a 'Geometry Centric' design approach. CAD services proposes an interface standard for CAD/CAM/CAE tools. This proposal focuses on establishing mechanical CAD system interfaces that provide Geometry and Topology data to analysis and manufacturing applications and tools. The intent is to establish a series of high-level engineering interfaces that do not require low-level data structures to answer mechanical engineering queries. To avoid many of the problems associated with data translation, this proposal provides CORBA interfaces with consistent functionality across native CAD implementations.

In the case of data exchanges between CAD/CAM systems, the CAD model does not vary too much. The CAM system takes as an input the CAD model and achieves manufacturing operation. If a modification is needed in the CAD model at the CAM stage, no support is given to send the information and to update the CAD model. Currently engineers fill this gap by developing their own knowledge and practices to maintain information coherency. In this work, we are interested by the CAD/CAM data exchanges. We try to provide a suitable framework to improve company's competitiveness through the adoption of a MDA-based extended environment, challenging and enhancing the interoperability between CAD tools and CAM tools. This approach could be extended to covers systems and applications in industry. MDA is here used to formulate specific know-how to allow the reuse of this knowledge in synchronisation issues.

MDA was initially developed for software engineering. The interest of the current study is to demonstrate the possible application of this technology in another field and to emphasise its limits for new applications.

3 Model-driven engineering and model-driven architecture

The MDE is a model-based design or approach. It was extensively developed for the aim of software engineering. Usually, the realisation of an application is based on its implementation. In the MDE point of view, an application is focused on its design. This design is represented as Models, usually expressed in the Unified Modelling Language (UML). These models offer an abstract point of view of the application: models are conforms to a meta-model; meta-modelling is a key concept of the MDE approach. MDA is the specification of reference implementing the MDE principles. It is conceived by the OMG and it formalises the MDE concepts. MDA is specified by the OMG, to offer a support to the MDE approach.

The MDA (Soley and OMG Staff Strategy Group, 2000) appeared after several years of existence of modelling and meta-modelling standards like UML (UML, 1997) or the Meta Object Facility (MOF) (MOF, 2003). The MDA offers a unifying framework necessary to the integration of these various activities and is mainly dedicated to software engineering. The MDA architecture is based on a hierarchy of three levels of abstraction for modelling software. The model: a representation of information produced by an expert on a specific project. The meta-model: the class identifying the grammar and dictionary available to create a model. The meta-model: a minimal grammar for meta-model description. In this architecture well known as defined by the OMG, each level maintains a relation of instantiation (conformance) with the higher level.

Through this meta-modelling architecture, the MDA should support the integration and the management of heterogeneous models and thus should make possible a total

and coherent development. Moreover, the transformation of model, key concept of MDA, authorises the passage from one modelling field to another. Czarnecki and Helsens (2003) provide a classification of model transformation approaches. This classification allows, starting from sources models, to obtain models adapted to a particular point of view while keeping a single conceptual framework (Alban et al., 2005). We wish to exploit this property in the design of manufactured products.

In this context, designers use heterogeneous business tools to perform their expertises. Since they contribute to the design of a same and unique product, the business models have almost correspondences which indeed are not formalised in any model. MDA seems to be relevant.

Once these models are completed and adopted, their implementation could be partially automated in any middleware platform supporting the MDA: in our example the PPO environment is used as a support for the collaborative work. In our example CAD/CAM would benefit from the interoperability that only the MDA can provide.

MDA approach, from a software point of view, could connect any heterogeneous tools (D'souza, 2001). This operation is made by developers who encodes different models, establish all possible combination and equivalence between these models and transforms a model into another. Figure 2 shows how MDA is used to ensure navigation from a business tool to another and how this could support the engineering knowledge.

Knowledge Engineering (KE) refers to the building, maintaining and development of knowledge-based systems (Simon and Creen, 2007). It has a great deal in common with

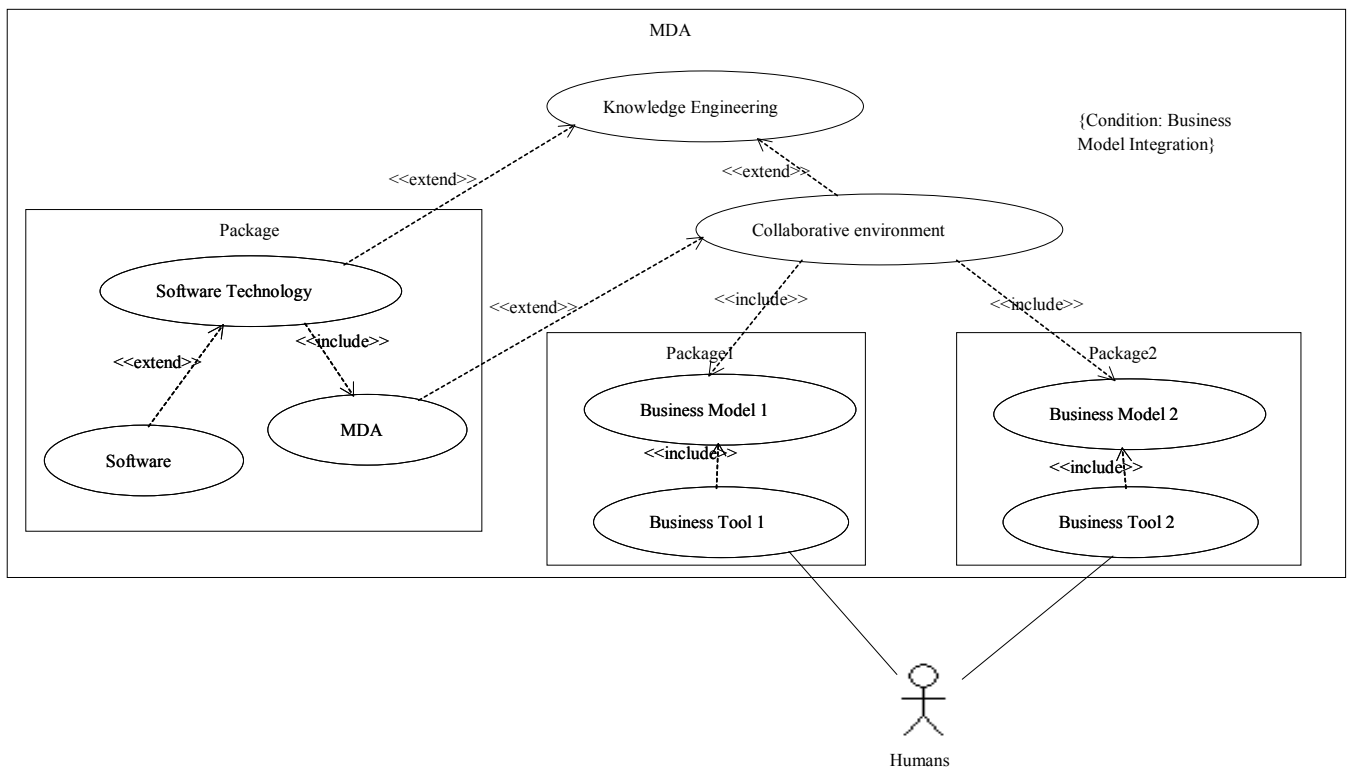
software engineering. MDA is a software technology that contributes to the KE by enhancing interoperability between heterogeneous business models (Kaufman et al., 2005).

MDA provides the way to describe business tool into a business model throughout modelling and meta-modelling architecture. This step should be carried by the expert tool who improves his model by specific business knowledge and constraints. Collaborative environment appeared as a middleware for information exchanges. MDA support the formulation of link between heterogeneous MOF compliant models throughout the model transformations concept. In a software point of view, this step could be totally achieved by MDA technology.

In the context of collaborative design, designers or actors should decide what information must be shared and in consequence what models must be shared. Models are not fixed and are evolving through the collaboration activities and the product lifecycle. The combination and equivalence between models need business expert knowledge which remains generally informal. Expressing possible combination need the intervention of specific business expert such as CAD designers or manufacturer. Synchronising heterogeneous models is a basic step to advance in collaboration and information sharing. Designers or actors of the collaboration negotiate each modification for validation. A main issue is then to assist synchronisation processes with MDA.

Our proposition to resolve this problem is a collaborative design environment whereby CAD and CAM tools could exchange information about the product and the manufacturing required operation, with exchanges driven by MDA.

Figure 2 Engineering knowledge support

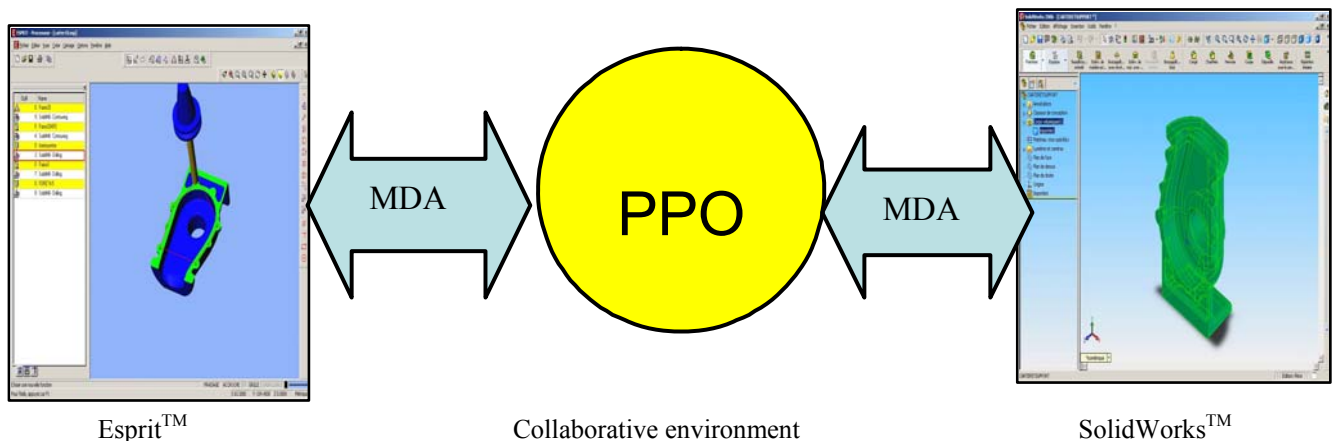


4 A collaborative design use case

Design and engineering of systems is increasingly becoming distributed and collaborative (Danesi et al., 2006). Combining multiple tools in a design process is a natural way to design a complex product. The effort for translation from CAD system to CAM system is costly. In a design process, CAD and CAM tools are applied to design and manufacture product. Let's focus on the scenario of collaborative design presented below. This simple scenario illustrates the problem of interoperability between CAD and CAM tools in the context of a manufacturing process. We have two main actors in this scenario:

- The designer is in charge of modelling the representation of the product in a CAD geometric modeller using SolidWorks™ (SolidWorks™, 2006). The designer knows how to take into consideration client's requirements and convert them into geometric constraints.
- The manufacturer is in charge of preparing the manufacturing of products. Here the Esprit™ manufacturing tool is used (Esprit™, 2008).

Figure 3 SolidWorks™ Designers, Esprit™ manufacturer, PPO environment are the players in this scenario (see online version for colours)



Let's imagine the manufacturer suggests some minor modifications to original design to take into account the compatibility between drilling tool diameter and an extrusion diameter. Until now there is no support that can propagate this kind of information from a tool like Esprit™ back to the CAD tool SolidWorks™. The suggestions are updated to the original CAD model and sent back to the manufacturer. After approval the design is frozen. Manufacturer develops process plans for each part. The manufacturing information is not attached to geometric CAD model. Each modification needs a CAD model modification and re-emission. This leads to information redundancy and loss.

Exchanged data is static and one-way; they do not incorporate details such as sketches, constraints and features, which represent the designer's intent. Some recent work attaches manufacturing information to the CAD model. This work is developed under the STEP-NC approach (Sääski et al., 2005). STEP-NC files are generated for the CNC machines. This concept does not fulfil the interoperability requirements.

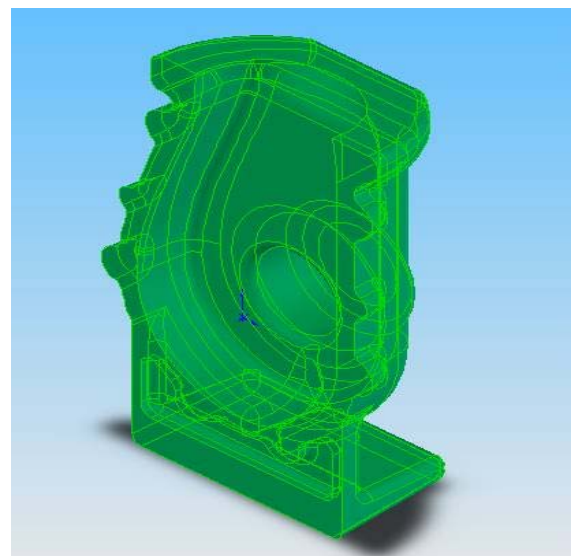
A shared PPO environment: PPO (IPPOP, 2007) is the collaborative environment chosen as a medium for information sharing and exchange and will be defined later in this paper (Figure 3).

The designer models a new product with the requirements and functionality fulfilling the market demands. He tries to express the engineering and industrial design intent. In this scenario the workpiece is a 'carter'.

The manufacturer:

- receives the client model and obtain information about workpieces,
- selects tools, mount and lay out tools,
- optimises a sequence of locations of the tools on each turret,
- generates a CNC code file,
- simulates machining of the workpieces,
- exports relevant production management information to production workflow.

Figure 4 CAO Representation of the workpiece (see online version for colours)



5 An environment to assist synchronisation between heterogeneous models

To validate our study we use the GAM framework (GAM, 2007). GAM (Figure 5 shows the graphic user interface of GAM, where a tree presents models and meta-models) provide an experimental platform for collaborative design in product development processes. It provides tools to manage information used along the product life cycle. Many works are already provided to define integrated meta-models with a similar goal as GAM. The intention in GAM is to build a very generic modelling framework enabling the easy management of every candidate meta-model. The framework could be used to compare them and to modify them.

Like in MDA, GAM is based on three-layered architecture. The lowest layer, Model, contains a particular model developed by final user, and consists of a set of linked entities in the design information layer. The meta-model layer determines the structure of a particular model. Finally, the meta-model layer describes the structure of the meta-models, and provides some application protocol interfaces in several computer languages (permanent information storage is ensured in XML files). The instantiation of the GAM meta-model provides either new meta-model description or conformed models. It is a bundle

of compatible modules dedicated to collaborative engineering support and provides a shared database. Simultaneous evolution of models and meta-models is traced, versioned and managed to seek the analysis of designer actions. GAM also takes in charge the distribution of meta-models and models through internet connection between server and client side applications.

In the GAM environment, we choose to use the PPO meta-model as a middleware for the information exchanges about the product. PPO meta-model is the result of integration of three models: a product meta-model, a process meta-model and an organisation meta-model (Girard et al., 2002; Noël et al., 2003). It is a light meta-model (with few concepts) but evolutionary. Figure 6 is an UML description of the product meta-model on which we concentrate our study. The major concepts of this meta-model are: component, interface, function and behaviour. A product is described by a component which is composed of one or more components. The class component inherits from the class Modelled Entity. With each component we associate interfaces (its boundaries and connections to connected components). A function binds one or more interfaces. A behaviour defines a state where associated components, interfaces and functions are active.

Figure 5 GAM environment (see online version for colours)

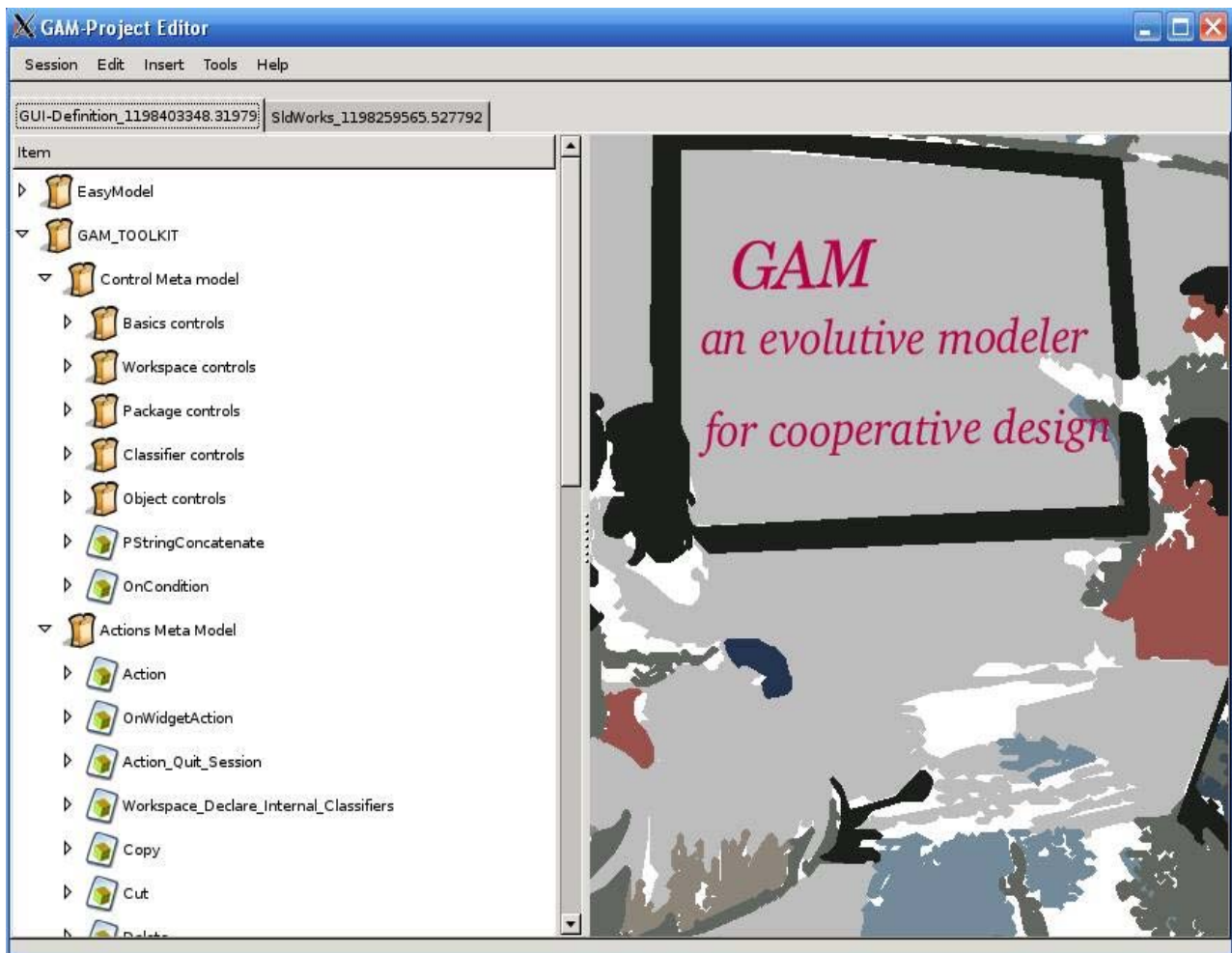
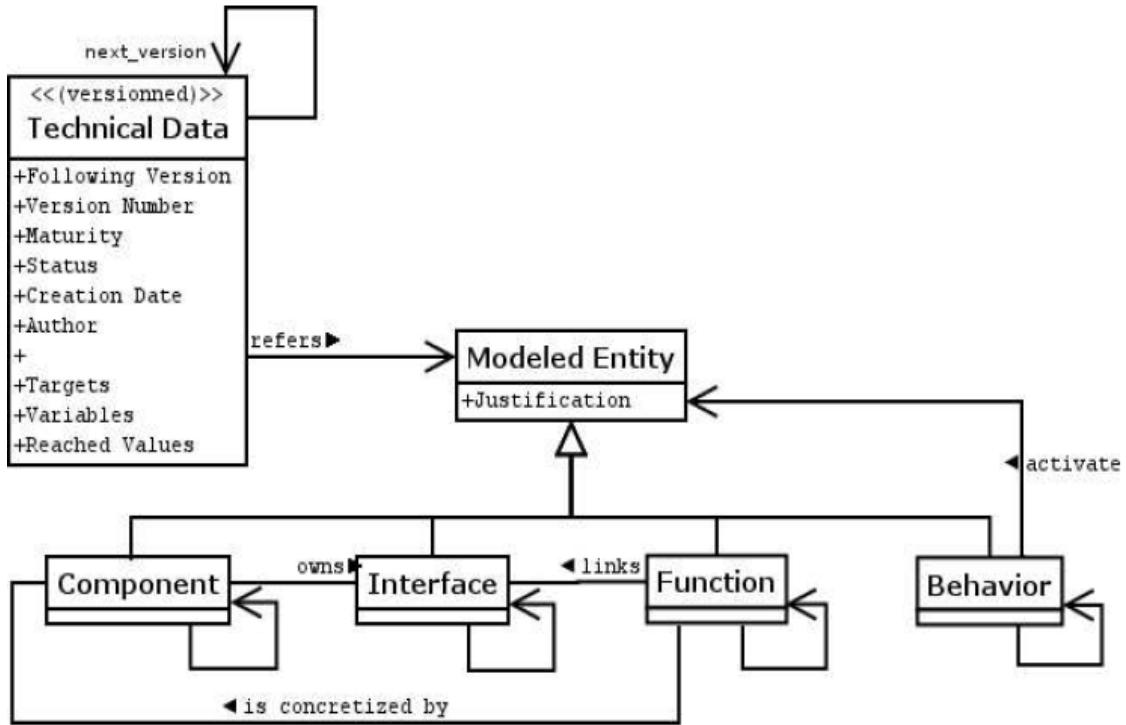


Figure 6 PPO product model



The PPO environment is expected to be the middleware for data exchange (IPPOP, 2007). Designers and manufacturers should be able to interact with this environment. PPO collaborative environment cannot integrate specific rules to the processing of data resulting from every expertise tool. It is thus chosen to let each expertise define connections rules to PPO framework.

A first step is to extract the business model from business tools. This step should be carried out by the business software developer. CAD model must incorporate information such as sketches, constraints and features, which represent the designer’s intent. Currently data exchange is carried by standard or proprietary format, feature tree is lost and the design intent also. In order to ease data exchange between CAD and CAM model, we adopt a feature-based model extraction: the model is a set of features; a feature is a set of parameters, constraints and references. Parameters represent the variables associated to that feature (i.e. sketch dimensions, extrusion distance, etc.); constraints hold the relationships between the geometric entities of the feature (i.e. perpendicularity, parallelism, etc.) and references represent the explicit geometric entities that are needed to define the feature (i.e. attaching plane, reference edges, etc.). Figure 7 presents the SolidWorks™ model extracted automatically from the SolidWorks™ tools in the GAM format.

What we mean by an automatic extraction is that the API learn automatically all the required parameters. But

required parameters should be specified by the expert tool. Experts specify information to extract from the business model. Information to extract is information needed for the collaboration. Expert is free to filter information to share and to keep his work confidentiality.

Some steps must be followed to connect business models in an environment like GAM. The business experts should describe its business meta-model in the GAM environment. This meta-model allow the creation of a library that joined to the business tool library enable the creation of the GAM model stating from the business model. The created API checks if the GAM model is already created or not. If created, required modification is achieved. If not, required model is generated. We follow this verification because the GAM environment manages model versioning.

Figure 8 presents the Esprit™ model extracted automatically from the Esprit™ tool in the GAM format. In this model manufacturing operation is achieved with a tool and applied to a geometric feature. In Figure 8, we detail the ‘SolidMil-Drilling 3’ operation which is achieved by the ‘foretacentrer’ tool and applied to the ‘11 perçage’ feature. Operation, Tool and Feature constitute the key concept of the Esprit™ model. Significant parameters of each concept are captured.

Figure 7 Instantiation of SolidWorks™ feature-based model in GAM environment (see online version for colours)

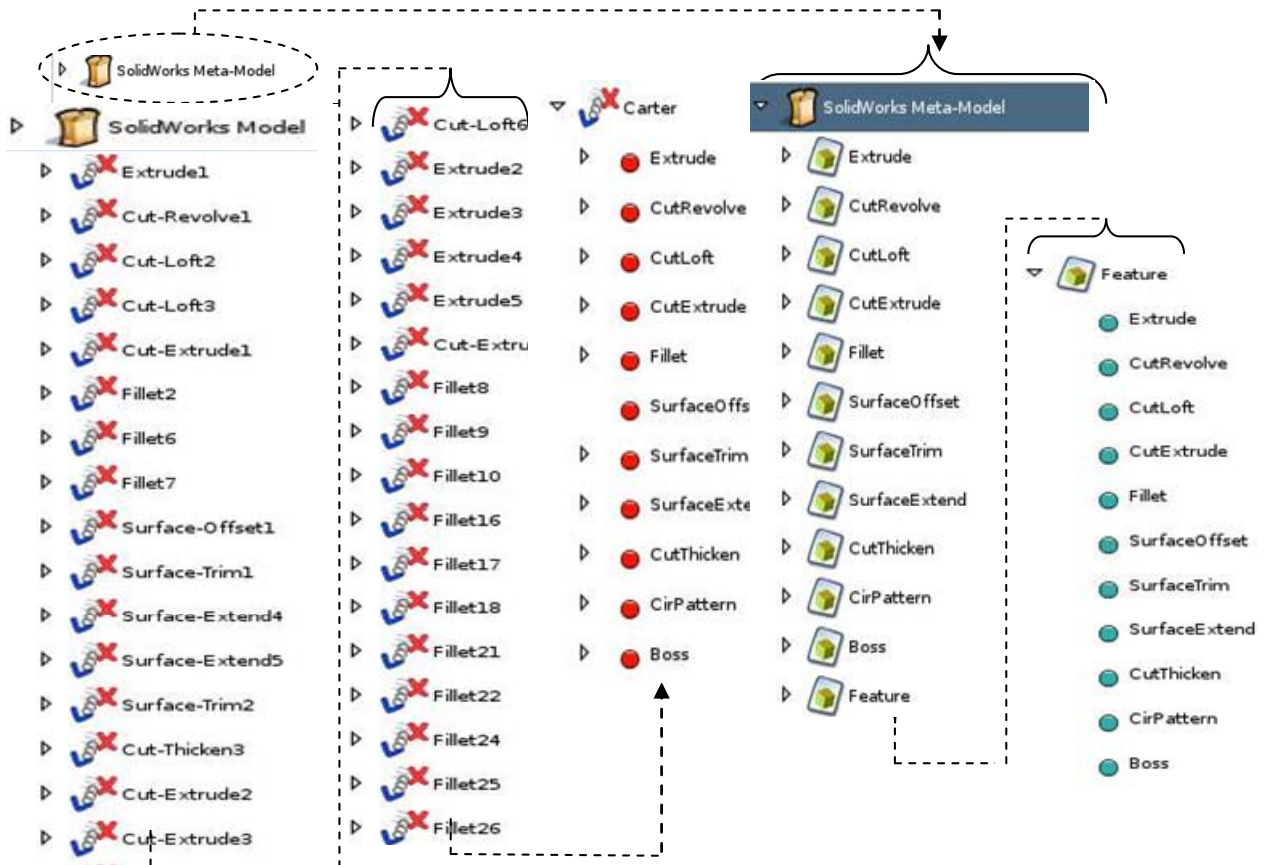
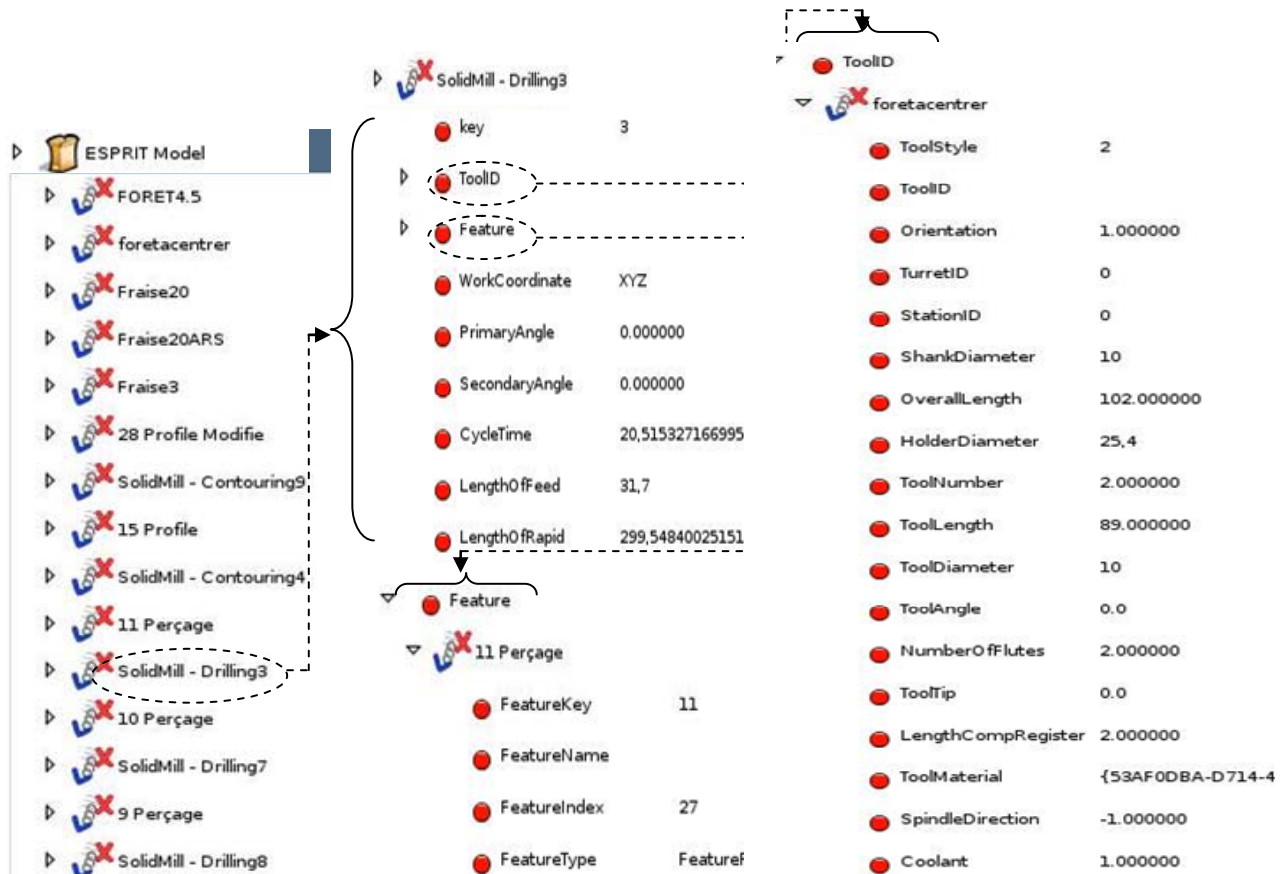


Figure 8 Instantiation of Esprit™ model in GAM environment (see online version for colours)



Once the Esprit™ and SolidWorks™ models are specified in the GAM environment, the manufacturer must specify the rules of connection between Esprit™ and the PPO. Designer should specify the rule of connection between SolidWorks™ model and the PPO model. These rules formalise the expert's knowledge about synchronisation. The Esprit™ model describes the structural decomposition of the machining operation system. The manufacturer needs primarily to share the data related to machining operation in order to get the required modification in the CAD model. In our demonstrative case, required modification is the angle used for the feature in which a drilling operation is applied. In fact, the angle of the feature used for the drilling operation is not adequate with the extrusion angle. The manufacturer shares this information via the collaborative environment represented by the PPO meta-model. We specified a correspondence rules between Esprit™, PPO and SolidWorks™ at the meta-model level in order to get the link between different entities in different tools. This correspondence formalises the generic knowledge to connect the two businesses.

Figure 9 shows a very simplified connection view between the CAD and CAM tool in the meta-model level. The correspondence at the model level between business models is done in respect to the rules at the meta-model level. As shown in Figure 9, the class 'Feature' in the Esprit™ meta-model corresponds to the Class 'Component' in the PPO meta-model. In the same way, the Class 'Feature' in the SolidWorks™

meta-model corresponds to the Class 'Component' in the PPO meta-model. So the relationship between CAD and CAM meta-model is carried out in the geometric level. The establishment of relationship between the business model and the collaborative environment is in charge of each expert tool. Experts connect to the collaborative environment, specify the adequate correspondence between their meta-model and the PPO meta-model; then they create the correspondence model between their model and the collaborative model. This correspondence obeys the correspondence meta-model. Once this entire step is achieved, the synchronisation between homogeneous models is expected. The synchronisation between homogeneous models is quite simple to achieve. There is only the need to negotiate whether to keep the expert suggested value or not. In this case (as shown in Figure 10) the manufacturer working with the CAM tool suggested an 'angle' of '0.2' to achieve the machining operation with his available fabrication tools. The designer working with the CAD tool agrees with the modification, a PPO synchronised model is created and each expert could read this new value thanks to the read/write API that we create. Models and meta-models express expert's knowledge and expert participate actively to define each step of the process. This environment provides an assistance to enable the expert to express collaboration need stating from the extraction of the expert business model, the specification of the connection rules, and the synchronisation of homogeneous models.

Figure 9 Correspondences at the meta-model level between Esprit™, PPO and SolidWorks™ (see online version for colours)

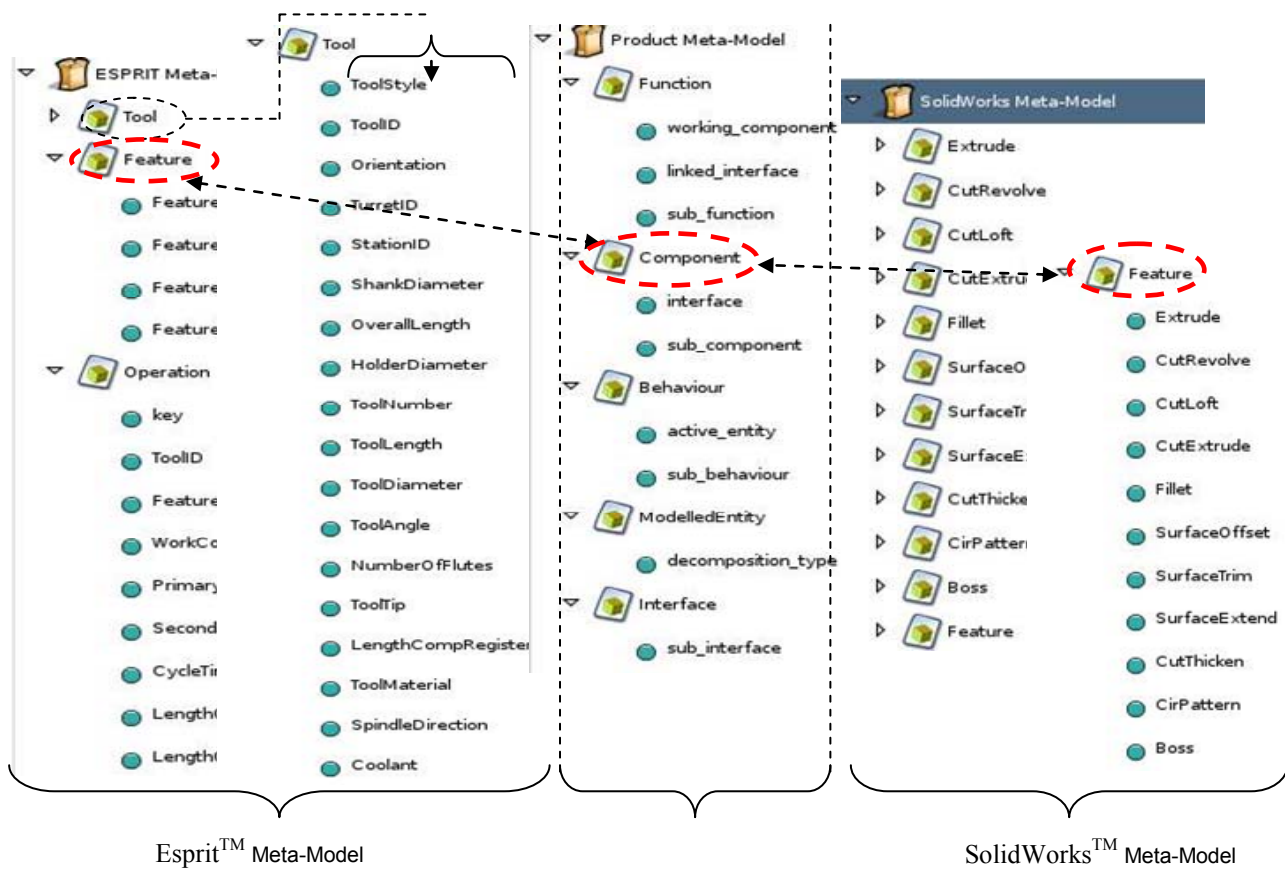
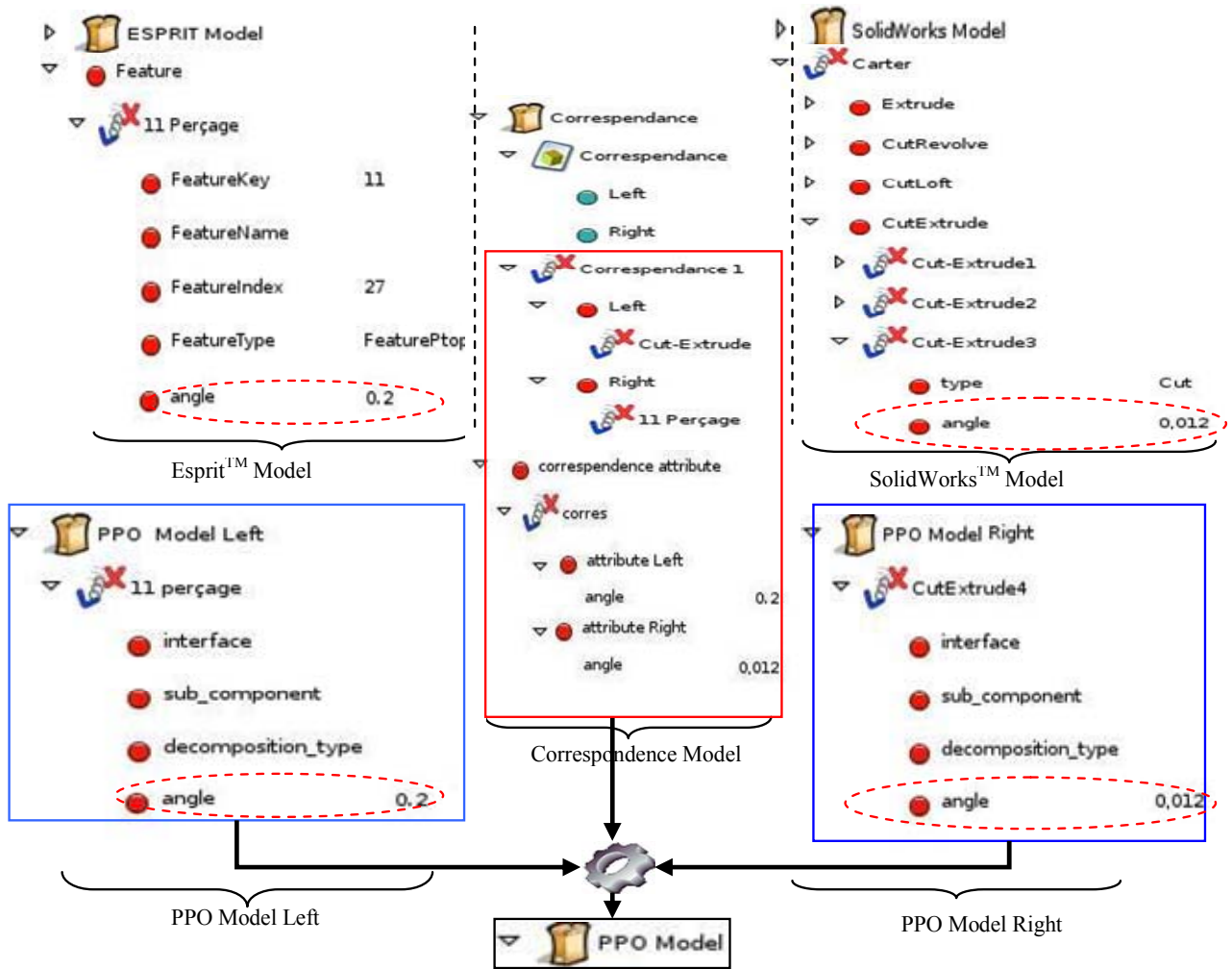


Figure 10 Correspondences at the model level between Esprit™, PPO and SolidWorks™ (see online version for colours)



In this example, the significant parameters to share is the attribute ‘angle’, the value specified by the designers does not fulfil the manufacturer demands and machining tools availability. The correspondence presented here is at the ‘Class’ level. We defined a correspondence at the ‘attribute’ level. The feature ‘Cut-Extrude3’ issued from the CAD model correspond the ‘11 perçage’ issued from the CAM model.

It is interesting to highlight that the same feature has different identification according to the expert point of view. For the designer the feature is Cut-Extrude by reference to the CAD operation that allowed the creation of this feature. For the manufacturer, it is a drilling (‘perçage’ in French) by reference to the manufacturing operation. Even if we are interested in studying the interoperability in the syntactic level of model heterogeneity we cannot ignore the semantic level of model heterogeneity. In this example, the attribute ‘angle’ of the Class ‘11 perçage’ corresponds to the attribute ‘angle’ of the Class ‘Cut-Extrude’. Designer accepts the manufacturer modification. As a consequence, a PPO synchronised model is generated.

Once the PPO synchronised model is generated, each experts tool read the modified value and update his business model. Experts continue to work in their models and do modification.

Expert wants to share again design or manufacturing related information in order to efficiently collaborate during the design and the manufacturing phase of the process of product development. The GAM environment provides a way to calculate the difference between homogenous models. The modification achieved by each expert could be calculated with ‘GAM-diff’ module of the GAM environment. The ‘GAM-diff’ calculates the difference between two models conforming to the same meta-model. In a mathematical way, the ‘GAM-diff’ is expressed as: $\Delta (\text{Business Model}_{\text{new}}, \text{Business Model}_{\text{old}}) = \text{Business Model}_{\text{new}} - \text{Business Model}_{\text{old}}$.

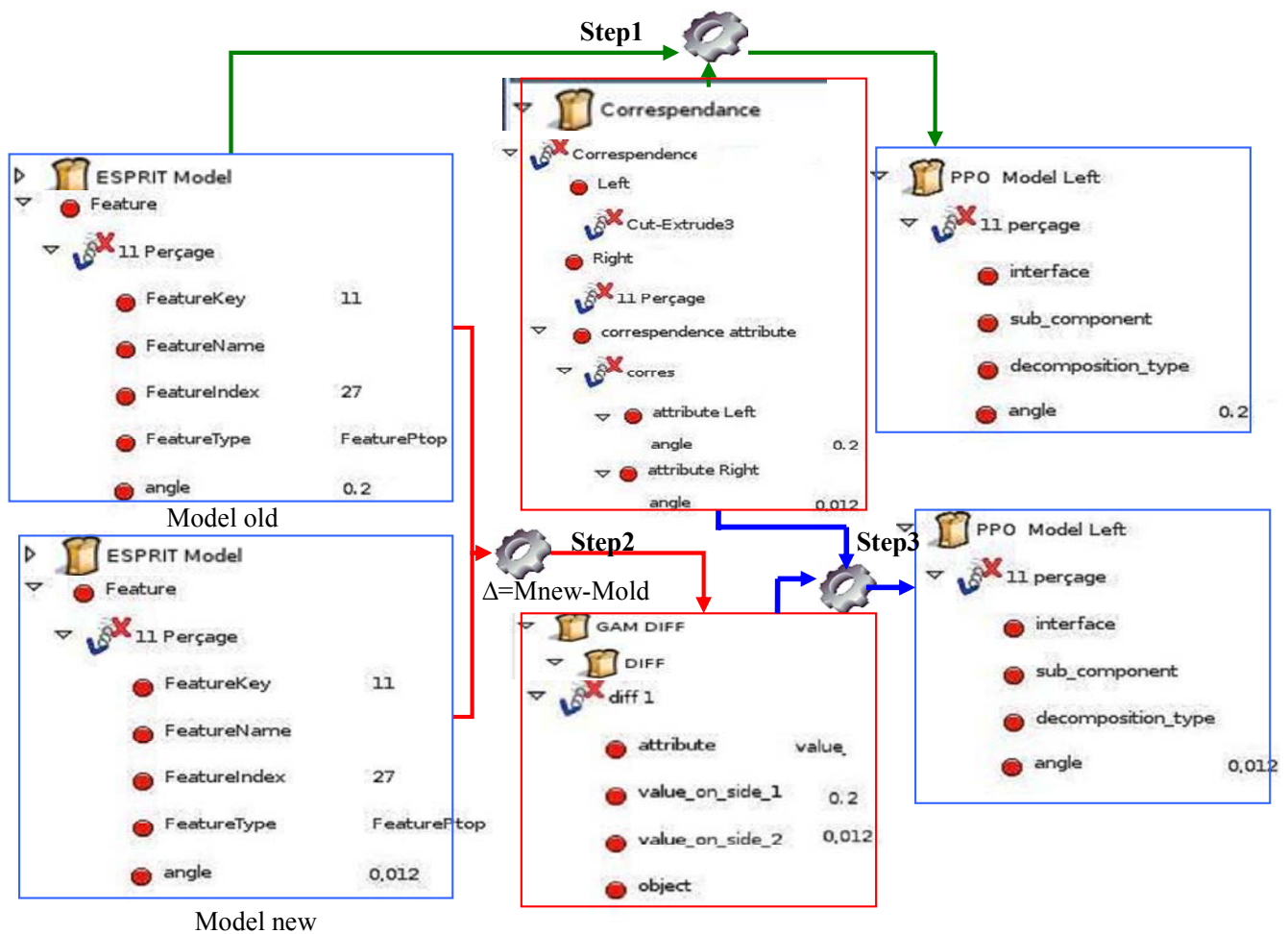
We assume that each modification could insert, delete, or modify an element of the model (a class, an object or an attribute). Once the model is modified, the difference between homogenous business models is obtained. Knowing correspondence between business models and collaborative model, we can deduce the collaborative impacted concept. Correspondences specified in the first connection to the collaborative environment are reused to help further business model connection to the collaborative environment. The knowledge formalised during the interaction between experts and the collaborative environment is recapitulated and not lost. The sum of different expert collaboration constitutes business knowledge. The GAM environment assists the expert to constitute this knowledge.

Model synchronisation is the process of propagating changes between models when one of them is edited. A model synchronisation methodology needs a representation framework to support model synchronisation. This framework should give essential concept to define the element needed to represent models at different levels of abstraction. The GAM environment replies to these requirements by providing a formulation for the specification of models and assistance for corresponding and expressing expert's knowledge for transforming business model to a target model.

We specify a simplified meta-model of correspondence specifying the correspondence between two or more elements of the model: Left and Right elements. Left is used to identify

the element of a mapping from a model while Right is used to identify the element of a mapping in the second model. Each correspondence between 'Class', may be detailed correspondence between attributes. In Figure 11, the left side of the correspondence contains the 'Cut-Extrude' feature; the right side contains the '11 perçage' feature. The correspondence between attributes included in the correspondence contains at the left side the attribute 'angle' with the value '0.2' and at the right side the attribute 'angle' with the value '0.012'. Figure 11 describes the entire process of a simplified collaboration situation in the case of design and manufacturing process.

Figure 11 Entire process of a simplified collaboration situation (see online version for colours)



In the step 1 of the collaborative activity, we have the business model and meta-model (Esprit™), the correspondence model and meta-model and the PPO meta-model. Using these inputs, we could generate the PPO target model.

In a collaborative activity, an expert makes multiple modifications and need to share their information many times in order to efficiently collaborate. In the step 2, the modification is calculated thanks to the 'GAM-diff' module of the GAM environment. As shown in the 'GAM-diff' model,

the modification concerns the angle 'attribute'. The value on side one and the value on side two are presented. The synchronisation of the Esprit™ model and the PPO model could be achieved at step 3. At the step 3, we take as input the 'GAM-diff' model and the correspondence model in order to generate the new PPO model. The process search for each object present in the 'GAM-diff' model the modification; check if this object is implicated in the correspondence model and propagates the modification.

The summary of the essential steps for model synchronisation between heterogeneous tools is as follows:

- To extract business model from business tool in the adequate format: Here we developed a read/write API that extract the business model such as Esprit™ model and SolidWorks™ model in the GAM format.
- To establish correspondence between business models and express business rules: here we assist the establishment of the correspondence between the business models throughout the collaborative environment. The business rules expressiveness needs more studies.
- To calculate the modification when a model is altered: we calculate the difference between two models thanks to the 'GAM-diff' module of the GAM environment.
- Knowing the difference and the correspondence we can synchronise models by propagating changes.

6 The MDA relevance in manufactured product development

The design of a product is generally achieved using the 3D representation by means of CAD tools. The CAD model is a set of assembly, part and volume. In the CAD model, we focus on features representing the *design intent* by reference to the feature-based modelling design.

The manufacturing stage generates the CAM model. The CAM model is represented by a set of operations achieved by tools and applied to specific features which are not linked to the geometric feature. The CAD model is transferred to the manufacturing stage by the use of standard which break the link between these models.

As demonstrated before, MDA provides new assistance step to model and manage correspondences between models of manufactured parts issued from heterogeneous tools. The

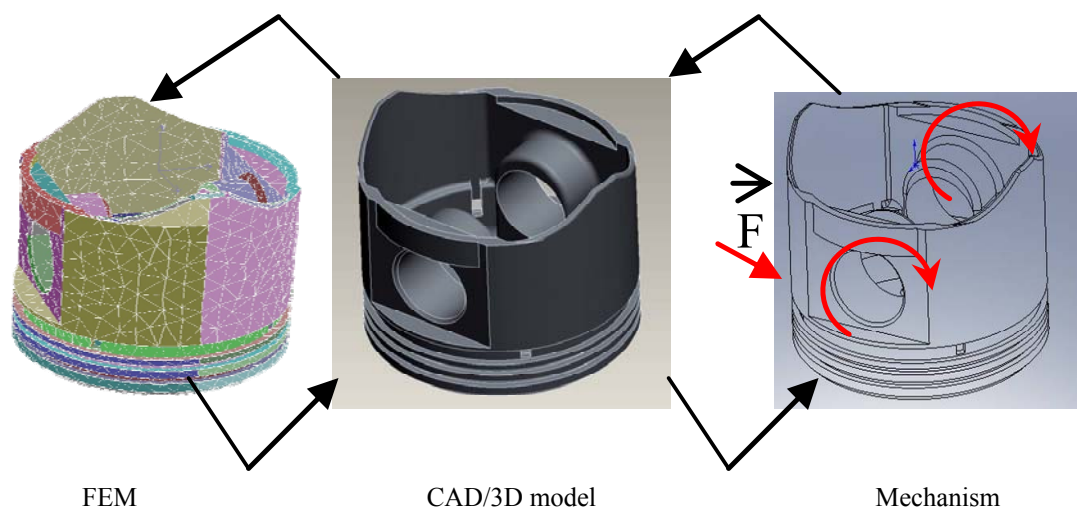
main impact takes place when correspondences between models are already established.

The correspondence between heterogeneous models is an associative approach to connect different objects of business models. The objects representing different business point of view of the same product are connected and information transfer via correspondence among them is possible. Models in different views can share information via the collaborative design environment PPO.

Obviously, improving interoperability between expert tools should enhance their collaboration capacity and provide easier product development process. MDA will be surely very efficient when new products are under consideration: with a new product (innovative) specific linkage of models is not well established. Experts need a flexible environment to formalise the new knowledge about these links. MDA can provide the formalisation environment. However, the practise of product development leads to loss of correspondence between business models. Then it must be rebuilt from scratch.

The synchronisation between business models needs a stage for link recognition (Bettaieb and Noel, 2006). The link between expert models is complex and difficult to reconstruct. Figure 12 shows three heterogeneous business models: CAD model, the Finite Element Model and the Mechanism model. The Finite Element Model is used to validate and optimise the product. The mechanism model is used to evaluate the kinematics, the dynamics and possibly the collision between parts. The link between these models needs a stage of recognition. For specific businesses, approaches were developed to automatically extract correspondence. One of the most difficult match concerns the 2D meshing and the 3D CAD representation. (Noël et al., 1995) develops a data structure and specific algorithms to perform mesh classification. Mesh classification was defined in previous work where (Schroeder, 1991) tried to accomplish a fully automatic three-dimensional mesh generation.

Figure 12 Initial models and links between their entities (see online version for colours)



In the context of CAD and CAM, some approaches have been developed to automatically recognise feature for manufacturing (Li et al., 2006). Feature recognition is a sub-discipline of solid modelling that focuses on the design and implementation of algorithms for detecting manufacturing information from CAD models. Automated feature recognition has been an active research area in solid modelling for many years and is considered to be a critical component for integration of CAD and CAM.

Approaches whether in the FEM/CAD context or in the CAD/CAM context are really specific to the concerned business and are mainly based on geometric rules which are not covered by MDA.

Combining techniques of heterogeneous model link recognition and MDA is essential to deal with the problem of correspondence matching between heterogeneous models.

7 Conclusion and future work

This paper studies how to formulate and to organise the synchronisation of heterogeneous models. The proposed approach enables business experts to formulate their knowledge. The expressed shared knowledge improves efficient collaboration and formalises expert's skill while preserving confidentiality.

MDA seems to be applicable for the synchronisation of design models of manufactured products. We demonstrate this interest in new field for the MDA usually applied to software engineering. The implementation of this approach is carried out for demonstrative case of interaction between CAD and CAM tools throughout the collaborative environment PPO.

The summary of our contribution is: (1) the creation of facilities to plug a new representation and extract business model in the GAM format; (2) the assistance for the creation of correspondence between business model and the collaborative model; (3) the management of interaction between commercial tool used by industry and the proposition of a strategy to connect several models together.

But it is still required: (1) to manage a complete set of possible interactions between tools used by industry; (2) to propose facilities to easily create and manage a set of business rules in order to well-express business knowledge; (3) to improve traceability in models' interactions to follow the evolution of the model level.

Future work will focus on combining existent techniques of feature recognition for manufacturing and MDA to automate correspondence between heterogeneous CAD and CAM models.

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Supplier-involved collaborative product development in PLM

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Abstract: Increasing economic competition, globalisation and well-informed demand is constantly challenging companies. Past research efforts paid to supplier-involved Collaborative Product Development (CPD) mainly related on collaboration method, platform, tools and standards. Unlike the past, the performance of an enterprise now depends much on the performance of its partners in the value chain. To address such challenges, this study proposes a framework of supplier-involved CPD and a new method to analyse the collaborative scenario and interaction relationships. A new supplier-involved CPD framework in product lifecycle management is presented in details in this paper, which consists of three layers: Supplier Collaborative Business model, Supplier Collaborative Process model and Supplier Collaborative Operation model. The collaborative scenario and interaction is analysed using five processes, which are product planning, conceptual design, detailed design, design review and project management. A case study is demonstrated to show the efficiency and effectiveness of the framework developed in this paper.

Keywords: CPD; collaborative product development; PLM; product lifecycle management; collaboration scenario; ESI; early supplier involvement.

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1 Introduction

Today, market pressure increases on time-to-market and cheapest price of delivery to the company. Customer requires tighter collaboration to keep strategic partnership with supplier. The role of suppliers changes from simple component provider to be a systematic development partner. Effective collaboration throughout the product lifecycle is critical to the success of product development. The products developed by suppliers have grown from single components to more complex systems which only need to be attached to the final product at the customer's side. This enables the company to concentrate on its own core activities and delegate to others specific ways to solve tasks inside subsystems.

To enhance core competitiveness, many companies only keep their key technologies in-house and outsource all other work to other enterprises. There are several advantages of such strategy: (1) customer concerns more on its core competence; (2) supplier is more special in its own domain; (3) full use of supplier's scale of economy effect; (4) cut down development risks.

A consensus shows that 70–80% product costs are determined during the early stage of design phase. Early Supplier Involvement (ESI) in product development is regarded as one of the ways to enhance product development performance in terms of product cost, speed and quality. Supplier-involved Collaborative Product Development (CPD) concerns the coherence between how customers deal with supplier involvement on a project basis and how they deal with more strategic and long-term processes between suppliers and the customer. There are many differences between the customer and suppliers, including enterprise culture, management, process, new technology concerning, experience in inter-enterprise collaboration, etc. These factors can take critical effect on the success of CPD. In such a sophisticated environment, any mistake could be a disaster at last.

Researches on supplier-involved CPD mainly focus on the topics of collaboration method, platform, tools and standard. However, introducing new technologies is not just to buy the tools or services. Deep understanding of current business and designing of appropriate processes are essentials for success. If suppliers do not know why to collaborate and how to collaborate in product development, the methods and technologies are useless to cope with the challenging business requirement.

To overcome these business challenges in supplier-involved CPD environment, this paper tries to provide a framework of CPD process and a new method to analyse the collaborative scenario and interaction relations during CPD. This paper is divided into seven sections. Section 2 introduces recent research results in CPD. Section 3 proposes a new framework for supplier-involved CPD. Section 4 elaborates details of collaborative scenario analysis. Section 5 depicts the system design and implementation of the framework. A case study of applying the framework is presented in Section 6. The paper ends with the conclusion and future perspectives in Section 7.

2 State-of-the-art review

As the physical borders between enterprises disappeared, more and more partners became the key node of the

business processes. Enterprises have to react to the raised innovation pressure, absorb the emerging product and process knowledge and facilitate flexible collaboration on a global scale by aligning their business processes. Past research results on supplier-involved CPD are mainly reported on the collaboration method, platform, tools and standard.

Adam et al. (2005) proposed a collaboration framework for cross-enterprise business process management by using ARIS modelling method. As-Is and To-Be model analysis is often used in Business Process Reengineering (BPR). Focusing on injection mould industry, Lu et al. (2005) presented the process analysis of As-Is and To-Be models by using Petri Net (PN). With the help of INCOME-4, a process simulation tool examined the performance of new business process mode.

Supplier selection plays a critical role in CPD. Firms improve their knowledge base by looking for suitable partners to collaborate with. Collaborative R&D opens firms' eyes to the need to access ideas and information from a variety of sources (diversity) to improve innovation performance (Nieto and Santamaria, 2007). Work Breakdown Structure (WBS) and Work Packages (WP) are applied in project management broadly. When integration with a supplier becomes a strategy, this functionally and departmentally established WBS and WP logic introduces barriers to communication as engineers did not know who was doing what and when. Few knew what kind of information others needed and who could provide them with the important information they needed. Danilovic (2007) gave a good solution by applying the dependence structure matrix method. Early thinking with disposal and recycle of product becomes much more important these years. Based on the disassembly planning and recycling strategy, Kuo (2006) proposed a model of disassembly and recycling bill of materials building and analysing.

Some other researchers aimed at different aspects of CPD methods. Tassarolo (2007) believes that product vision construct is defined as a firm's ability to define clear objectives and a well-recognised strategy for the development process and to share these objectives and strategy with all those involved in the development. Grebici et al. (2005) proposed a conceptual framework to support asynchronous collaborative activities, especially the exchange of preliminary information. Lam and Chin (2005) proposed 13 critical success factors of conflict management to provide organisations with directions and targets for establishing and improving their conflict management practices. Chen and Siddique (2006) presents a Petri-net process model that captures the dependency relationships of design decision-making and information exchanges among multiple design problems in a distributed environment.

After a large amount of business practice implementations, the famous PLM solutions vendor, PTC divided the product development into 24 processes (http://www.ptc.com/WCMS/files/51720/en/2352_Windchill_Brochure_EN1.pdf), which cover the whole product lifecycle phases from planning to concept, to system development, to demonstration, to production and deployment, to operations and support. They called this PTC Process Framework. According to this framework, enterprises would know where they have deficiency in business processes with the help of PTC. And then, of course, together with PTC's software, enterprises would

optimise their processes to form a CPD environment. Before this, Ming et al. (2005) divided the product lifecycle into 18 processes.

New information technologies provide new opportunities for tighter collaboration between suppliers and customers. Professional exchange of data based on semantic web, as well as the use of ontology combined with standardised business transactions. The majority of research in CPD talks about the collaborative associated technologies and their applications for platform implementation. In CPD environment, describing the knowledge for interoperability across disparate application systems, sharing semantics of the system/process functionality and its information is very difficult. Ontology is a new way to tackle these interoperability difficulties, which is a lexicon of specialised terminology along with some specification of the meaning of terms in the lexicon (followed the definition of ISO 18629-1). Each field has its own ontology. And there is no standard ontology language yet. An ontology language usually consists of entities, attributes of entities and associations between entities. To build ontology about product knowledge, Product Semantics Representation Language (PSRL) (Patil et al., 2005) is presented. Syntax for encoding the PSRL is based on the Web Ontology Language (OWL) (<http://www.w3.org/TR/owl-ref/>).

Workflow management tools are embedded in most IT systems (such as ERP, PDM, OA, etc.). Workflows can be defined and processed within the system. But under the collaborative environment, business process involves intra- or inter-enterprise workflows, which often cross multi-IT systems. Standalone workflow engine is needed for CPD. Baina et al. (2006) established a process service interconnection model to support dynamic interconnection of enterprise workflow processes. This model is structured in three main layers, including workflow layer (workflow process application level), process layer (business level) and process service layer (interconnection and cooperation level). Workflow can be separated into dynamic and static. A static workflow has to be finished or aborted once it is initiated, while a dynamic workflow can change during execution time. Most commercial PDM systems perform their workflow as static. Qiu and Wong (2007) gave a solution about dynamic workflow engine with SmartTeam PDM by using PN and directed network graph techniques. These methods can also be introduced to establish inter-system workflow engines. Tan and Fan (2007) provided a workflow model fragmentation method to partition a workflow model into fragments. They separate one integrated workflow model into small partitions and allot them to different servers to be executed by means of PN. This can alleviate the heavy load of centre server.

Product knowledge and process knowledge are the main source of New Product Development (NPD) and collaborative innovation. Some researchers show interests in acquiring knowledge from partners or customers. Sua et al. (2006) proposed an E-CKM model (a customer knowledge management-model implemented by IT), which uses data mining techniques to obtain customer's knowledge for NPD. To support engineering designers and specifically the decision-makers, Robin et al. (2007) defined collaborative knowledge

and modelled the associated design system Integration of Product, Process and Organisation for engineering Performance improvement (IPPOP). Jung et al. (2007) defined process knowledge as, "three types of knowledge that supports process-related activities efficiently throughout the lifecycle of business processes". The three types of process knowledge are process template knowledge, process instance knowledge and process-related knowledge. The integrated framework of knowledge representation includes three layers, i.e. a knowledge frame in the 'lower' layer, a knowledge formula in the 'middle' layer and a knowledge rule in the 'upper' layer (Chiang et al., 2006).

For the complexity and lack of software vendors supports, there is slow progress in STandard for the Exchange of Product (STEP) data (ISO 10303) technology which involves too much technical standard (still new standards emerge till now). Only a few collaborative platforms were constructed based on STEP these years (Tanaka and Kishinami, 2006). More and more CPD systems directly use SOA and web services to establish their work environments (Kim et al., 2006; Lee et al., 2006).

Collaboration is integration between business processes, workflows, knowledge, IT systems, resources, etc., like system integration, but at a much larger scale. A good framework or platform is the precondition to realise the CPD. Some or all the management methods and technologies will be used in these platforms. Mejia et al. (2007) provided a method about developing collaborative engineering environments. Using open standard, open source is a general way to develop CPD. With the help of special tools, like peer-to-peer tools, these systems could get the similar performance like commercial software. Li and Qiu (Aziz et al., 2005) summarised the CPD systems as three aspects – visualisation-based collaborative systems, co-design collaborative systems and Concurrent Engineering (CE)-based collaborative systems. Sharma (2005) divided CPD into three levels: intra-enterprise CPD, inter-enterprise CPD and just-in-time CPD. Cooperative-collaborative design system architecture was proposed by Chen and Siddique (Li and Qiu, 2006) to support various design behaviours, synchronised workspace, social communication, perspective coordination and management functions that are depicted in the process model.

In the viewpoint of enterprise managers, the process and associated analysis on supplier-involved CPD is more critical than realisation techniques. However, introducing new technologies is not just to buy the tools or services. Deep understanding of current business and designing of appropriate processes are essentials for success. If they do not know why to collaborate and how to collaborate during development, the methods and technologies are useless to cope with the challenging business requirement. But so far, few research results are reported to tackle this challenge, and additional attention is urgently needed.

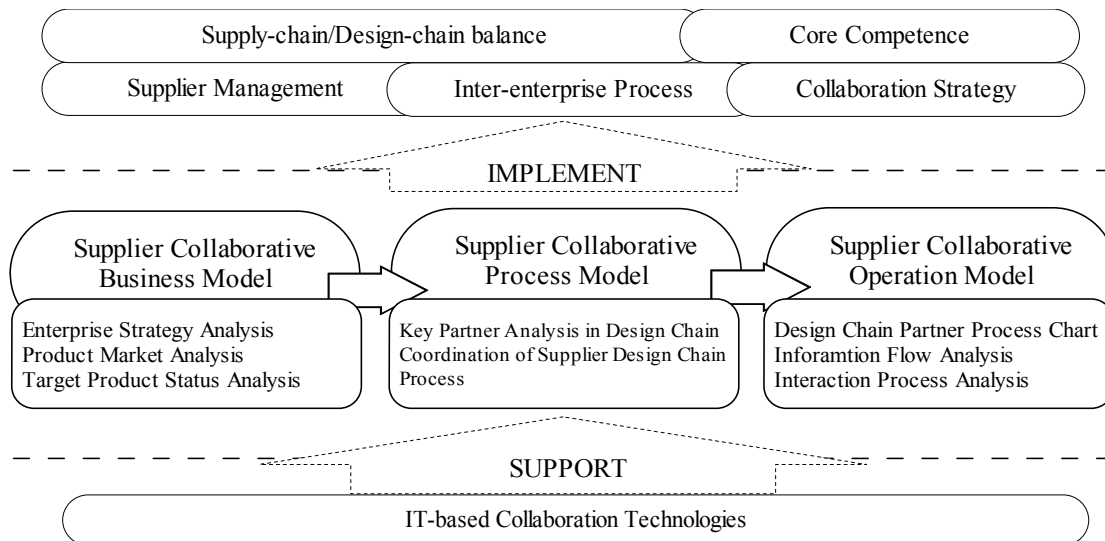
3 A framework of supplier-involved collaborative product development

The Design Chain Operations Reference (DCOR) model is a cross-industry diagnostic tool for design-chain management. DCOR enables users to address, improve and communicate

design-chain management practices within and between interested parties. It spans product development and research and development, but does not describe sales and marketing (demand generation) and post-delivery customer support.

Based on DCOR model, a supplier CPD framework is proposed in this paper. The framework consists of three hierarchical levels representing the degree that suppliers involve in CPD operation processes and application (Figure 1) as follows:

Figure 1 A framework of supplier-involved CPD



3.1 Supplier Collaborative Business model

After the strategy analysis of enterprise competition environment and the status of the product in market, the Supplier Collaborative Business model is used to confirm the characters and strategy of target product with the supplier collaboration strategy. If the new product to be collaboratively developed is modified based on the initial product, the components for this new product provided by suppliers may need small modification. If the new product to be collaboratively developed is totally a new one, the supplier should completely meet the requirement of its customer, provide enough and sufficient domain knowledge to support the complete development of the new product efficiently. For each developer, this model defines the corresponding role and the scope of functions by analysing the requirement of the end user, customer and supplier in the CPD environment.

3.2 Supplier Collaborative Process model

Supplier Collaborative Process model depicts how to coordinate the process of customer and suppliers in CPD environment. The collaborative processes with supplier in the design chain are categorised into five stages, which are project planning, conceptual design, detailed design, design review and project management.

- Supplier Collaborative *Business* model, which is used to analyse the enterprise strategy and confirm with the supplier collaboration target.
- Supplier Collaborative *Process* model, which is used to coordinate the partners' processes in such a collaborative development environment.
- Supplier Collaborative *Operation* model, which is used to analyse detailed activities of each collaborative process.

Different partners playing different roles in the design chain require different collaboration processes. Among these processes, the key success factor is the clear definition of stages of CPD processes, and the clear assignment of roles of each partner in design chain.

Detailed characteristics of Supplier Collaborative Process model are listed in Table 1. According to the model, the enterprise takes the corresponding collaborative process in each stage of design chain, and then confirms the supplier collaboration process characters. By comparing with the characteristics listed in Table 1, the enterprise selects the detailed process that fits it best. For example, in the process of a product development, the customer needs to collaborate with suppliers at the product planning phase. This product is mainly developed by the customer together with the support of supplier's development team. From Table 1, this scenario is called as PP01, which can be selected as the reference process model.

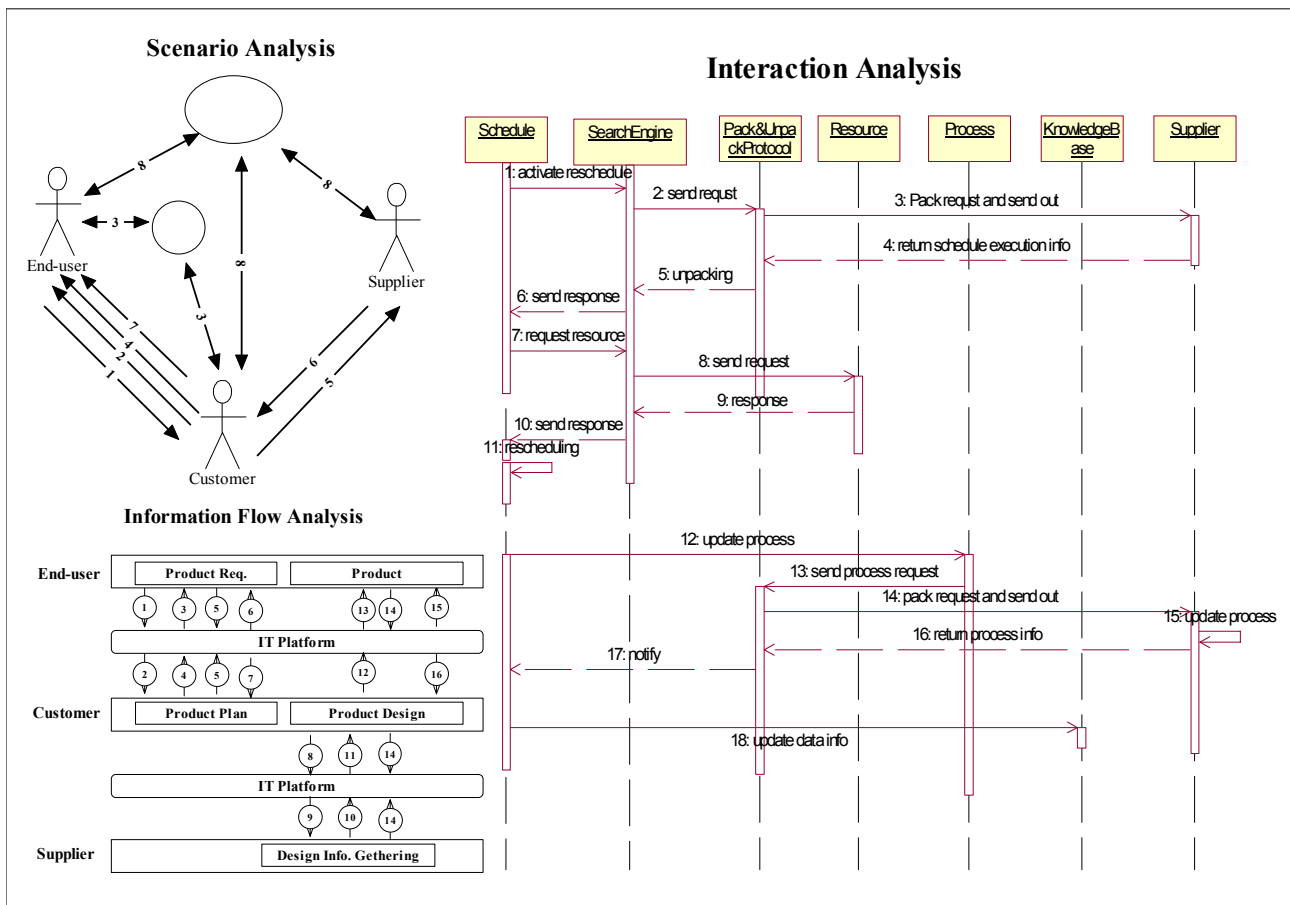
3.3 Supplier Collaborative Operation model

Supplier Collaborative Operation model analyses the detailed activities at the operational level in the CPD environment. The model decomposes the process coming from Supplier Collaborative Process model and analyses the coordination between customer and supplier's CPD process. It consists of three aspects, which are collaborative scenario analysis, collaborative information flow analysis and collaborative interaction analysis.

Table 1 Characteristics of Supplier Collaborative Process model

Core Process	S. N.	Characteristics of process
Product Planning	PP01	Customer design mainly, supplier design partly
	PP02	Customer design mainly, supplier assistant
	PP03	Design outsourcing, supplier design partly
	PP04	Design outsourcing, supplier assistant
Conceptual Design	CD01	Customer design mainly, supplier assistant
	CD02	Outsourcing
	CD03	Customer design all
Detail Design	DD01	Supplier design all
	DD02	Customer design mainly, supplier assistant
	DD03	Outsourcing
Design Review	DR01	Customer test and verification mainly, supplier assistant
	DR02	Customer test and verification, end-user participation
	DR03	End-user test and verification itself
Project Management	PM01	End-user determine the deadline, customer control development procedure
	PM02	End-user determine the deadline, customer collaborate with supplier to control development procedure
	PM03	Customer determine the deadline, customer control development procedure
	PM04	Customer determine the deadline, customer collaborate with supplier to control development procedure

Figure 2 Supplier Collaborative Operation model (see online version for colours)



3.4 Advantages of the framework

Supplier-involved CPD framework covers most of early states in the product lifecycle, including market analysis, conceptual design, detailed design and design review. The advantages of this framework are as follows:

- a top-down framework help the company to easily understand how to collaborate with supplier involved in the product development
- each model of framework can be expanded to an executable level
- scenario analysis is based on objective techniques and methods, rather than subjective bias.

4 Supplier-involved collaboration scenario

Supplier-involved CPD framework is a pre-defined framework that can be implemented before the CPD project started. First, the customer should make sure the Supplier Collaborative Business model. After the collaboration strategy confirmed, the customer should select the real collaboration scenario according to Supplier Collaborative Process model table. In the meanwhile, the analysis of collaborative scenario and collaborative interaction should be performed accompanied with the processes. From the results of Supplier Collaborative Operation model, the customer may alter the process selection. In some extreme situation, the Process table may be modified according to the real scenario. That means, Supplier Collaborative Operation model not only based on Supplier Collaborative Process model, but also influences it.

In order to make the correct collaborative processes that fit customer and supplier best, the fine and uniform analysis of collaborative process is most important. As mentioned above, this analysis contains three parts: scenario, information flow and interaction. Information flow and interaction are not easy to analyse before the project started, yet the scenario analysis can be achieved by detailed investigation and interview.

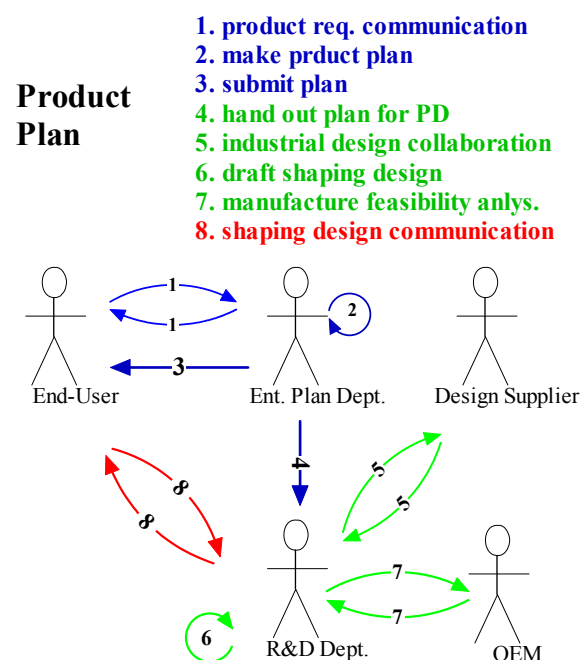
In this paper, the authors try to suggest some standard patterns based on the collaborative scenario analysis. We take the five most commonly used processes as the inputs of analysis patterns.

4.1 Collaborative scenario for product planning

By gathering product requirements from market investigation, the customer makes the product planning and establishes a product idea team. Team members collect associated information and begin with idea development. Product idea focuses the new product itself and the difference to other similar products. After analysing the enterprise technique and decomposing the product into sub-products and components, the customer selects CPD partners. The supplier selection criteria are not the same to traditional ones because the collaboration functions in nature.

The collaboration in product planning phase usually looks like that: the customer makes the design requirements and main design parameters, and then the supplier's teams discuss and reply whether they could fulfil these demands. After the requirements and parameters are confirmed by two sides, the customer should analyse technical difficulties and product costs to decide developing product platform whether or not. With the help of collaboration techniques, such as web-based online discussion, the customer affirms the final decision of platform development together with supplier's team. At the end of this phase, the customer should optimise its developing resources to make the profits maximisation, shorten product planning time, balance resources of different projects, etc. Figure 3 illustrates the detailed scenario of product planning collaboration process.

Figure 3 Product planning collaborative scenario analysis (see online version for colours)

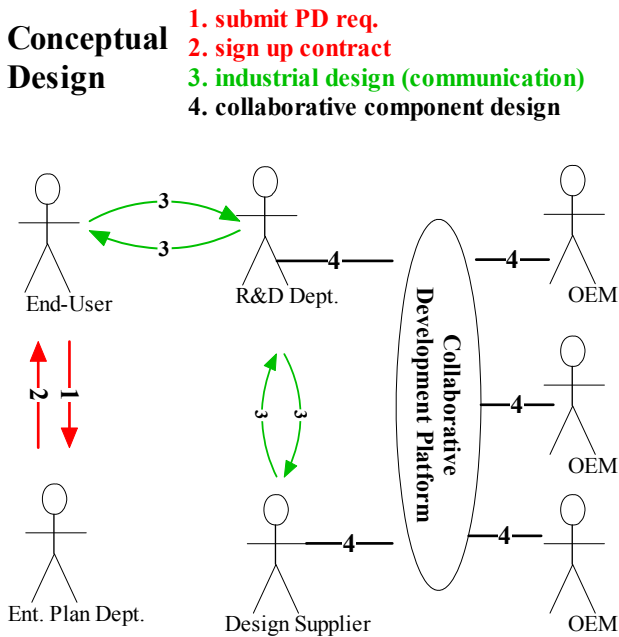


4.2 Collaborative scenario for conceptual design

The significant feature of conceptual design scenario is that the customer and end user design the product mainly and suppliers assistant.

It needs strong information sharing mechanism to assist the conceptual design process. Firstly, the supplier updates its components and parts database related to the project and let the customer know these changes. Secondly, the customer starts conceptual design based on suppliers' collaborative database and upload design draft to exchange platform. And then, the customer notifies the end user to evaluate drafts after it finished. The end user downloads it from the platform and discusses with the customer team to make the final conceptual design plan. After several such iterations, the end user validates the final plan and notifies the customer. The detailed scenario of conceptual design collaboration process is illustrated in Figure 4.

Figure 4 Conceptual design collaborative scenario analysis (see online version for colours)



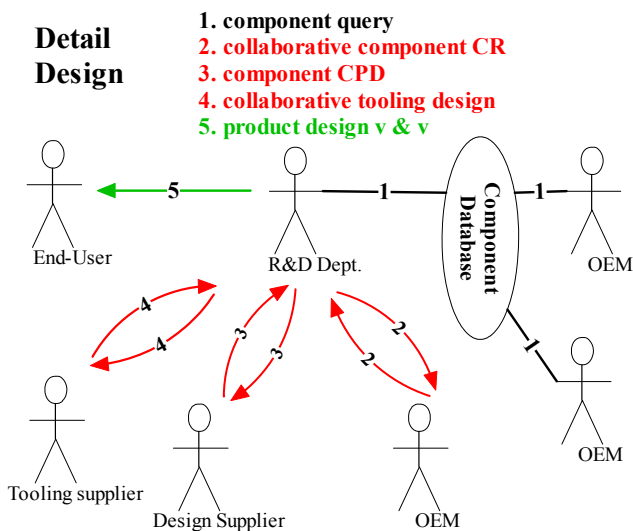
4.3 Collaborative scenario for detailed design

Detailed design is accomplished mainly by the supplier development team.

Supplier teams develop sub-products or components on the standard come from conceptual design plan. They upload design documents (drawings, test data, tables, etc.) to the exchange sharing platform after they have finished detailed design. The customer contacts with supplier on web-based CPD platform to validate the virtual assembling and virtual simulation process. This is similar to the process of conceptual design, which needs a series of repetition and modification.

Figure 5 illustrates the scenario of detailed design collaboration process.

Figure 5 Detailed design collaborative scenario analysis (see online version for colours)



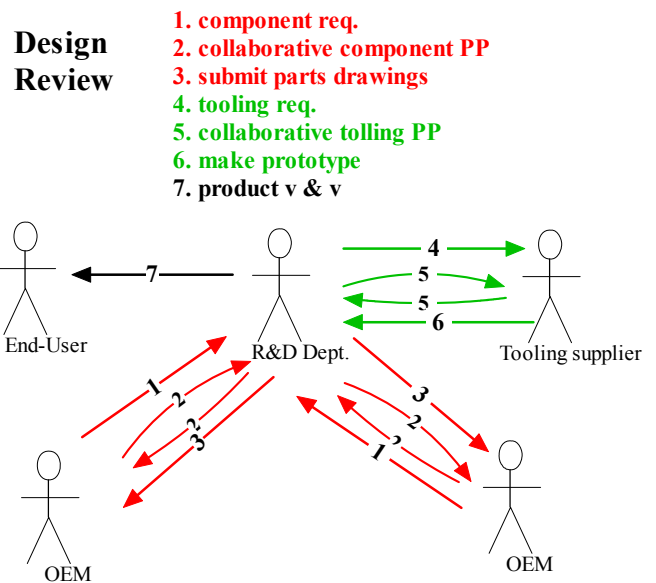
4.4 Collaborative scenario for design review

Prototype verification and validation is the main feature of design review scenario.

The OEM suppliers (maybe different to design partner) produce the prototype of product. After they have finished this work, they upload production planning reports to the platform. Then, the customer does prototyping and sends design validation report to the OEM if there is no mistake. If disagreement appears, the OEM will modify the prototype and the customer will continue with new a new design review. This is also a spiral iteration process.

Figure 6 illustrates the scenario of design review collaboration process.

Figure 6 Design review collaborative scenario analysis (see online version for colours)



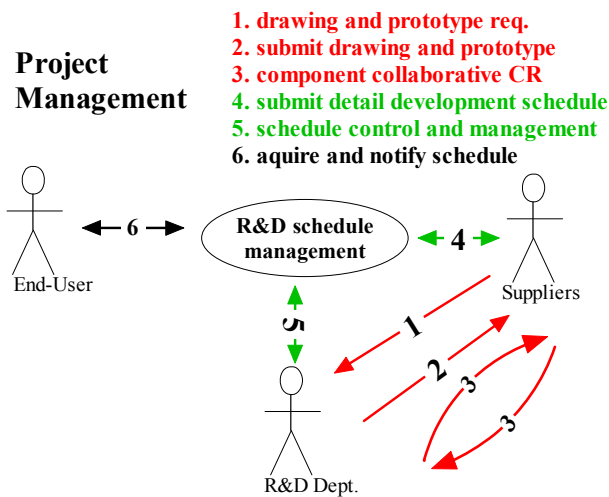
4.5 Collaborative scenario for project management in CPD

The feature of project management scenario is that the end user determines the deadline of project (time-to-market), the customer is charged of the project management procedure.

Product management process is not like the process we have shown before. According to the product lifecycle management theory, the product planning, conceptual design, detailed design and design review process are product lifecycle oriented. They are vertical process. But product management process is horizontal that appears at different lifecycle stages.

The end user schedules the deadline of product delivery and notifies it to the customer. The customer makes detailed schedule with suppliers to comply with this deadline. This schedule should be updated constantly to balance resources of both sides. In some industries, this collaborative schedule can be refreshed day after day. The product management in CPD execution is something the same as traditional product management, but high relies on the collaboration platform.

Figure 7 Project management collaborative scenario analysis (see online version for colours)



4.6 Technical advantages

Collaborative scenario analysis is based on business process management (BPR) with associated modelling and analysis tools. The results of analysis are easy to other uses, such as system design and implementation, process reengineering, business trends estimation, risk analysis, etc. The supplier-involved CPD scenario analysis method is easy to comprehend and spread. It is also the implementation tools of supplier-involved CPD framework.

5 System design and implementation

To implement supplier-involved CPD, an integrated information system is required. This system can provide collaborative functions as follows:

- the system should support the collaborative management in the entire product lifecycle
- it should be an extendable and flexible system because the collaborative environment is uncertain and capricious
- the system should implement the function required by the collaborative scenario of each design stage.

5.1 System design based on UML

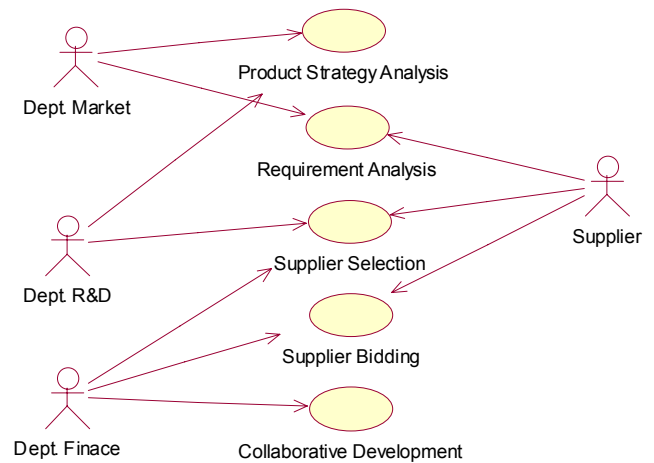
Unified Modelling Language (UML) is a well-accepted technique in information system development. It can help developers to analyse complex process relations and model the information system visualised. Supplier-involved CPD system is designed by using UML.

Business use case diagram is the description of system requirement, which expresses the system functions and services. Actors in model represent the system units interacting

with outer environment. By analysing the business process, department of market, R&D and finance of customer and supplier are selected as the system actors.

From scenario analysis, the main functions in supplier-involved CPD include product strategy analysis, requirement technology analysis, supplier selection with criteria weight setting, supplier bidding, collaborative environment establishing and development process collaboration. These functions and services should be provided by the system. The use case diagram of the prototype system (Figure 8) depicts the relations of actors and functions.

Figure 8 Use case diagram for supplier-involved CPD (see online version for colours)



5.2 System framework for implementation

A number of project management system architectures have been proposed. There is a method about developing collaborative engineering environments (Mejia et al., 2007). Using open standard, open source is a general way to develop CPD. With the help of special tools, like peer-to-peer tools, these systems could get the similar performance like commercial software. Normally, a CPD system should provide at least three functions – visualisation, co-design and CE. This requires the prototype system architecture should be an open, portable, operation system neutral and easy extendable system.

A five layer Java-based system framework was developed to satisfy these technical requirements, as illustrated in Figure 9. Supplier and customer have their own portal to access the system. The supplier-involved CPD framework and models are implemented in the layer of supplier collaboration management. Collaboration application layer contains three platforms: data exchange, virtual simulation and product development. Supplier database stores suppliers’ basic information mostly used by supplier selection. Project database is for project management data storage. Product database is the main database for CPD in each PLM phases. The infrastructure layer is responsible for maintenance and system administration.

Figure 9 System framework for supplier-involved CPD

Portal	Supplier Portal		Customer Portal		
Supplier Collaboration Management	Collaboration Strategy Creation/Selection				
	Collaborative Process Selection				
	Collaboration R&D Mgt.				
Collaborative Application Platform	Data Exchange Platform		Product Development Platform		
	Collaborative Virtual Simulation Platform				
Distributed Database	Supplier DB		Project DB	Product DB	
Infrastructure	Data Transfer	Log	Resource	Statistic Analysis	Computing

5.3 System advantages

Supplier-involved CPD processes and scenarios contain multiple firms, roles, users and resources, which need robust and comprehensive tools to design and implement the information systems. As one of the most popular system modelling tools in software engineering, UML is introduced in supplier-involved CPD system design. This system implementation is mainly based on Java language, which largely diminishes the redundant development for its cross-platform nature. The thin client (web browser) application is easy to use. System integrations may be solved with the help of uniform XML-based interface documents and web services extensions.

6 A case study

6.1 Case demonstration

THN is a special automotive company in mainland China. It produces most components and parts, and assembles them on its own. Recently, THN wants to extend its market to foreign countries for new profit. It also hopes to cut costs and shorten developing time to enhance the competitive advantage. In the mean time, THN initiatively cooperate with suppliers in product development. By outsourcing most of general components design and manufacturing, THN becomes 'leaner'. This is accomplished by the re-planning of collaborative design chain.

Here is a case on the CPD procedure of headlight development to illustrate this conversion. Although light development and manufacturing is not so difficult as chassis and engine, it contains a series of technologies such as appearance (industrial design), assembly (mechanical), illumination (optical) and wire layout (electronic).

At first, the light supplier only plays as an OEM and THN conducts all the design work. With the shorter overall time-to-market, THN found that it often delays for light design. In later product development, they tried to associate the light design with supplier in the CPD environment. THN provides the outline, critical size, illumination and

prospective fixing situation parameters to the supplier. According to these requirements, light design specialists from supplier conduct the detailed design by considering the new market trends. With the support of IT platform, supplier design team and THN team complete the product development with constant collaboration. But there are still questions on this degree of CPD:

- design interaction appears too much during CPD
- too much modification delays during CPD
- IT platform cannot perform all the collaboration work as expected.

To tackle these challenges, THN decides to make a big step in light design, that is, design outsourcing entirely to supplier, THN team only collaborates in critical outline size matching design. Based on the supplier-involved CPD framework, THN makes collaborative process analysis and collaborates with suppliers on a new IT platform.

After a comprehensive investigation, THN management board decides to outsource its light system from conceptual design to manufacturing. From Supplier Collaborative Process model table, PP01, CD02, DD03, DR01 and PM02 were selected as CPD processes.

The delivery deadline was made by the end user, which is the input of backward schedule made by THN. Then, THN select qualified design supplier with the product planning. The selected company promotes a feasibility plan to THN according to results coming from PP01 process. The supplier-involved CPD thus starts.

For the reason of full design outsourcing, THN can decrease the frequency of collaboration during design phase. Collaboration partner refreshes its component database at first. THN engineers accomplish pre-development plan including anticipated colour, size, power, illumination, etc. by querying from database. The supplier downloads this plan draft, contacts with THN online, and makes use of details of material for further development. Supplier leads the detailed design process with limited cooperation with THN. Data transfer, virtual assembly, interference inspection and other work can be done on the secure inter-enterprise collaboration platform based on modern PLM/CAD/CAE. In design review phase, such collaboration expands to the OEM. Figures 8–10 depict the collaborative interaction of conceptual design, detailed design and design review, respectively.

Collaboration platform plays a very important role in this business environment. Figure 11 sketches a prototype system in the process of supplier selection and interaction. This prototype was developed on the four layer browser/server infrastructure based on J2EE. These four layers contain resource management, data management, application collaboration and device-independent presentation layer. Collaborative expression is based on the XML and web services technologies.

Figure 10 Collaborative process analysis for conceptual design (see online version for colours)

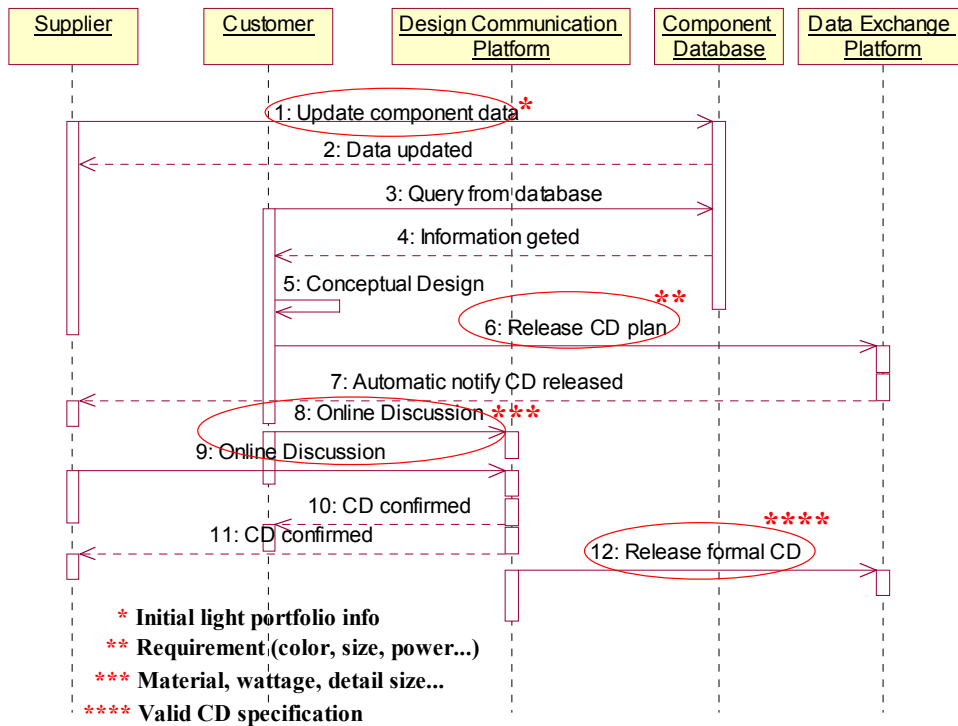


Figure 11 Collaborative process analysis for detailed design (see online version for colours)

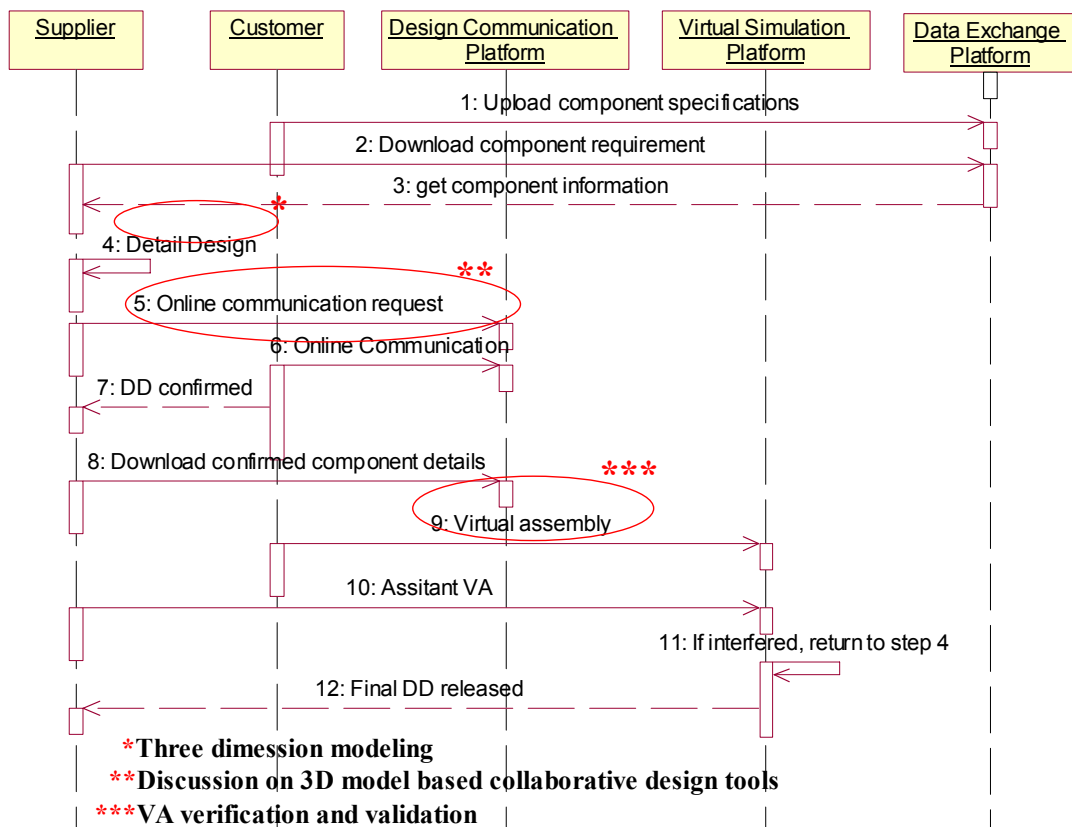


Figure 12 Collaborative process analysis for design review (see online version for colours)

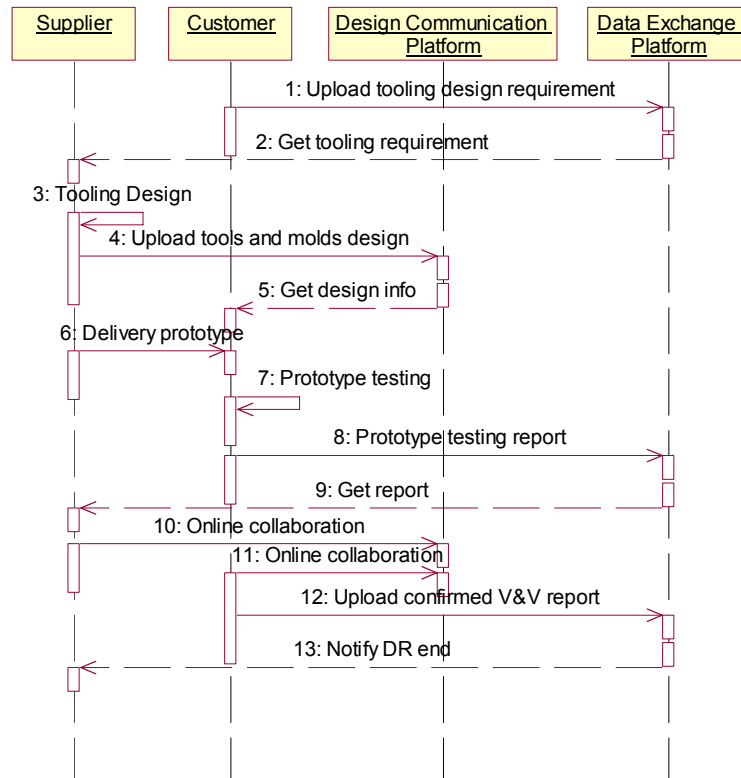
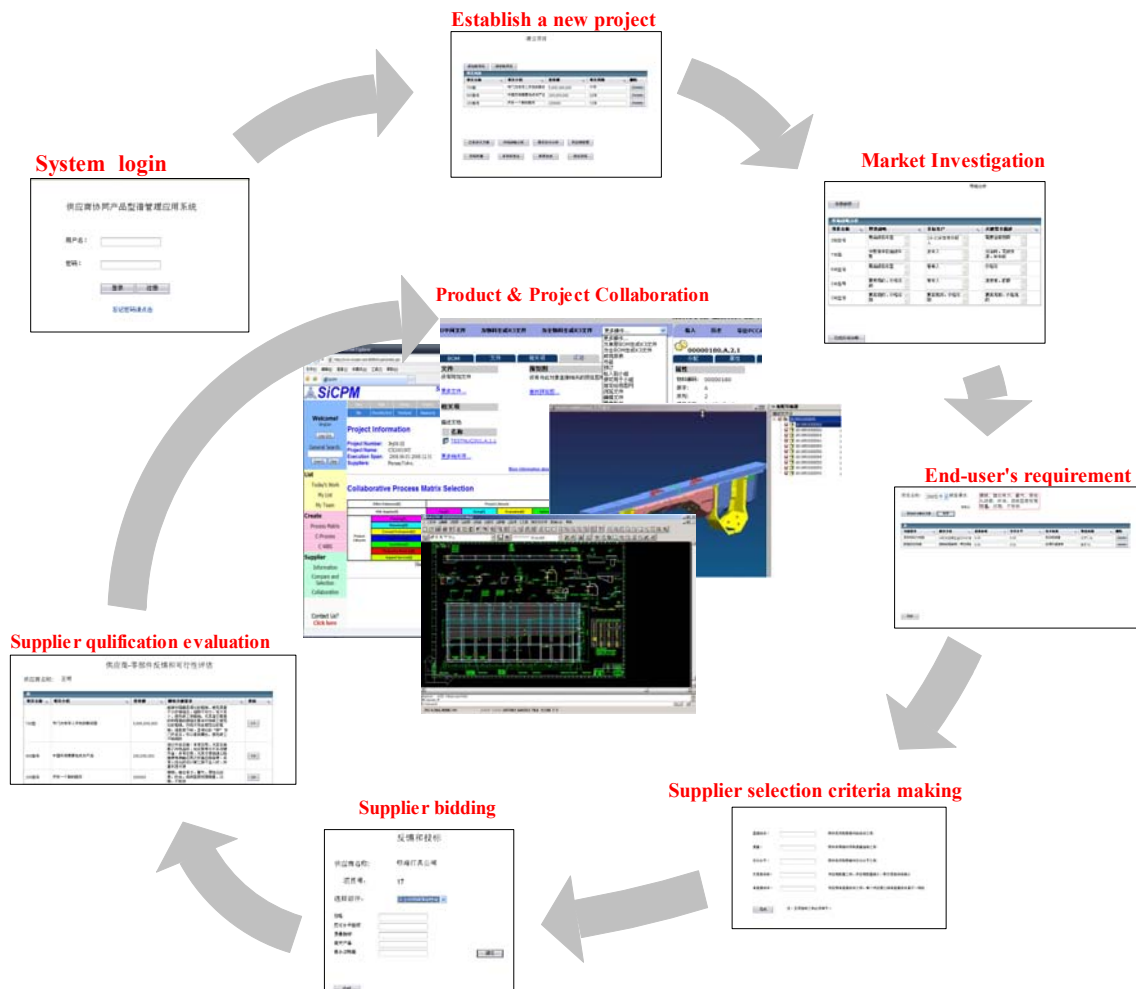


Figure 13 Illustration of prototype system for supplier-involved CPD (see online version for colours)



By ESI and design outsourcing strategy, THN can focus on its core business to pursue higher profits. Design suppliers gain more power in product development. By collaboration, a new win-win situation is forming step by step. In the future, THN wants to expand its CPD process with more suppliers and more product lifecycle phases.

6.2 Potential industrial benefits

The case is just the beginning of THN supplier involvement strategies. Potential industrial benefits from the implementation of supplier-involved CPD framework includes:

- the responsibility of each role in collaboration environment is much clearer than before
- collaboration processes become standardised and can be easily reused in other projects
- engineer's ability of product design and development is promoted with the help of IT platform
- enterprise R&D knowledge is accumulated and core competence is enhanced.

7 Conclusion and future perspectives

Supplier-involved CPD is a new trend in NPD. Traditionally, the literatures mainly focus on the benefits gained from supplier involvement, risk management in CPD and associated support systems. Few studies paid attention to supplier-involved product development process analysis and lack of a general framework to guide companies for the effective CPD. This paper proposes a framework called as supplier-involved CPD, which associates business, process and operational hierarchies to model the supplier-involved CPD processes. Detailed analysis of supplier collaborative scenarios is also presented. The case of a special automotive company, THN, is introduced to illustrate the potential application of supplier-involved CPD framework in future.

Future research works will be carried out based on the above results to tackle the further challenges as follows:

- Supplier selection criteria are not very sound because the traditional criteria take supplier as more a competitor than a collaborator. The effect factors are cost, risk and delivery, but little association with collaboration. Furthermore, there are too many subjective criteria in the selection modelling function, which are not easy to implement.
- Deeper collaboration needs stronger IT-based techniques. For the knowledge sharing and intellectual properties, this is not easy to do. It is a technology challenge on the one hand, but a management challenge on the other.
- Project management in CPD environment is not the same as traditional. There is little good solution on how to let the other part know schedule changes and resource reallocation yet.

Acknowledgements

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A knowledge-based approach for calculating setup times

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Abstract: The production mode of high variety and small batches is very popular because it can satisfy various and rapidly changing demands from customers. High variety results in the large and high increasing numbers of product type, which make the traditional Bill-of-Material (BOM) unapplicable because the traditional BOM means a type of item has a unique item number. Earlier researches showed Generic BOM (GBOM) is suitable for this environment. Small batch means the more frequent adjustment of machines, which make setup times to be a un-neglected factor in scheduling. Earlier approaches to obtain setup times are to enumerate all setup times according to experience knowledge. Those approaches should be based on the traditional BOM when they are implemented. As a result, they are not applicable for the high variety and small batch environment. Consequently, after the introduction of GBOM, a knowledge-based approach is proposed to calculate setup times in this paper. And the implementation algorithm is presented then. An application case shows our approach is an applicable one.

Keywords: setup times; knowledge-based; GBOM; generic bill-of-material; high variety and small batch; scheduling.

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1 Introduction

In recent decades, due to drastic competition and increasing individual demands from the market, enterprises with fewer types of products are being eliminated gradually and enterprises with high variety and small batch production are becoming popular. Though the production mode of high variety and small batch has been of great benefit to enterprises, it has also challenged the scheduling at the same time.

On the one hand, high variety and small batch mean that the adjustment operations, such as adjusting fixtures, changing

cutters, etc., are more frequent. It means that setup times are either not very shorter, or even longer than processing times. As a consequence, setup times are turning to be an un-neglected factor in scheduling. Then, researches on scheduling that have not taken setup times into account will become unapplicable for this environment (e.g. Yalaoui and Chu, 2002; Iyer and Saxena, 2004). Researches on scheduling that take setup times into consideration can be classified into two types. Some researches (Hwang and Sun, 1997; Sethanan, 2001; Kim et al., 2003; Lin and Liao, 2003) were usually based on the assumption that the number of product type is fewer.

As a result, setup times can be obtained through experiences directly, which means the experienced values of setup times can be employed directly and there is no requirement to calculate them consequently. Others researches (Schutten and Leussink, 1996; Cheng et al., 1999; Schaller et al., 2000; Webster and Azizoglu, 2001; Kim et al., 2002; Kurz and Askin, 2004; Lee and Jung, 2005; Gupta and Schaller, 2006; Wang and Cheng, 2007) did not show how to obtain setup times although they considered setup times as one of important factors that affects scheduling.

On the other hand, since the current approaches to obtain setup times are the enumeration of setup times with experience knowledge, the implementation approach of them should be based on the traditional Bill-of-Material (BOM), i.e. a type of item with a unique item number. It means that a new BOM structure must be created for any new variant of a product. This will work with a limited set of variants, but will result in a large number of BOM structures in the customer-oriented production, which usually means the high variety and small batch production. Design and maintenance of such a large number of complex data structures will be impossible. Generic BOM (GBOM) (Olsen et al., 1997) emerged then.

GBOM is based on a programming language notation. This notation makes it possible to describe the set of possible variants of a product by handling both functional and structural relations between components. The user can explode (execute) any part of the BOM to define a specific product variant. User specifications are given dynamically, as the GBOM is executed. The system will then automatically generate a specific BOM for this particular production variant. Items in GBOM are described with attribute names and attribute values, not with item numbers, which is the main differentia between GBOM and the traditional BOM.

As a result, it is necessary to develop a knowledge-based approach to obtain setup times on the base of GBOM structures. There are two types of setup times (Cheng et al., 2000). One type of setup times is sequence independent, which means that the setup operation of a job on a machine does not depend on any other job. The other type of setup times is sequence dependent, which means that the setup operation of a job on a machine depends on the job that is being produced on the machine. Obviously, sequence-dependent setup times are more complex than sequence-independent setup times.

The remainders of this paper are organised as follows. In Section 2, a knowledge-based approach for calculating setup times is proposed. The implementation algorithm of it is developed in Section 3. An application case is presented in Section 4. Section 5 concludes this paper.

2 A knowledge-based approach for calculating setup times

2.1 The model of the approach

The model of the approach is shown in Figure 1. Firstly, with the aid of the *classification device*, the more types of detailed items in the *detailed product domain* are classified as the fewer types of classified items. The set of classified items is named as the *temporary product domain*. Secondly, classified items are mapped into the *process domain* through the

corresponding *mapping rules* and setup times of equipment parameters in the process domain can then be obtained. Thirdly, setup times of classified items in the scheduling environment can be determined according to the functions about setup times of equipment parameters. Finally, setup times of detailed items in the scheduling environment can be obtained according to the relationships between detailed items and classified items. Related terms mentioned above would be defined in detail in the following sections.

2.2 The knowledge-based model of the detailed product domain

In GBOM, all items are described with attribute names and attribute values, not with item numbers. Several attributes are required in order to describe an item clearly. An example is given below. Three attributes (length, width and height) are required in order to describe a cuboid item. Another attribute (material) is required if the item is made of several materials such as 45#, 40 Cr, CrV, etc.

Suppose item p has M_p attributes. The set of them is denoted by A_p . Then:

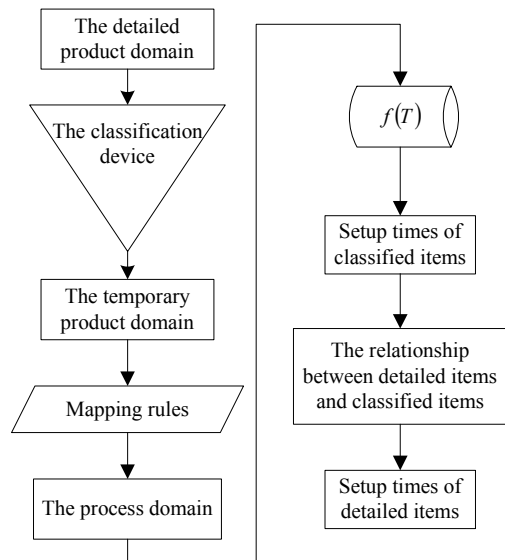
$$A_p = \{a_{(p,i)} \mid i \in \{1, 2, \dots, M_p\}\} \quad (1)$$

where $a_{(p,i)}$ denotes the attribute name of the i th attribute of item p . Suppose $a_{(p,i)}$ has $N_{(p,i)}$ attribute values and the set of them is denoted by AV_p . Then:

$$AV_p = \{av_{(p,i,j)} \mid i \in A_p, j \in \{1, 2, \dots, N_{(p,i)}\}\} \quad (2)$$

where $av_{(p,i,j)}$ denotes the j th attribute value of $a_{(p,i)}$. Then, item p can be described clearly with the union of A_p and AV_p .

Figure 1 The model of the proposed approach



Consequently, the *detailed product domain* is defined as the set of all items that exist at all workshops and are described with attribute names and attribute values. Items in the detailed product domain are named as *detailed items*. Let DPD denote the detailed product domain and P denote the set of all detailed items. Then:

$$DPD = \{A_p \cup AV_p \mid p \in P\}. \quad (3)$$

2.3 The knowledge-based model of the temporary product domain

The process method of a detailed item on an equipment is usually determined by some of its attributes, not by all of its attributes, which means different detailed item may have the same process method on an equipment. For instance, the item named by the wrench body, which has four attribute names (Type, Material, Size and Logo). While drilling on the wrench body, the selection of the drills is dependent on the Material and the Size of the wrench body, not on the Type and the Logo of it. And the selection of the fixtures is dependent on the Type and the Size of wrench body, not on the Material and the Logo of it. Here are two different wrench bodies. One is the item (Type: WB-02A; Material: CrV; Size: 10 inches; Logo: FACOM) and the other is the item (Type: WB-02A; Material: CrV; Size: 10 inches; Logo: JET). Though they are two different detailed items, they are the same wrench body (Type: WB-02A; Material: CrV; Size: 10 inches) for drill machines. The wrench body (Type: WB-02A; Material: CrV; Size: 10 inches) is called a *classified item* of drill machines. In the high variety small batch environment, there are a large number of detailed items. Consequently, if all detailed items are grouped according to the approach mentioned above, the quantity of item type would be decreased greatly and our research would be simplified.

As a result, the *temporary product domain* is defined as the set of all classified items, which is denoted by TPD . The reason to call it *temporary* is that it exists only while calculating setup times and will be deleted immediately after calculating so as to economise the system resources. Classified items are also described with attribute names and attribute values. However, they usually are ‘some of the corresponding detailed items, not all of detailed items’. Classified items are related to equipments and detailed items are not related to equipments, i.e. a detailed item may be related to different classified items on different equipments.

Suppose the classified item of item p on equipment e has M_p^e attribute names, which is denoted by A_p^e and their corresponding attribute values is denoted by AV_p^e . The set of all equipments is denoted by E . Then the temporary product domain is the union of A_p^e and AV_p^e , i.e.

$$TPD = \{A_p^e \cup AV_p^e \mid e \in E, p \in P\} \quad (4)$$

where $A_p^e \subseteq A_p$ and $AV_p^e \subseteq AV_p$.

2.4 The knowledge-based model of the classification device

The *classification device* is the set of knowledge rules. Which of its attribute names is the process method of a detailed item on an equipment determined by? Knowledge rules will show it. For example, the wrench body (Type: WB-02A; Material: CrV; Size: 10 inches; Logo: FACOM). Its process method on the drill machine is determined by Type, Material and Size, i.e. the classified item of wrench body on the drill machine is described with Type, Material and Size. This rule can be represented as follows:

IF (Item Name = ‘the wrench body’) and (Equipment = ‘the drill machine’) THEN

(The first attribute name of the classified wrench body = ‘Type’) and (The second attribute name of the classified wrench body = ‘Material’) and (The third attribute name of the classified wrench body = ‘Size’).

2.5 The knowledge-based model of the process domain

It is widely accepted that setup times are dependent on times spent on essential operations, such as, changing cutters, adjusting fixtures and so on. As a result, the *process domain* is defined as the set of process information related to these essential operations. The process domain consists of three parts: equipment parameters, setup times of equipment parameters and the knowledge of the process values of equipments.

- 1 *The knowledge of equipment parameters*: Equipment parameters are the objects of equipments that should be adjusted while changing items. They are described with parameter names and parameter values. Parameter names may be the name of cutters, such as drills, the parameter values of which might be No. 1 drill and No. 2 drill. Parameter names may be the name of fixture, such as the lathe fixture, the parameter values of which might be Type JJ01 fixture, Type JJ02 fixture, etc. As for heat treatment, parameter name might be the temperature, the parameter values of which might be 600°C, 800°C, etc. As for electroplating, parameter name might be plating, the parameter values of which might be Zn, Cr, Ni, etc.

Suppose equipment e has X_e equipment parameters. The set of them is denoted by C^e , then:

$$C^e = \{c_{(e,i)} \mid i \in \{1, 2, \dots, X_e\}\} \quad (5)$$

where $c_{(e,i)}$ denotes the parameter name of the i th equipment parameter of equipment e . Suppose $c_{(e,i)}$ has $Y_{(e,i)}$ equipment values. The set of them is denoted by CV^e , then:

$$CV^e = \{cv_{(e,i,j)} \mid i \in C^e, j \in \{1, 2, \dots, Y_{(e,i)}\}\} \quad (6)$$

where $cv_{(e,i,j)}$ denotes the j th parameter value of $c_{(e,i)}$.

- 2 *The knowledge of setup times of equipment parameters*: Compared with the quantity of item type, the quantity of equipment parameter is much fewer and setup times of equipment parameters are easy to be obtained in the real-world production. Consequently, setup times of equipment parameters are suitable for storage in database. Equipment parameters can be classified into two classes according to setup times: invariable and variable. Invariable equipment parameters means that setup times of equipment parameters do not change along with the change of parameter values, i.e. an equipment parameter name owns a unique setup times. For example, setup times of changing drills are usually constant whatever type drill will be replaced. Variable equipment parameters, however, are opposite to invariable ones. Variable equipment parameters means that setup times between different equipment parameter values are different. For example, the changing fire temperature of heat treatment. Setup times of a temperature increase from 600°C to 800°C and that of from 600°C to 1000°C are different obviously.

Denote the set of invariable equipment parameters by C^e1 , the set of variable equipment parameters by C^e2 , the set of setup times of equipment parameters by T , the equipment parameter value before changing by $cv_{(e, i, j)}$ and that after changing by $cv_{(e, i, k)}$. Suppose setup times of changing from $cv_{(e, i, j)}$ to $cv_{(e, i, k)}$ is $t(cv_{(e, i, j)}, cv_{(e, i, k)})$. Then, T can be represented as following:

$$T = \{t(cv_{(e,i,j)}, cv_{(e,i,k)}) | e \in E, j, k \in \{1, 2, \dots, Y_{(e,i)}\}, \text{ and } j \neq k\} \quad (7)$$

where $t(cv_{(e, i, j)}, cv_{(e, i, k)})$ is constant if equipment parameter is invariable, i.e. $c_{(e, i)} \in C^e1$.

- 3 *The knowledge of the process values of equipments:* The same item may be processed with different processes on an equipment, which require different equipment parameter values. For example, drilling holes on the same item with different diameters requires different drills. Consequently, different processes should be set with different process values.

Suppose equipment e has Z_e process values. Denote the set of all equipment process values by PV , which can be represented as following:

$$PV = \{pv_{(e,i)} | i \in \{1, 2, \dots, Z_e\}, e \in E\} \quad (8)$$

where $pv_{(e,i)}$ denotes the i th process value of equipment e .

2.6 The representation of mapping rules from the temporary product domain to the process domain

The adjustment operation of an equipment is dependent not only on items that will be processed on it but also the processes to be used. Thereby, *mapping rules from the temporary product domain to the process domain* is defined as the relationship among classified items, equipments and process values. An example is given as follows. There is a kind of wrench body in the temporary process domain of drills, which has three attribute names: Type, Material and Size. When the wrench body (Type: WB-02A; Material: CrV; Size: 10 inches) is processed with the process of ‘drilling the big hole’ on the drill machine, Type JJ01 fixture and No. 2 drill are required. This rule can be represented as follows:

IF (Item Name = ‘the wrench body’) and (Equipment = ‘the drill machine’) and (The first attribute name = ‘Type’ and its attribute value = ‘WB-02A’) and (The second attribute name = ‘Material’ and its attribute value = ‘CrV’) and (The third attribute name = ‘Size’ and its attribute value = ‘10 inches’) and (The process value = ‘drilling the big hole’) THEN

(The first equipment parameter name = ‘the fixture’ and its parameter value = ‘Type JJ01 fixture’) and (The second equipment parameter name = ‘the cutter’ and its parameter value = ‘No. 2 drill’).

2.7 Functions from setup times of equipment parameter to setup times of scheduling environment

Mapping from the temporary product domain to the process domain can only get setup times of an equipment parameter. However, scheduling environment consists of one or several

equipments and an equipment might has several equipment parameters. Therefore, functions from setup times of equipment parameter to setup times of scheduling environment will be developed. According to the characteristic of different scheduling environments: single machine scheduling, parallel machines scheduling and flow shop scheduling, functions will be developed, respectively as follows. Let $ST_{(A, B)}$ denote setup times of changing from item p_A to item p_B in the scheduling environment.

2.7.1 The function in the single machine scheduling environment

Single machine scheduling studies the problem that scheduling n jobs on a single machine, which is the simplest scheduling problem.

Suppose equipment e has only one equipment parameter, i.e. $X_e = 1$ and the parameter value before adjustment is $cv_{(e, i, j)}$ and that after adjustment is $cv_{(e, i, k)}$. Obviously, setup times in the environment, $ST_{(A, B)}$, is equal to the setup times of this equipment parameter, i.e. $ST_{(A, B)}$ can be calculated with the following equation:

$$ST_{(A, B)} = t(cv_{(e,i,j)}, cv_{(e,i,k)}) \quad (9)$$

where $t(cv_{(e, i, j)}, cv_{(e, i, k)})$ can be obtained with the knowledge of setup times of equipment parameters in the process domain.

Suppose equipment e has several equipment parameters, i.e. $X_e > 1$. If those equipment parameters can be adjusted simultaneously, i.e. they are in parallel, setup times in the environment is equal to the maximum one of those of equipment parameters, i.e. $ST_{(A, B)}$ can be calculated with the following equation:

$$ST_{(A, B)} = \max\{t(cv_{(e,i,j)}, cv_{(e,i,k)}) | i \in C^e\}. \quad (10)$$

If those equipment parameters must be adjusted in turn, i.e. they are in series, setup times in the environment is equal to the sum of those of equipment parameters, i.e. $ST_{(A, B)}$ can be calculated with the following equation:

$$ST_{(A, B)} = \sum_{i=1}^{X_e} t(cv_{(e,i,j)}, cv_{(e,i,k)}). \quad (11)$$

2.7.2 The function in the parallel machines scheduling environment

Parallel machine scheduling studies the problem: scheduling n jobs on m machines and each job may be processed on any one of m machines.

If m machines are identical, this problem is equal to the single machine scheduling.

Otherwise, if m machines are not identical, setup times in the environment is equal to the minimum one of setup times of equipments. Let $st_{(A, B, e)}$ denote setup times of changing from item p_A to item p_B on equipment e , which can be got with the approach in single machine scheduling environment. Let E denote the set of m machines. Then setup times of changing from item p_A to item p_B in the parallel machines scheduling environment, $ST_{(A, B)}$, can be calculated with the following equation:

$$ST_{(A, B)} = \min\{st_{(A, B, e)} | e \in E\} \quad (12)$$

2.7.3 The function in the flow shop scheduling environment

There are m machines in series. Each job has to be processed on each one of the m machines. All jobs have to follow the same route. This is the flow shop scheduling environment.

Suppose that the time spend on transportation is included in the processing time; there is no setup times between the same kind of items; once the production of a job on the first machine is completed, the production of next job on the first machine could start immediately, not necessary until the production of the previous job on the last machine is also completed.

Setup times of the i th machine is denoted by $st_{(A,B,i)}$, which can be got with the approach in single machine scheduling environment. The processing time of item p_A on the i th machine is denoted by $P_{(i,A)}$ and that of item p_B is denoted by $P_{(i,B)}$.

The time from the completion of item p_A on the first machine to the readiness of the i th machine to process item p_B is denoted by TP_i , which can be calculated with the following equation:

$$TP_i = st_{(A,B,i)} + \sum_{k=2}^i P_{(k,A)}. \tag{13}$$

The time from the readiness of the first machine to process item p_B to the completion of item p_B on the $(i - 1)$ th machine is denoted by TA_i , which can be calculated with the following equation:

$$TA_i = ST_{(A,B,i-1)} + P_{(B,i-1)} \tag{14}$$

where $ST_{(A,B,i-1)}$ denotes setup times of the top $(i - 1)$ machines. Obviously, $ST_{(A,B,1)} = st_{(A,B,1)}$.

If the i th machine is not ready to process item p_B when item p_B arrives at the i th machine, i.e. $TP_i > TA_i$ (Figure 2), the additional setup times of the scheduling environment because of the i th machine is required, which is $(TP_i - TA_i)$. Otherwise, if the i th machine is ready to process item p_B , i.e. $TP_i \leq TA_i$ (Figure 3), no additional setup times is spent because of the i th machine. In conclusion, setup times of the top $(i - 1)$ machines, $ST_{(A,B,i)}$, can be calculated with the following equation:

$$ST_{(A,B,i)} = ST_{(A,B,i-1)} + \sum_{j=2}^m \max\{TP_j - TA_j, 0\}. \tag{15}$$

Obviously, setup times of the flow shop scheduling environment, $ST_{(A,B)}$, is equal to setup times of the top m machines, $ST_{(A,B,m)}$, i.e.

$$ST_{(A,B)} = ST_{(A,B,m)}. \tag{16}$$

Figure 2 The situation with a gap between p_B reaching the i th machine and entering it

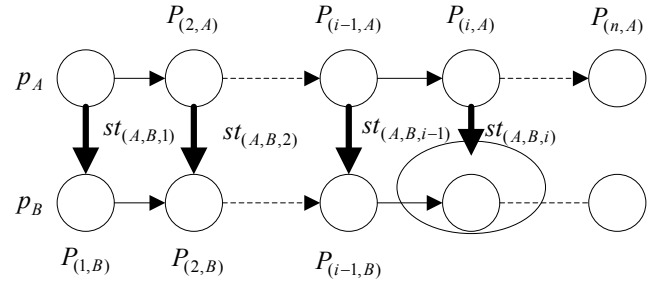
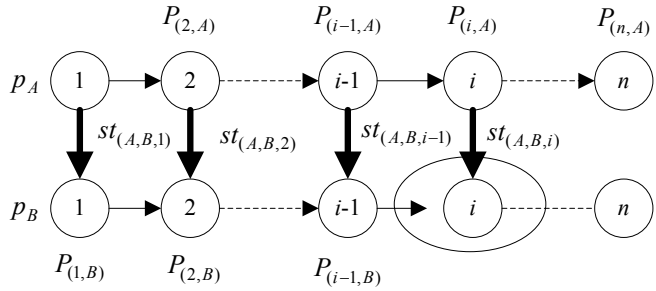


Figure 3 The situation with no gap between p_B reaching the i th machine and entering it



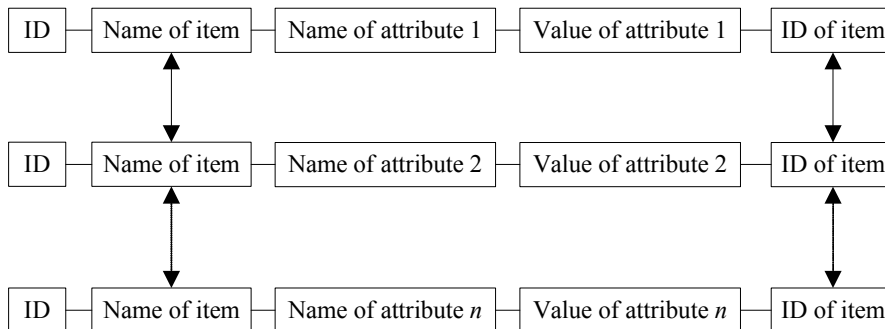
3 Implementation

In order to implement the knowledge-based approach for calculating setup times, the knowledge databases for the detailed product domain, the temporary product domain and the process domain, the rule database for the classification device and mapping rules from the temporary product domain to the process domain, implementation algorithm must be developed. This section will present them.

3.1 The knowledge database of the detailed product domain

Suppose that a detailed item has n attribute names, the data structure of the detailed item consists of n records (Figure 4). ID is the primary key of the data table. These n records have the same item name and the same item ID. The item ID is the identifier of different detailed items. The knowledge database of the detailed product domain consists of records of all detailed items.

Figure 4 Data structure of the knowledge base of the detailed product domain



3.2 The knowledge database of the temporary product domain

The data structure of any classified item in the temporary product domain is shown in Figure 5. The data structure of the part in the rectangle is similar to that of the detailed item. The equipment name in Figure 5 denotes the equipment that the classified item belongs to and the detailed item ID in Figure 5 denotes the sum of item ID strings of detailed items that belongs to the classified item.

3.3 The rule database of the classification device

Suppose the process method of a detailed item on an equipment is determined by its n attributes. The data structure of this rule is shown in Figure 6, where ID is the primary key of the data table and these n records have the same item name and the same equipment name.

3.4 The knowledge database of the process domain

- 1 *The knowledge database of equipment parameters:* The data structure of equipment parameters consists of two parts: the data table of parameter name (as shown in the top part of Figure 7) and the data table of parameter value (as shown in the bottom part of Figure 7). Each parameter name has a record in the database and its parameter values have n records if it has n parameter values.
- 2 *The knowledge database of setup times of equipment parameters:* Setup times of equipment parameters are stored in the setup times database. Its data structure is shown in Figure 8. The parameter ID before adjustment and that after adjustment are equal to the corresponding ID in parameter value data table (as shown in the bottom part of Figure 7).

Figure 5 Data structure of the knowledge base of the temporary product domain

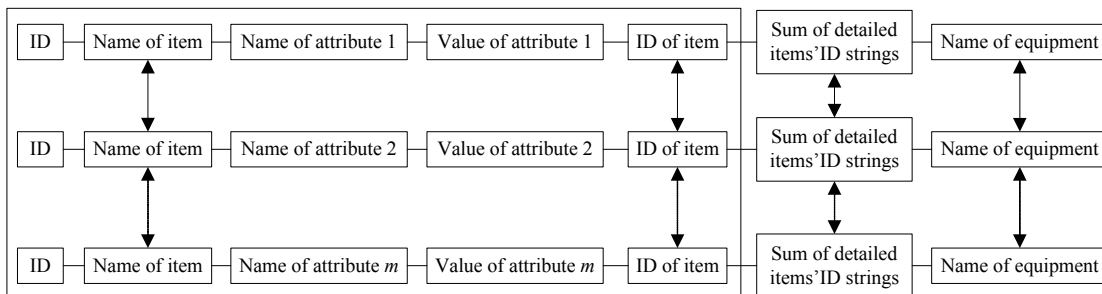


Figure 6 Data structure of the rule base of the classification device

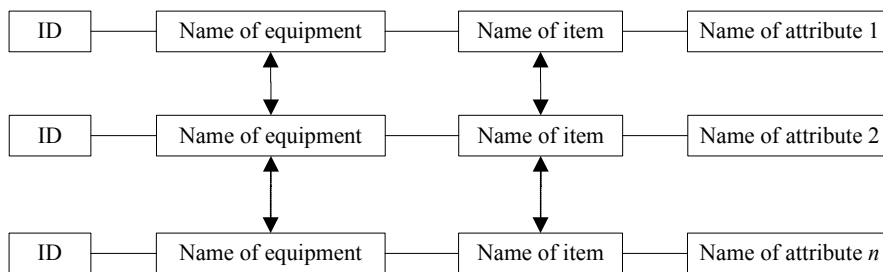


Figure 7 Data structure of the knowledge base of equipment parameters

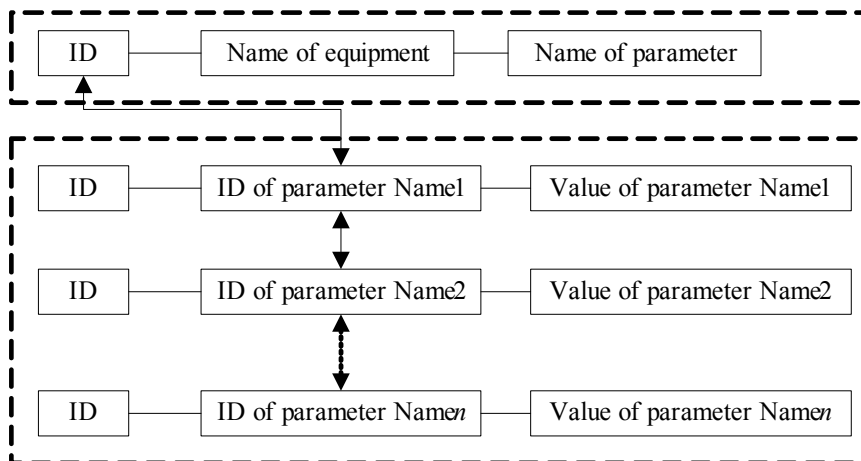


Figure 8 Data structure of the knowledge base of setup times of equipment parameters



3.5 The rule database of mapping rules from the temporary product domain to the process domain

The data structure of any mapping rule from the temporary product domain to the process domain is shown in Figure 9. Each rule has several records in the data table, which have a same rule number and a same equipment name. Record that the value of item name and the value of attribute name are NULL belong to the data of equipment process value (as shown in the middle part of Figure 9). Records that only the value of item name is NULL belong to the data of equipment parameters (as shown in the bottom part of Figure 9). Other records belong to the data of the temporary product domain (as shown in the top part of Figure 9).

3.6 The algorithm

The implementation algorithm is integrated in a production management system. As a result, the main data tables used

in the algorithm will be introduced firstly before elaborating the detailed algorithm.

- The data table of the relationship of equipments and equipment parameters: it stores the relationship of machines in all workshops (single machine, parallel machines or flow shop) and the relationship of equipment parameters of any machine (in parallel or in series).
- The data table of work-in-process inventory: it stores the information of item inventory that are located at every workshop and are waited to be processed.
- The data table of semi-finished items inventory: it stores the information of item inventory that are located at every workshop and have been processed in the workshop.

Suppose there are n detailed items that are waiting to be processed and a detailed item that is being processed in a workshop, which consists of m machines. Then, the flow chart of the implementation algorithm is shown in Figure 10.

Figure 9 Data structure of mapping rules from the temporary product domain to the process domain

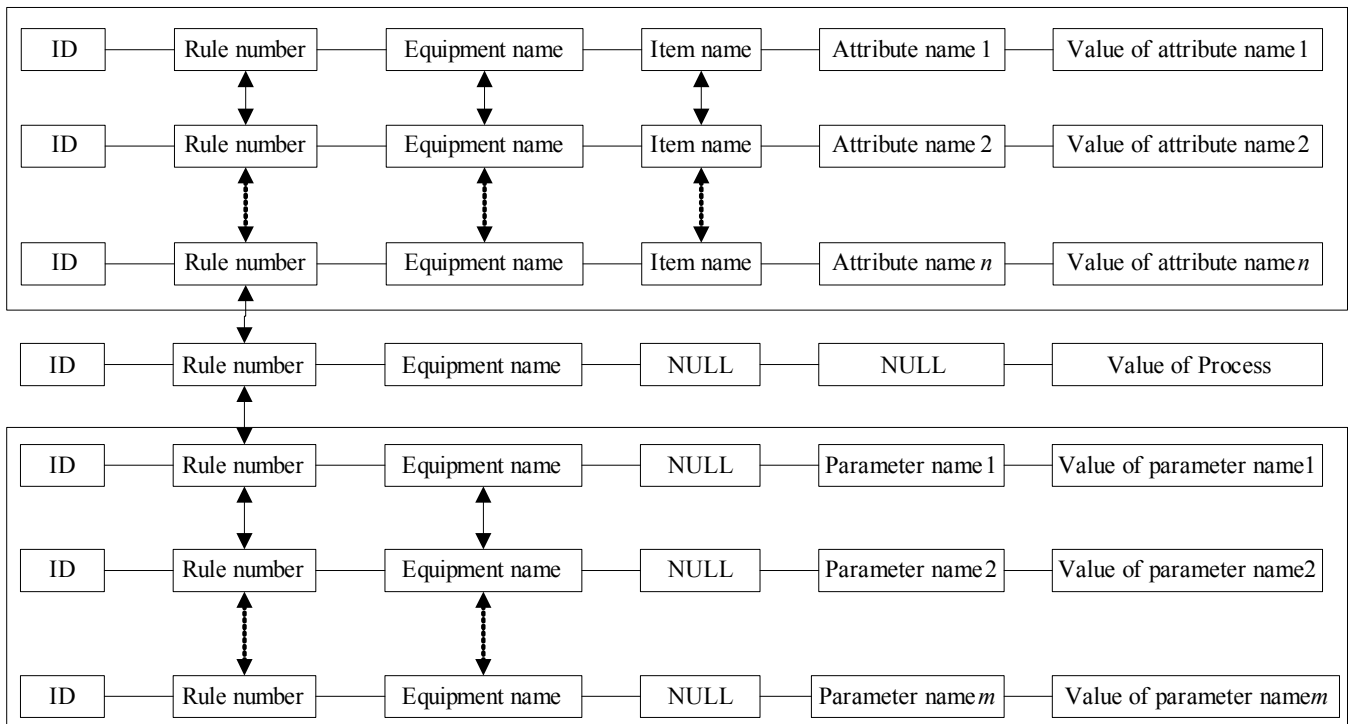
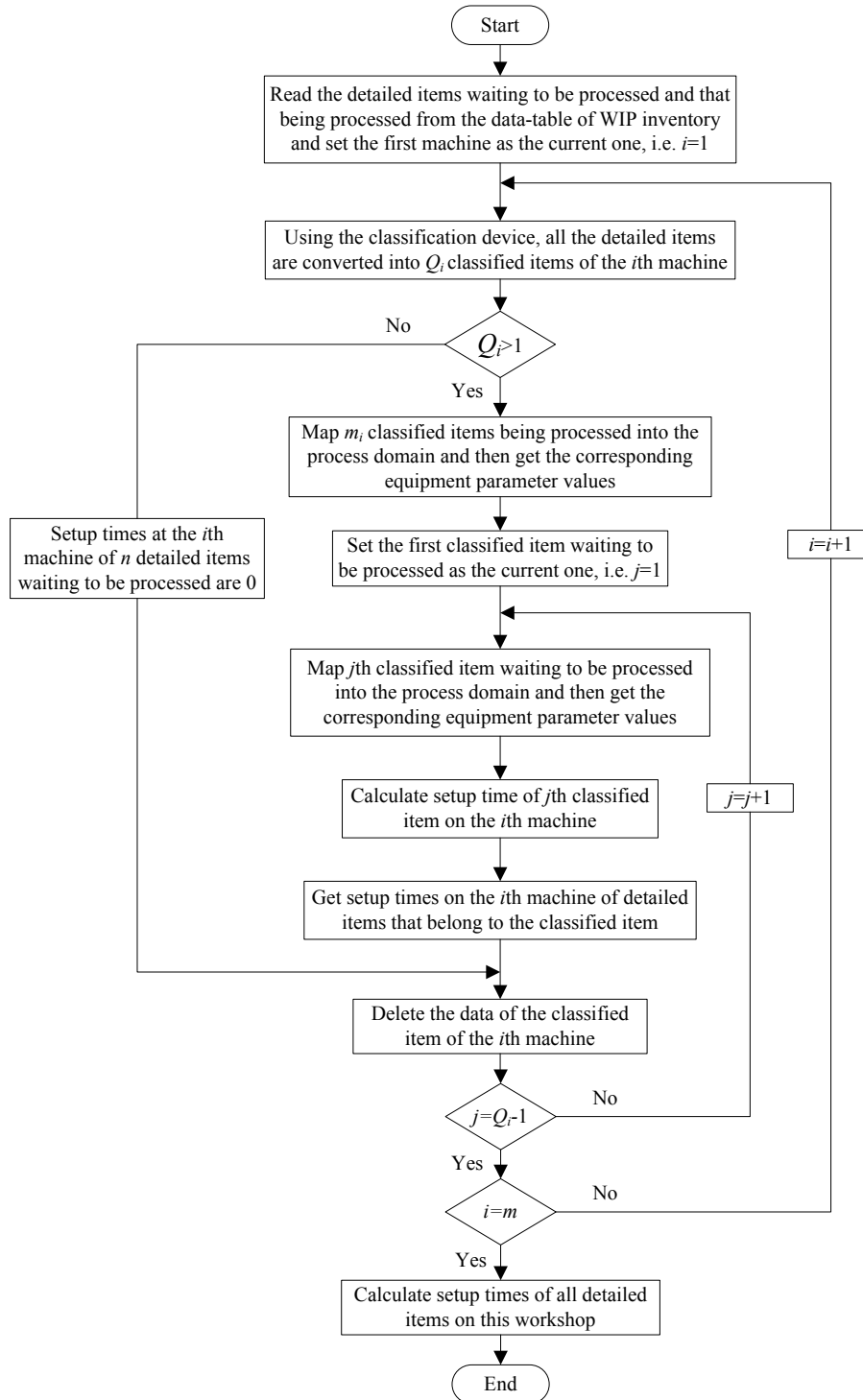


Figure 10 Flow chart of the algorithm



4 Case study

A large-scaled hand tool enterprise in China produces various hand tools for customers from all over the world, which have more than ten series. For example, the adjustable wrench series, which have three kinds of material, more than ten kinds of size, more than 20 kinds of customised process, more than 70 kinds of type, more than 400 of logo and about 10,000 kinds of adjustable wrenches. The annual output of the adjustable wrench is more than 20 million and the everyday output of it is

about 100,000. The highest customer order quantities are less than 1000. About 100 customer orders are produced every day in a workshop. Consequently, the production environment is typically high variety and small batch. Confronted with so heavy a scheduling job, manually scheduling a hundred customer orders every day not only has lower efficiency, but also is difficult to get the optimal scheduling result. Thereby, we developed a Browser/Server (B/S)-based workshop scheduling system for them, which has been applied in this enterprise as a sub-system of a production management system.

The production of the wrench body, the main part of the adjustable wrench, is a multi-stage production system, which consists of forging, machining, heat treatment, polishing and electroplating in turn. Wrench bodies are processed in the machining workshop with seven main processes: punching the tail hole, drilling the big hole, broaching the quadrate hole, milling the mouth face, milling the two side faces, drilling the small hole and milling the trough in turn. Machines used for these seven processes are the No. 123-17 punching machine, the No. 09-32 drilling press, the No. 123-18 broaching machine, the No. 06-29 milling machine, the No. 26-54 milling machine, the No. 09-65 drilling press and the No. 07-24 milling machine, respectively.

The approach for calculating setup time is introduced as follows with the example of the wrench body in the machining workshop.

4.1 The detailed and temporary product domain, the classification device

Figure 11 is a scheduling interface of the machining workshop on 29 May 2007, which shows all customer orders about wrench bodies waiting to be processed and the sum of them is 254. Constrained by the length of the paper,

only 5 of 254 customer orders are selected as the case to show the application of our approach (Table 1). Wrench bodies have four attribute names in the detailed product domain: Type, Material, Size and Logo. The item being processed in the workshop is the No. 1 wrench body.

Table 2 shows the classification devices of all machines about wrench bodies in the workshop. They are identical. Thereby, the classified wrench bodies of all machines about detailed wrench bodies in Table 1 are identical too (Table 3). Obviously, with the aid of the classification device, the quantity of the type of wrench bodies has been decreased from 5 in the detailed product domain to 3 in the temporary product domain.

4.2 The process domain and the mapping rules

In the process domain, all machines have same parameter names: the cutter and the fixture. Mapping rules from the temporary product domain to the process domain are shown in Table 4. All parameters of machines, i.e. the cutter and the fixture, belong to invariable ones and should be adjusted in series. The left part of Table 4 shows values of equipment parameters. Setup times of them are constant (Table 5) and processing times of classified wrench bodies (Table 3) are shown in Table 6.

Figure 11 A scheduling interface of the machining workshop



Table 1 The detailed wrench bodies

No.	Item name	Type	Size (inch)	Material	Logo	Quantity
1	The wrench body	WB-02	8	CrV	Facom	210
2	The wrench body	WB-02	8	CrV	Stanley	673
3	The wrench body	WB-15	10	45#	Jet	80
4	The wrench body	WB-15	10	45#	Stanley	321
5	The wrench body	WB-02	8	45#	Jet	1300

Table 2 The classification device

<i>Machine</i>	<i>Item name</i>	<i>Attribute 1</i>	<i>Attribute 2</i>	<i>Attribute 3</i>
The No. 123-17 punching machine	The wrench body	Type	Size	Material
The No. 09-32 drilling press	The wrench body	Type	Size	Material
The No. 123-18 broaching machine	The wrench body	Type	Size	Material
The No. 06-29 milling machine	The wrench body	Type	Size	Material
The No. 26-54 milling machine	The wrench body	Type	Size	Material
The No. 09-65 drilling press	The wrench body	Type	Size	Material
The No. 07-24 milling machine	The wrench body	Type	Size	Material

Table 3 The classified wrench bodies

<i>No.</i>	<i>Item name</i>	<i>Type</i>	<i>Size (inch)</i>	<i>Material</i>	<i>Quantity</i>
I	The wrench body	WB-02	8	CrV	883
II	The wrench body	WB-15	10	45#	401
III	The wrench body	WB-02	8	45#	1300

Table 4 Mapping rules from the temporary product domain to the process domain

<i>Machine</i>	<i>Process</i>	<i>No. I</i>		<i>No. II</i>		<i>No. III</i>	
		<i>The cutter</i>	<i>The fixture</i>	<i>The cutter</i>	<i>The fixture</i>	<i>The cutter</i>	<i>The fixture</i>
The No. 123-17 punching machine	Punching the tail hole	CT21	YJ02	CT24	YJ04	CT26	YJ02
The No. 09-32 drilling press	Drilling the big hole	ZT37	ZJ15	ZT32	ZJ12	ZT35	ZJ15
The No. 123-18 broaching machine	Broaching the quadrate hole	CT41	YJ02	CT44	YJ03	CT43	YJ02
The No. 06-29 milling machine	Milling the mouth face	XD33	XJ03	XD38	XJ06	XD34	XJ03
The No. 26-54 milling machine	Milling the two side faces	XD73	XJ73	XD73	XJ76	XD74	XJ73
The No. 09-65 drilling press	Drilling the small hole	ZT57	ZJ35	ZT56	ZJ32	ZT51	ZJ35
The No. 07-24 milling machine	Milling the trough	XD93	XJ43	XD97	XJ44	XD95	XJ43

Table 5 Setup times of equipment parameters (unit: sec)

<i>Machine</i>	<i>Parameter</i>	<i>Setup Times</i>	<i>Machine</i>	<i>Parameter</i>	<i>Setup Times</i>
The No. 123-17 punching machine	The cutter	2	The No. 26-54 milling machine	The cutter	5
	The fixture	16		The fixture	42
The No. 09-32 drilling press	The cutter	5	The No. 09-65 drilling press	The cutter	4
	The fixture	28		The fixture	31
The No. 123-18 broaching machine	The cutter	3	The No. 07-24 milling machine	The cutter	5
	The fixture	19		The Fixture	40
The No. 06-29 milling machine	The cutter	5			
	The Fixture	36			

Table 6 Processing times of classified items (unit: sec)

<i>Machine</i>	<i>Process</i>	<i>No. I</i>	<i>No. II</i>	<i>No. III</i>
The No. 123-17 punching machine	Punching the tail hole	4	4	4
The No. 09-32 drilling press	Drilling the big hole	24	34	20
The No. 123-18 broaching machine	Broaching the quadrate hole	8	8	7
The No. 06-29 milling machine	Milling the mouth face	34	21	18
The No. 26-54 milling machine	Milling the two side faces	24	24	19
The No. 09-65 drilling press	Drilling the small hole	18	18	16
The No. 07-24 milling machine	Milling the trough	18	21	18

4.3 Calculating setup times

With our approach, all machines' setup times of changing from No. I classified wrench bodies to No. II one and setup times of changing from No. I one to No. III one are shown in Table 7.

Table 7 Setup times of machines (unit: min)

Machine	From No. I to No. II	From No. I to No. III
The No. 123-17 punching machine	18	2
The No. 09-32 drilling press	33	5
The No. 123-18 broaching machine	22	3
The No. 06-29 milling machine	41	5
The No. 26-54 milling machine	47	5
The No. 09-65 drilling press	35	4
The No. 07-24 milling machine	45	5

Given that the scheduling environment of wrench bodies is the flow shop, setup times of from No. I classified wrench body to No. II one and that from No. I one to No. III one in the machining workshop can be calculated with equations (13)–(16):

$$ST_{(I, II)} = 48.78 \text{ min}; ST_{(I, III)} = 5.33 \text{ min}.$$

According to the relationships between detailed wrench bodies and classified ones, setup times of changing No. 1 to No. 2–No. 5 can be obtained as follows:

$$ST_{(1, 2)} = 0 \text{ min}; ST_{(1, 3)} = 48.78 \text{ min};$$

$$ST_{(1, 4)} = 48.78 \text{ min}; ST_{(1, 5)} = 5.33 \text{ min}.$$

Now, setup times of detailed items in Table 1 are calculated completely.

5 Conclusion

In the high variety and small batch environment, the traditional-BOM-based enumeration approach to obtain setup times is incapable of implementation. Based on GBOM, a knowledge-based approach for calculating setup times is proposed. The implementation algorithm and an application case are then presented. Case study shows that the approach proposed in this paper is a feasible one for calculating setup times of items with a large number of item types in the high variety and small batch environment.

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Modelling and simulation of new product diffusion with negative appraise based on system dynamics: a comparative perspective

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Abstract: The enterprises often neglect the consumers' negative appraise, and as a result it leads to shrinkage in market and operating landslide. In our former research, the multi-agent model has been established to study the negative appraise on new product diffusion and some meaningful results have been obtained. But it is still unclear on the macro-level factors' relationships. In this paper, a system dynamics model of new product diffusion with negative appraise is established based on innovation diffusion theory, and the negative appraise effect is analysed on macro-level aspect. Through simulation experiments, the new product diffusion process is affected obviously by the negative appraise. The diffusion process is sensitive to the probability of negative appraise and produce life cycle. By comparing with multi-agent simulation, the results of macro-level simulation are the same as the multi-agent ones, and the two simulation ways can testify the effectiveness by each other.

Keywords: new product; diffusion; negative appraise; system dynamics; multi-agent; diffusion equation; word-of-mouth; Bass diffusion model; PLC; product life cycle; sensitivity analysis.

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1 Introduction

New product promoted in the market is usually of the highest cost, largest risk and biggest lack of management (Souder and Sherper, 1994). There are approximately over 10,000 new products to be put in the market every year in China, and no more than 5% are successful. So the probability of the new product to succeed is low.

The theoretical research of new product diffusion can be traced back to the early 20th century. Schumpeter created innovative theory firstly, and he researched the imitation behaviour of individual in diffusion. In the 1960s, researchers started to study the diffusion model extensively, and Dodson and Muller (1978) have reviewed those new product models through advertising and word-of-mouth. Based on the different research objects and methods, the

diffusion models can be mainly divided into two categories: one category is of the mathematical model on macro-level based on overall statistics of the potential adopters; the other one is of the simulation model on micro-level based on individual's adoption decision-making behaviour.

It is established the macro-level analysis of the mathematical model firstly. Mansfield (1961) studied the S-shaped curve of the diffusion. The Bass diffusion model (Bass, 1969) and other developed models (Mahajan et al., 1990, 1995) are regarded as the main representatives. Since Bass's original work, a number of models have been proposed to capture the other related dynamics of the innovations diffusion process. Mahajan et al. (1990, 1995) have reviewed these developments in the past two decades.

Macro-mathematical model is most widely used, and most of the diffusion modes belong to this category (e.g. Dipak et al., 1991). However, the above models study the new product diffusion pattern among the crowd mostly on overall perspective, and the consumers are presumed as homogenous, while not explicitly consider the heterogeneity of consumers' structure. The difficulty of mathematical analysis increased as the variables added in the model, so some complicated models need to be analysed in a simulation way (Harser et al., 2006). System dynamics is a macro-level simulation model, and it has many applications in new product diffusion (e.g. Schmidt and Baier, 2006).

Through the simulation of individual behaviour and interaction, the micro-level simulation model is to obtain the macro results along with the total individuals increasing. In order to describe the micro principle of new product diffusion, some simulation methods are gradually being introduced such as Cellular Automata simulation and multi-agent simulation (e.g. López-Sánchez et al., 2004). Goldenberg et al. (2001) have studied that, how consumer heterogeneity impacts the diffusion process and the micro-mechanism of public praise effect with cellular automata simulation. Garcia (2005) has established a multi-agent model to study the valid impact to diffusion model with individual heterogeneity and the network structure of system.

New product diffusion is mainly spread by the impact of word-of-mouth and mass media. These two effects have been reflected in both the Bass model and other various simulation models. The former researches are often limited to positive word-of-mouth effects to promote new product diffusion. The negative appraisal has not been considered enough, and the negative word-of-mouth effect on new product diffusion has not been analysed enough. The enterprises always pay more attention to mass media promotion such as public relations and advertising, and neglect various word-of-mouth behaviours of consumers. Therefore, it is helpful to study negative appraisal in a simulation way.

In our former research, a multi-agent simulation model has been established to explore the negative word-of-mouth effect on micro-level (Xiao et al., 2008). By repeating simulations, it has studied the characteristics of negative appraisal diffusion, and it is also analysed the dynamic characteristics of negative effect in diffusion. But it is still not enough to understand the diffusion equation on macro-level, and it is not clarified to be analysed in mathematics. So the effectiveness of this

simulation needs to be tested. In this paper, a system dynamics model of new product diffusion with negative appraisal is established based on innovation diffusion theory. Through the simulation results, it shows the negative effect in diffusion. Finally, by comparing with multi-agent simulation, the differences and similarities between the two simulation ways are analysed.

2 An analysis of new product diffusion

2.1 The reason for analysing new product diffusion

Multi-agent simulation method studies the overall diffusion behaviours and equations by the micro-correlation behaviours between the agents. As the above reason, it is not needed to analyse the overall diffusion equations in multi-agent modelling (e.g. Xiao et al., 2008). However, through analysing individual's behaviours of consumption, it needs to be defined the agents' rules to establish the model. The overall diffusion curve can be obtained by simulation experiments. Multi-agent simulation is a kind of micro-level reductionism method, which studies individuals to obtain the overall structure. System dynamics carries out the modelling and simulation based on analysing the diffusion structure and equations clearly on macro-level. It is a kind of holism method on macro-level. Many academics have researched on the concept of diffusion and the nature of the diffusion process extensively, and the diffusion theory is relatively clear until now. The diffusion theory is a necessity for system dynamics modelling and simulation, so it is necessary to analyse the spread patterns and diffusion models.

2.2 An analysis on product spread patterns

New product diffusion is a part of innovation diffusion theory, and the diffusion theory has been researched extensively. Innovation diffusion is that, 'the innovation as a pattern of product spread among the social members in certain period of time through some channels' (Rogers, 1995). Similarly, new product diffusion is the process of being accepted by the market with some spread ways. It has the characteristics of rapid recognition, easy imitation and fast spread. The spread ways of new product diffusion are mainly divided into mass media such as advertising and word-of-mouth communication. Mass media promotion such as advertising is an external impact on diffusion, which is promoted to the potential adopters by the enterprises, and it plays a positive role in diffusion. Word-of-mouth communication is an internal impact, and it is a reference to passing the information by verbal communication, especially recommendations in an informal way. Its impact is negative or positive. Dichter (1966) first analysed the consumers' motivation, the effective advertising and how advertising affect the word-of-mouth. If consumers are satisfied with the products, they will have positive appraisal, such as praise the product with others. If they are not satisfied with the products, they will have negative appraisal, such as complain and defame the product with others. It has

all been researched on the negative and positive effects qualitatively (e.g. Kidwell and Jewell, 2003; Cheng et al., 2006). It is meaningful to simulate this effect in another way.

2.3 Bass model of new product diffusion

The Product Life Cycle (PLC) is the fundamental marketing concept for managing resource commitments to a new product. It hypothesises that sales of a new product go through the stages of launch, growth, maturity and decline, over time in a target market (e.g. George, 1981). Several descriptive, normative, behavioural, managerial and analytical models and frameworks have been proposed to depict, explain, forecast and manage a new product's life cycle. New product diffusion models focus on the models which analytically capture the PLC in a target market over time in the form of differential equations. The underlying behavioural theory in the development of these models is that, the innovation is first adopted by a few innovators, who in turn, influence others to adopt it by word-of-mouth effect. The interaction or the imitation effect, between adopters and non-adopters, explains the shape of the sales trajectory over time (Rogers, 1995). Examples of the best-known diffusion models in marketing are those of Bass (1969) and Mansfield (1961). The Bass model describes the diffusion process with the differential equation as equation (1).

$$\frac{dN(t)}{dt} = p(M - N(t)) + \frac{q}{M} N(t)(M - N(t)) \quad (1)$$

where $N(t)$ is the cumulative number of adopters at time t , M is the size of the potential adopters, p is the coefficient of innovation and q is the coefficient of imitation. The first term in the equation denotes adoption due to external communication channels such as advertising, and the second term denotes adoption due to the imitation effect such as word-of-mouth.

Diffusion equation models are widely used and they are seen as the basis model in new product diffusion study. Its basic assumption is based on propagation theory, which makes the potential adopters imitate to purchase new products; the diffusion speed is affected by the two important channels of information spread such as mass media and word-of-mouth. In multi-agent simulation, it is mass media and word-of-mouth communication are adopted to establish the individual's correlation. As Bass diffusion model is the basis model to study new product diffusion and in order to compare with multi-agent simulation, it also adopts mass media and word-of-mouth communications to set up the system dynamics model.

3 An analysis on system dynamics

3.1 Basic principles of system dynamics

System dynamics was originally proposed by Forrester (1958), and it is a tool to study the whole system structure by information feedback. The basic principles of system dynamics are feedback, causal graph and flow graph. Firstly, feedback is the relationship between outputs with inputs in a subsystem, and it can be distinguished in the form of positive or negative.

It can produce a self-reinforcing mechanism with a positive feedback and self-restraint mechanism with negative feedback. Secondly, causal graph is founded on the basis of feedback. It can reflect the interaction between various subsystems of the overall structure. It also can reveal the reason for variations of the system. Thirdly, based on casual graph, a flow graph can reflect the cumulative effect of variables and the dynamic performances. It can be seen as the system dynamics model to some extent.

3.2 The characteristics of system dynamics compared with multi-agent

Schieritz and Milling (2003) have compared the two simulation ways. Compared with multi-agent simulation, system dynamics has its own advantage, and some characteristics are analysed as following:

- Compared with multi-agent simulation, system dynamics is a macro-level simulation, while multi-agent simulation is based on micro-level modelling. The basis of modelling needs to be understood as the basic structure of the real system, and the relationship between every subsystem of the whole system should also be understood.
- System dynamics can be used as the complex system laboratory of the actual system, particularly the complex social, economic and ecological systems. System dynamics can be used to solve strategy choice and conduct virtual experiments to explore the optimum structure and system parameters, in which multi-agent simulation is weak.
- Both system dynamics and multi-agent simulation can be applied to study the problem with inadequate data. System dynamics explores the system structure to simulate system functions with integration of qualitative thought, quantitative thought, comprehensive reasoning and the overall thinking. The data is often inadequate or difficult to quantify in modelling. But it can be reasoned and analysed to solve complex problems by virtue of the causal relationship between the elements, certain limited data and the system structure.

3.3 The tools for system dynamics modelling

There are some software packages for system dynamics simulation, e.g. Vensim, Powersim, AnyLogic®, iTthink and ModelMaker. Vensim developed by Ventana Corporation is the most famous one for system dynamics, and it is a standard platform for modelling, debugging, running and analysing the simulation result. It is widely used in the research fields of economics and sociology (e.g. Li and Xiao, 2006).

It has been established a multi-agent simulation model with AnyLogic® (Xiao et al., 2008), so in this paper we also use AnyLogic® to develop the system dynamics model in order to compare with the multi-agent simulation in the same platform. AnyLogic® is a hybrid simulator, which can integrate the models of discrete event, the models of system dynamics and agent-based models. It is based on unified modelling language for real time and has been applied to many different domains to build business models, strategy

models, business games, economic models, social system models, war-gaming models, biological systems models, physics models and software performance models. The models generated by AnyLogic® can be easily uploaded to web by creating a Java applet.

4 The system dynamics model of new product diffusion with negative appraisal

4.1 An analysis on the model assumptions

It has been carried out some relevant assumptions to establish the multi-agent simulation model (Xiao et al., 2008). The similar assumptions as those in multi-agent model are adopted to design the system dynamics model. The overall structure of system dynamics is different from the micro individual level of multi-agent, so the assumptions also have some differences. The assumptions are proposed as following:

- All potential adopters are homogeneous except for the adopting time.
- The diffusion environment is not changeable, that is to say, there are some unchangeable model parameters in the model.
- New product diffusion process is in a competitive market environment. If consumers dissatisfied with the product, they may choose an alternative one.
- The new product will be diffusing through mass media, such as television advertisements, while consumers' word-of-mouth communication is also an important channel. This is the foundation for system dynamics modelling based on Bass model.
- The negative appraisal caused by the inherent problems of the products, such as quality defects or bad services, is considered during the diffusion process. The malicious negative assessment is not considered.
- If consumers are satisfied with the products in the process of consumption, they will spread a positive word-of-mouth assessment; if they are not satisfied, they will spread a negative assessment.
- A negative assessment has larger spread range and larger number of affected persons than a positive one.
- Product's nature life is limited, that is, consumers will repurchase when the products cannot be in use.
- The first purchase decision-making is decided by two factors: The first one is that individuals should acquaint with the new product through mass media and word-of-mouth's spread. The other one is that, the new product should have high reputation generally produced by word-of-mouth's spread. The repurchasing behaviour is decided by three factors: individuals' acquaintance, high reputation and consumers' feelings. If consumers are not satisfied with the product after consumption, they will not repurchase it.

4.2 Design the rates and levels

System dynamics modelling is based on differential equations, and it is important to design series of Rate-Level variables and equations in system dynamics modelling. The Rates in system dynamics modelling just refer to the diffusion equations. The Levels refer to the different kinds of individuals.

1 Levels and equations

In multi-agent modelling, the person agents are divided into potential agents, adopter agents and sleep agents. Compared with multi-agent modelling, in system dynamics modelling, the individuals are also divided into three different groups: adopters, potential adopters and sleep adopters. There are three Levels designed towards the three groups: *Adopters*, *Potential Adopters* and *Sleep Adopters*. According to the three Levels, there are also three patterns that change into another state from other states. Firstly, some potential adopters change into adopters on the impact of mass media and word-of-mouth communications, and let *Adoption_Rate* be for the transformation per time between potential adopters and adopters. The *Adoption_Rate* makes potential adopters increase and reduces the total number of adopters. Secondly, as the product's natural life, some adopters will change into potential adopters, and the Rate between the two is *Discard_T*, which makes adopters decline and potential adopters increase. The last, on the impact of negative appraisal, some potential adopters and adopters will change into sleep adopters, who will never purchase the product. Some adopters discard the product and change into sleep adopters, and Let *Direct By BWOM_Rate* be for this transformation rate. Also, some potential adopters reduce as the transformation rate *Indirect By BWOM_Rate*. The sleep adopters increase with the sum of these two Rates, and sleep adopters are unabated. Equations (2)–(4) show these series of equations as follows:

$$\begin{aligned} \frac{d(\text{Adopters})}{dt} = & \text{Adoption_Rate} \\ & - \text{Discard_Rate} \\ & - \text{Direct_By_BWOM_Rate} \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{d(\text{Potential_Adopters})}{dt} = & \text{Discard_Rate} \\ & - \text{Indirect_By_BWOM_Rate} \\ & - \text{Adoption_Rate} \end{aligned} \quad (2)$$

$$\frac{d(\text{Sleep_Adopters})}{dt} = \text{Bad_WOM_Rate}. \quad (3)$$

2 Other variables and equations

The Level equations are only about the decrement and increment about different states, and the related rates are reflected in Rate equations. *Adoption_Rate* is composed of the two Rates: *Adoption_From_Advertising*, which

reflects the advertising effect, and *Adoption_From_WOM*, which is related to the word-of-mouth effect. As the first term $p(M - N(t))$ in equation (1), p is just the innovation coefficient reflected the advertising average effect, $M - N(t)$ is just the amount of adopters and a delay effect is designed as equation (7). The word-of-mouth effect is consistent with the second term. The related Rates equations are shown as equations (5)–(8).

$$Adoption_Rate = Adoption_From_Advertising + Adoption_From_WOM \quad (4)$$

$$Adoption_From_Advertising = delay(Advertising_Effectiveness, Ad_Effect_Time) \quad (5)$$

$$Advertising_Effectiveness = Potential_Adopters \times expenditure / 10000 \quad (6)$$

$$Adoption_From_WOM = Contact_Rate \times Adoption_Fraction \times Adopters \times \frac{Potential_Adopters}{Total_Population} \quad (7)$$

The *Discard_Rate*, which is the rate for transforming from adopters to potential adopters, is related to *Adoption_Rate*. If there is no negative appraise, after a PLC, all these transformers will change back to potential adopters. As the negative appraise, some of them are lost, and they will change into sleep adopters. So it should be verified to the returning rate to some extent. Equations (9) and (10) show these equations as below:

$$Discard_Rate = delay(Discard_Eff, Discard_T, 0) \quad (9)$$

$$Discard_Eff = Eff_coeff \times Adoption_Rate \quad (10)$$

The negative appraise affects adopters and potential adopters to change into sleep adopters in accord with the two Rates. These Rates are similar to the second item in Bass diffusion model. Equations (11)–(13) show these equations as below:

$$Direct_By_BWOM_Rate = Adopters \times bad_trans_coeff \times \frac{Adopters}{Total_Population} \quad (11)$$

$$Indirect_By_BWOM_Rate = Adopters \times bad_trans_coeff \times \frac{Potential_Adopters}{Total_Population} \quad (12)$$

$$Bad_WOM_Rate = Direct_By_BWOM + Indirect_By_BWOM_Rate. \quad (13)$$

Auxiliary equations are auxiliary for Levels and Rates equations, or for the purpose of certain simplified to modelling. Some equations in this type are related to Rate or Level equations. Equation (14) shows this auxiliary equation as below:

$$bad_trans_coeff = bad_ratio \times bad_cont_rate \times bad_wom_eff. \quad (14)$$

4.3 System dynamics simulation model

On the basic assumptions and relative analysis on Rates, Levels and equations, Figure 1 shows the systematic flow graph model, which is used to do simulation experiments. The relations between different variables are reflected clearly in the model, and the transformations of the three Levels also can be understood clearly. There are three Levels in the flow graph model, and there is a Rate variable for transformation between every two Levels, so there are four Rates in Figure 1. The model can be simulated to do the experiment to study new product diffusion and be used to explain the new product diffusion process.

After enterprise has developed the new products, the products will be put into the market. All the persons in market will be in the state of potential adopters, but on the impact of mass media, such as advertising, some persons start to accept the new product and change into adopters by purchasing the product, that is, reflected in Figure 1, potential adopters will change into adopters at the rate of *Adoption_Rate*. With the adopters increasing, some adopters will have different attitude towards the new product, namely, they will be satisfied or not with the new product. So the arising appraise has negative or positive effect. The positive appraise makes more persons accept the product and change into adopters. The negative one makes some persons change into sleep adopters. On the impact of negative appraise, some potential adopters will change into sleep adopters directly at the rate of *Indirect_By_BWOM_Rate*, and some adopters will also change into sleep adopters as the rate of *Direct_By_BWOM_Rate*. As the limited product's nature life, some adopters will change into potential adopters at the rate of *Discard_Rate*. Figure 1 also shows these transformations.

Figure 1 New product diffusion model based on system dynamics (see online version for colours)

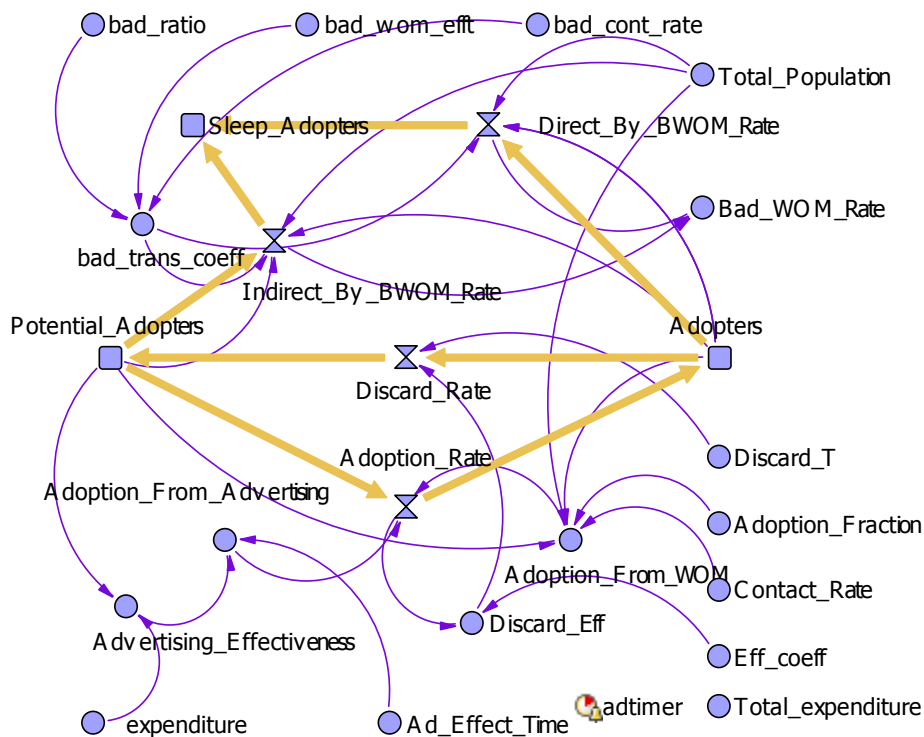


Table 1 Variables and constants in the model

Variables and constants	Type	Explanations
Potential Adopters	Level	Number of potential adopters
Adopters	Level	Number of adopters
Sleep Adopters	Level	Number of sleep adopters
Adoption Rate	Rate	Adoption rate
Discard Rate	Rate	Discard rate
Indirect By BWOM Rate	Rate	Indirect transforming rate by NWOM
Direct By BWOM Rate	Rate	Direct transforming rate by NWOM
Bad WOM Rate	Auxiliary	Total rate by NWOM
Adoption From Advertising	Auxiliary	Rate by advertising
Adoption From WOM	Auxiliary	Adoption rate of positive WOM
Advertising Effectiveness	Auxiliary	Advertising effectiveness
Discard Eff	Auxiliary	Advertising output in a cycle
delay AD	Auxiliary	Delay effect of advertising
bad_trans_coeff	Auxiliary	Transformation coefficient
Total population	Constant	Number of total population
bad_ratio	Constant	Probability of NWOM
bad_wom_eff	Constant	Effectiveness of NWOM
bad_cont_rate	Constant	Frequency of NWOM to other persons
Contact Rate	Constant	Frequency of PWOM to other persons
Adoption Fraction	Constant	Effectiveness of positive WOM
Total expenditure	Constant	Total expenditure
expenditure	Constant	Expenditure monthly
Ad Effect Time	Constant	Delay time of advertising effect
Eff_coeff	Constant	Transformation coefficient
Discard T	Constant	PLC

The auxiliary variables are related to some Rates, and they are always the independent variables in Rate equations. Constants are related to the diffusion environment. The simulation experiments are running with different values of the constants. Table 1 shows all the constants and their meanings, and it also shows all the other variables with explanations in flow graph (Figure 1). All the constants and variables are defined in real data type.

5 Simulation experiments and comparative analysis

5.1 Negative appraise simulation and comparative analysis

When there is no negative appraise in diffusion, that is, variable *bad_ratio* values 0. Table 2 shows the default value to simulate, and their data types are all real.

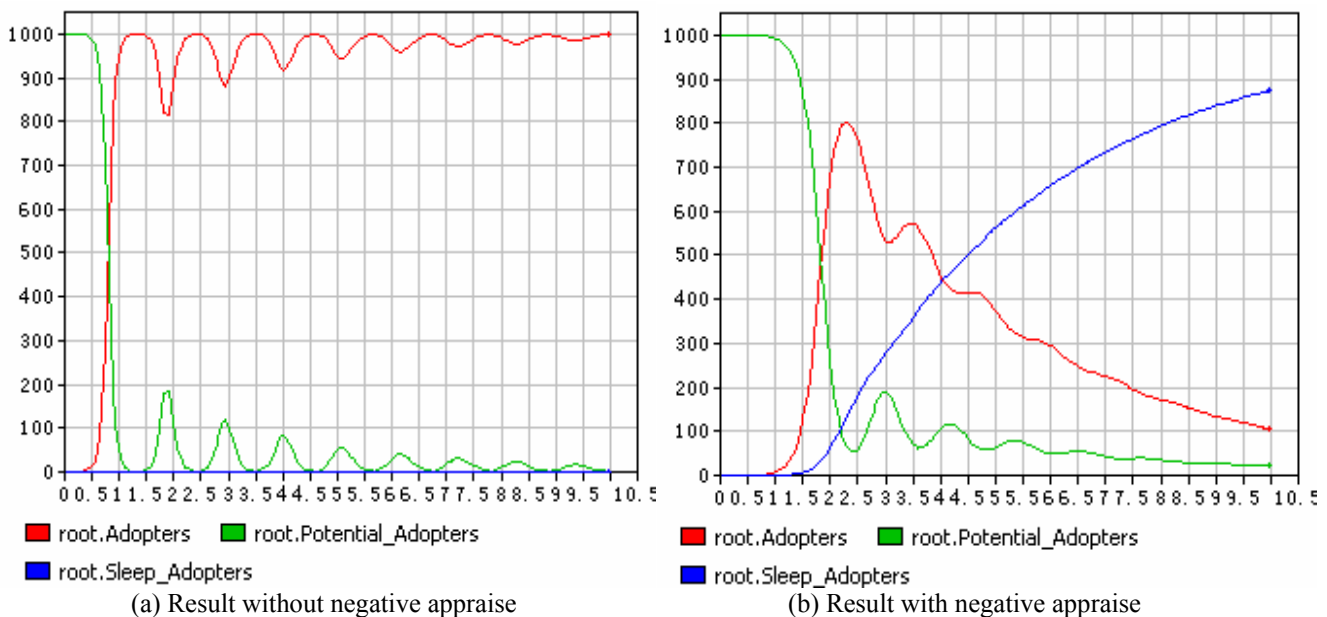
Table 2 Default values

Variable name	Default value
Total_population	1000
bad_ratio	0.00
bad_wom_eff	0.3
bad_cont_rate	500
Contact_Rate	100
Adoption_Fraction	0.06
Total_expenditure	-
expenditure	1100
Ad_Effect_Time	1
Eff_coeff	0.7
Discard_T	1

Running the simulation model for ten years, Figure 2(a) shows the relative diffusion curves of the three Levels: *Adopters*, *Potential-adopters* and *sleep_adopters*. Because there is no negative appraise along with time, *Sleep_Adopters* values zero along with all the simulation period. In the early simulation period, there is only advertising effect, so the number of adopters increases at a high rate. As the positive appraise arising with the word-of-mouth communication, the number gets much higher, and the adopters rise sharply in the number as shown in the diffusion curve with an S-shaped characteristic. As the product's natural life is limited, some Adopters then transform into potential adopters after a PLC. The returning rate to potential adopters is higher than adopting rate, so the number of adopters reduces sharply until the returning rate is equal to the adopting rate. As time going, the adoption rate starts to be higher than the returning rate, then the number of adopters starts to arise, also a cyclical fluctuation has been formed shown in diffusion curve. In this fluctuation, the amplitude is getting smaller and smaller along with time, and at last, the system will be in a stable state. When there is no negative appraise, there are only two states of potential adopters and adopters, two states either-or. The degree of adopters' growth is the degree of the potential adopters' decrease, and vice versa. Figure 2(a) shows that the diffusion curves of *Adopters* and *Potential_Adopters* are symmetrical about the line $x = 500$.

Where the probability of the negative appraise (*bad_ratio*) is 0.002, the simulation result is shown in Figure 2(b). The negative appraise effect makes another state *Sleep_Adopters* arise, and the number of sleep adopters has a relatively gentle similar to the linear growing mode with the number increasing along with time. The number of adopters and the number of potential adopters both decline in volatility at the same time. As part of the communication failure, the amplitudes of the two fluctuations get smaller and smaller, and the diffusion curve decreases gentle.

Figure 2 Compare the two results (see online version for colours)



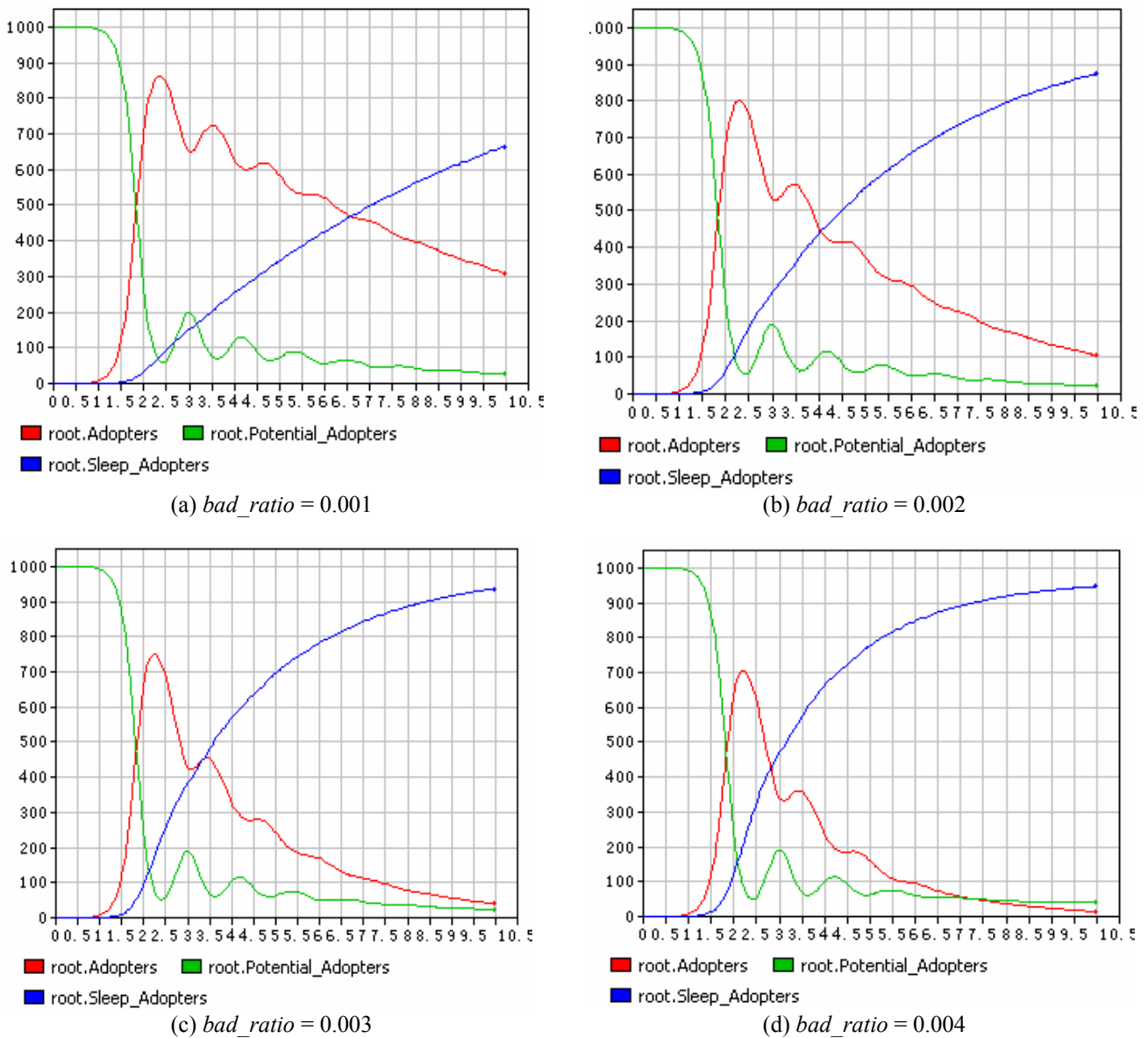
5.2 Sensitivity analysis: probability of negative appraisal

In order to test the negative appraisal effect, change the probability of negative appraisal (*bad_ratio*) to simulate the *bad_ratio* values 0.001, 0.002, 0.003 and 0.004 in turn. Figure 3 shows these diffusion curves along with time. It is very sensitive to the probability of negative appraisal in new product diffusion process, and the dynamic characteristic of diffusion is very obvious. As the reason of the effect of negative appraisal and repurchasing behaviour, the number of adopters in four situations rises quickly, and decreases with fluctuations after getting at the peak. The number's trend of potential adopters is opposite to adopters'.

The negative appraisal has significant impact on the number of sleep adopters. As the probability of negative appraisal increasing, the number of sleep adopters increases much faster. Where *bad_ratio* values 0.001, the diffusion curve of sleep

adopters has a relatively gentle similar to the linear growing mode on the increasing number in Figure 3(a). Figures 3 (b–d) show that, in these three situations, the number of sleep adopters also increases with probability of negative appraisal, but compared with Figure 3(a), the curve shows the S-shaped upward trend, and with the probability increasing this S-shaped curve becomes more steep. Figure 3(b) shows that in early simulation time, it arises sharply as the negative appraisal and shows the similar to linear model in the end in the diffusion curve of sleep adopters. In Figures (c and d), with the increasing probability, the diffusion curve of sleep adopters shows the S-shaped characteristic. It is seen that the higher probability the greater proportion occupied by sleep adopters, and a general tendency of the amount of adopters is zero. The new product developer should take some measures to control the spread of negative appraisal, otherwise, it will create mass loss of customers, and make developers out of the market.

Figure 3 Sensitivity analysis: probability of negative appraisal (see online version for colours)



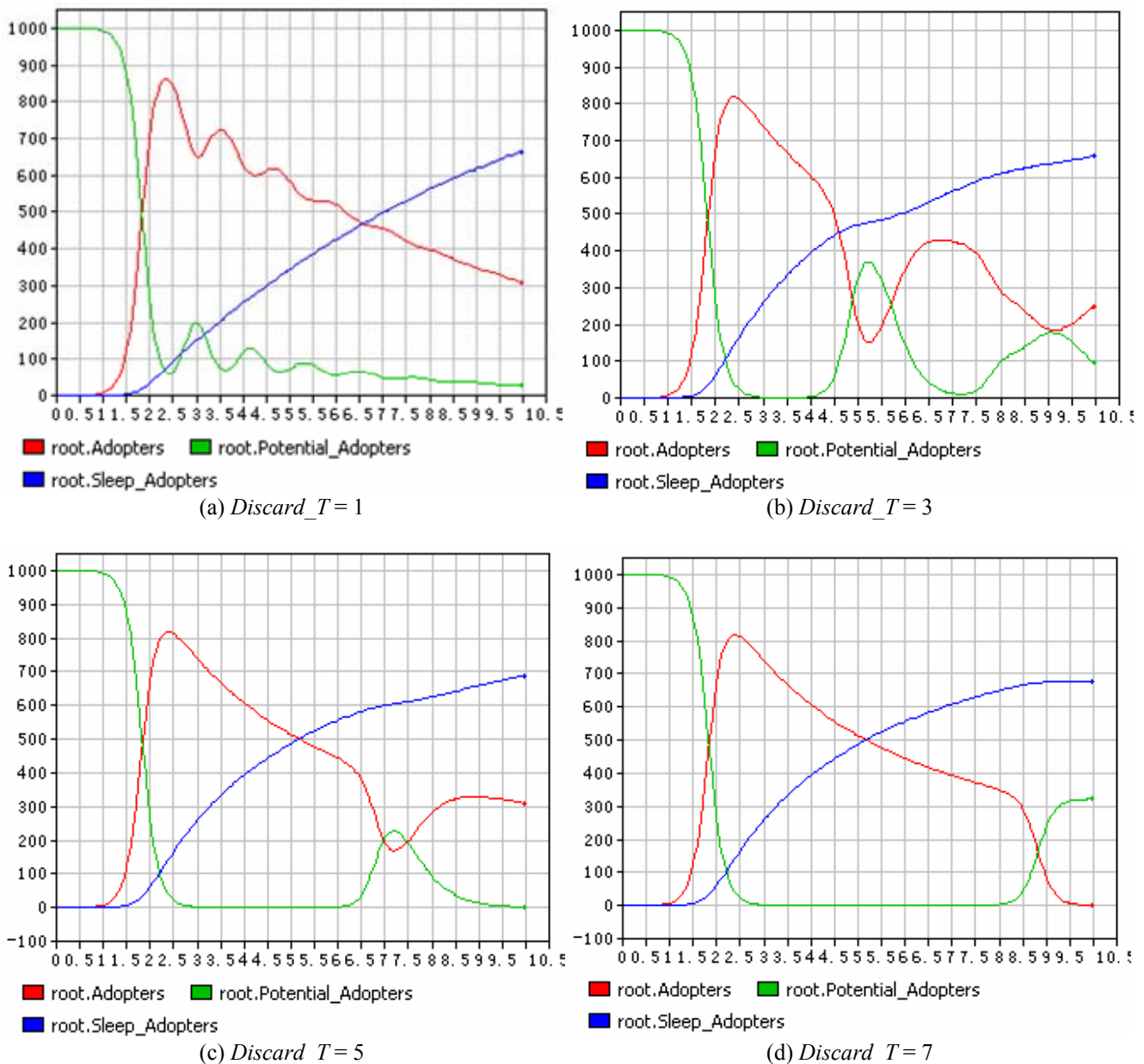
5.3 Sensitivity analysis: product life cycle

Product’s natural life affects consumers’ repurchasing behaviours frequency. In order to do the repeat simulation experiments and analyse the sensitivity, we adjust PLC in three, five and seven, and other constants as default value. The simulation results are shown in Figure 4. PLC has important effect on new product diffusion process, and the diffusion is very sensitive to these changes with obvious dynamical characteristic. The number of adopters or potential adopters is remarkable on the impact of different PLCs. Compared with the four different values, it is seen that the fluctuation has a much higher frequency with a smaller cycle, and the number of adopters or potential adopters also fluctuates more sharply with a smaller PLC. With a small life cycle, when the market opens for the new product, namely,

the adopters increase to the highest amount, the decline of the adopters is getting fast at this time. But with a large life cycle the decline is slow, and sleep adopters are hardly affected by the PLC.

When the sales of new products fall faster with a large life cycle, the developers of the enterprises will pay vigilant attention to the negative appraisal spread and take some measures to control this situation. While, for a product with small life cycle, the developers of the new product pay hardly attention to the fast falling sales. When they found the problem coming from the negative appraisal effect, there is not enough time for them to control the situation. Although the product diffusion of negative appraisal is hardly affected by the repurchasing behaviours, it will affect the developers to perceive the negative appraisal diffusion.

Figure 4 Sensitivity analysis: PLC (see online version for colours)

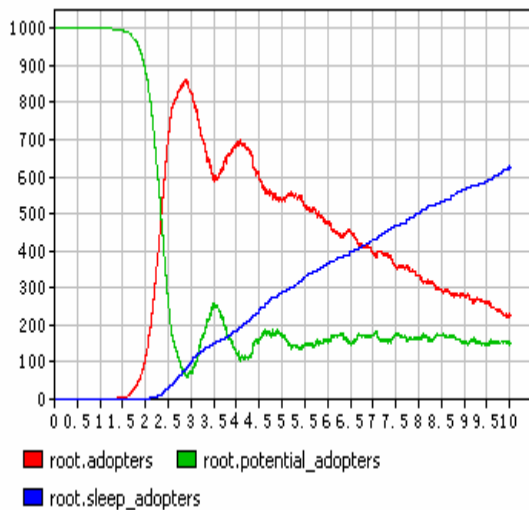


5.4 Compare with the two simulation methods and analysis

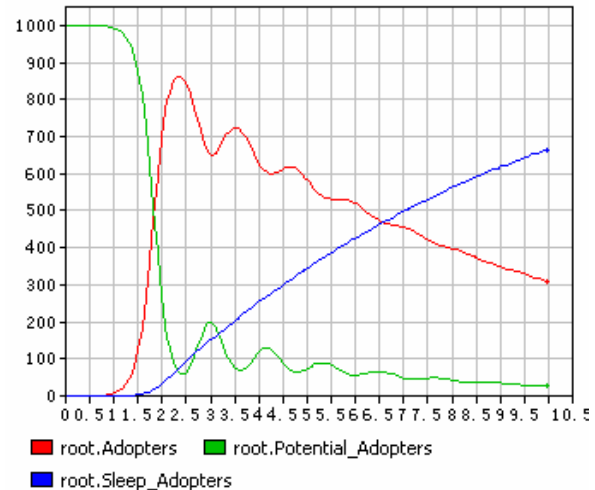
System dynamics is different from multi-agent simulation. The negative appraisal in diffusion has been analysed as above. In our former research, the multi-agent simulation with negative appraisal has also been established to simulate (Xiao et al., 2008). Figure 5 shows these two simulation results with the same constants. The compared results are almost the same, especially in the diffusion curve characteristics. On an overall perspective, the number of potential adopters has a sharp

decline after the early simulating period, and then declines with fluctuations in the trend of stability. The number of adopters rises sharply at the beginning, and then decreases with fluctuations. Also, the amplitudes of these two different simulations are exactly the same at the same time. The diffusion curve of sleep adopters shows the similar linear growth mode, and the two results of sleep adopters almost are the same even at each simulation time. This shows that the negative appraisal plays exactly the same role in the two different simulation methods.

Figure 5 The compare of the two simulation results (see online version for colours)



(a) Multi-agent simulation result



(b) System dynamics simulation result

The two different simulations have almost the same simulation results, so to some extent, this demonstrates the effectiveness by co-verification of the two simulations. At the same simulation time, the reasons need to be analysed in the essence of the similarity of the two results. New product diffusion on macro-level is based on diffusion equations especially the Bass diffusion models. In this paper, the system dynamics model is also based on the Bass diffusion models. The essence of system dynamics diffusion model is in the differential equation. There are two terms in equation (1), one is related to advertising effect, and the other one is about to word-of-mouth effect. The diffusion equations of system dynamics are similar to the structure of Bass diffusion equation, and they are reflected in the design of system dynamics equations. In multi-agent simulation, the agents' spread patterns are also mass media and word-of-mouth among the agents, so the two simulations results are the same to some extent. In this analysis above, the essence of the two different simulations is the same, and it should not be known the system structure in multi-agent modelling. Differently, it should be known the system structure in system dynamics modelling, and this is the reason for analysing the diffusion theory at the beginning of this paper. In Figure 5, the curve of system dynamics is smoother than the one

of multi-agent simulation. Because multi-agent simulation studies the macro behaviours on the micro-level, and the composition of the system is each agent, the three multi-agent curves show the strong randomness in their respective changes. Although the multi-agent diffusion curves are the same as the system dynamics to some extent, the curve has small amplitude with fluctuation behaviours as the randomness of each agent.

The foundations of the two simulations are different. The essence of the diffusion needs to be understood to establish a system dynamics model, but it only needs to know each agent's diffusion rules to establish a multi-agent model. So although it can be analysed by multi-agent simulation, it is unable to understand the diffusion equation better on macro level.

6 Conclusions

In this paper, a new product diffusion model with negative appraisal is established based on system dynamics and diffusion theory. AnyLogic® is used to simulate the system dynamics model. By repeating simulation experiments, it is analysed the simulation results, and the negative appraisal in

diffusion is explored. In our former research, a multi-agent simulation model has been established with AnyLogic®. The two simulation methods are compared at last. All the conclusions are drawn as following.

The new product diffusion process is affected obviously by the negative appraise. When the probability of negative appraise is greater than a certain value, the negative appraise will have a greater effect than the developer's own positive publicity and the positive appraise among consumers. After a large life cycle, product is accepted by the market, the sale of the product will be stable in a long range, which will make the developers more careless.

The new product diffusion curve adopting mass media and word-of-mouth rules on micro level shows S-shaped growth form on the macro level, and the diffusion curves are the same as Bass diffusion equations on the macro level.

System dynamics and multi-agent simulation draw the similar conclusions to study the negative appraise in diffusion, and they can testify the effectiveness of its simulation result by each other, and the reason is that they have adopted the same diffusion pattern, namely, mass media and word-of-mouth communication. It is not the real world in simulation, so it is helpful to use different simulation methods to solve the problem and testify each result.

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Multi-level contextual product development knowledge management in PLM

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Abstract: Product Lifecycle Management (PLM) manages product data and processes and generally forms a huge product knowledge base, but how to leverage it for later product development is not well emphasised and discussed. Based on the practices of PLM implementation, a model of multi-level contextual knowledge management, called C-A-B, was proposed which contains three elements (knowledge context, knowledge aspects and knowledge base) and two engines (aspects mapping engine and knowledge acquisition engine). The context was constructed by leveraging the nature of WBS and workflow in PLM which provides a scenario for product knowledge capture and sharing. Knowledge retrieval was triggered by context and complete by passing contextual attributes to knowledge base through knowledge aspect. A system based on C-A-B model was developed for a vehicle OEM which demonstrates the add-on value to PLM adoption, making the knowledge access and sharing more efficient and productive in context.

Keywords: contextual knowledge management; PLM; product lifecycle management; product development; WBS; work breakdown structure; workflow.

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1 Introduction

In an age of information-centric economy, more and more enterprises recognised that the secret weapon to survive in extensive competition is intelligent assets instead of physical assets (McCampbell et al., 1999; McGrath, 2004). For a company, knowledge has already been the first priority to build up and maintain its core competitiveness, especially for those who mainly focus on product development (Ramesh and Tiwana, 1999). Thus, Knowledge Management (KM) has been getting increasing attention from both industry and academy.

Meanwhile, more and more companies have introduced Product Lifecycle Management (PLM) system to improve their product related data and process management. Actually, PLM adoption will always result in a huge central and consistent repository with rich knowledge of product development (Bilello, 2006) which can be as a basis for knowledge management. Currently, to leverage the knowledge in PLM is not easy. The users have to get a good and right understanding of the classification, codification and storage structure of the data. Full-text search always returns the results that you do not want (Yang et al., 2004). Current PLM cannot effectively support knowledge management also because so far it mainly focuses on product development results and relevant processes. The know-how on guiding to get those results is not well emphasised and managed.

The evolution of organisation and management of product development knowledge has experienced stages from file server to attributes-based search engine, and then to knowledge portal. Much of efforts have been dedicated in developing knowledge repositories, which typically make the knowledge structured or store documents with knowledge embedded in them. This way has been proved to be inefficient (Kwan and Balasubramanian, 2003; Liao, 2003; Donk and Riezebos, 2005). Four facts may account for non-use. Firstly, there is a learning curve to become familiar with the knowledge architecture and the methods of searching. Secondly, knowledge acquisition is difficult and time-consuming. The search results based on key words or full-text retrieval are always not exactly what we want. Thirdly, contributing knowledge to a repository always amounts to an extra work required of contributors, which holds back the accumulation of knowledge. Lastly, a culture of knowledge acquisition and share has not been established across the organisation.

Knowledge management in context was known as an effective way to increase the efficiency and productivity of knowledge accumulation and acquisition (Huang et al., 2004; Jennex, 2006). That is to put the organisation and usage of knowledge under a specific context (also called scenario) so that to narrow the knowledge search scope and promote the accuracy of acquisition. There are a few studies that contribute to this area of research. Meta data model (Raghu et al., 2007) was suggested to address knowledge storage, retrieval, sharing and synthesis within a business process context; A three-layer, collaboration-intention-behaviour, design process model combined a user model (Yang et al., 2004) was proposed to facilitate the active recommendation

of design knowledge items. A Knowledge in Context (KIC) model (Kwan and Balasubramanian, 2003) was worked out from four perspectives: functional, behavioural, organisational, and informational. A model of Knowledge Management Integrated Context (KMIC) based on Knowledge Context (KC), knowledge process, knowledge (items) and knowledge agent was introduced to deal with the context and its relevant information to endow KM system with context sensitivity (Pan et al., 2006). A Knowledge Context (KC) model for virtual collaborative work, called KC-V model, was suggested to facilitate the creation, management and utilisation of knowledge (Ahn et al., 2005).

Most of the researches are academically focused on the representation of knowledge context and with no relationship with PLM. Based on the practices, a new knowledge management model was proposed which takes advantage of PLM as a knowledge base. The product development knowledge was captured, organised and shared along with the product development context which is constructed by leveraging the characteristic of PLM environment. In such way, knowledge can be easily retrieved and accessed, which significantly reduces the time for knowledge acquisition and finally increase the productivity of product development.

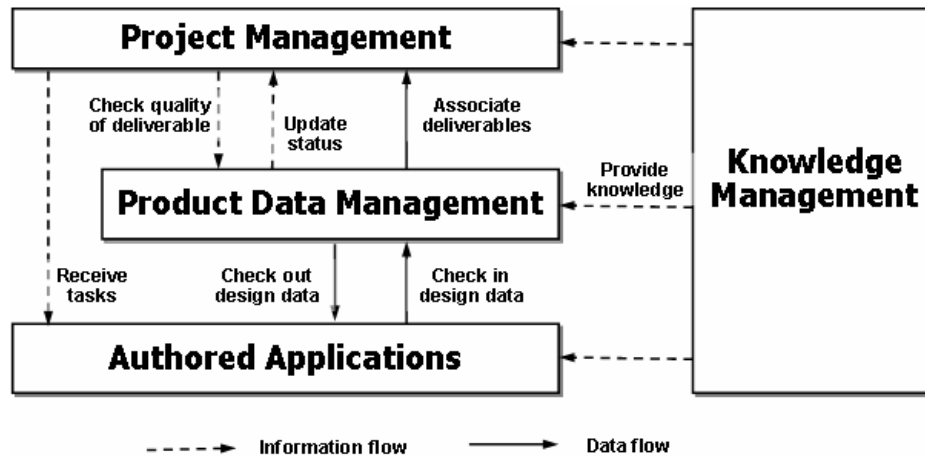
2 Knowledge, context and PLM

2.1 PLM and knowledge management

Figure 1 shows that there are four key capabilities for PLM architecture: data management, project management, knowledge management and authored applications. Data management addresses what is managed, which maintains consistent status of data and corresponding review and change processes. Project management indicates when to create the data, which controls and monitors time, cost and resources from a higher management level. Authored applications are used to complete the tasks and generate data. Knowledge management provides knowledge to guide product engineers on how to generate data and how to manage product development.

The importance of knowledge management has already been well understood, but till today its function and benefits are not properly fulfilled by PLM adoption. Traditionally, knowledge management under PLM environment was treated as content management. The contents were catalogued in a central repository and searched by keywords when necessary. There are some limitations on this approach. First of all, content management mainly covers instances of data type, which is not enough to fully support a product development activity. Second, the efficiency of knowledge reuse by search is rather low. Product engineers have to be trained and practised well to get a high productivity. Third, without a full-scale knowledge support, designers will get their work done based on their own understanding and experiences outside the system, which may be very different and inconsistent from one another.

Figure 1 Position of KM in PLM



An ideal business process of knowledge creation, capture and reuse in PLM environment can be described as below.

- Project manager works out project plan and delivers assignments through project management system.
- Project participants receive an assignment, and then collect all possible knowledge related to the work (so called contextual knowledge) from knowledge management.
- Using authored applications such as CAD Office to create the deliverables and relate them to current context and other data, and then check in to PLM system for reuse.
- Update the project status to reflect the progress, which can be referred as project performance benchmark.

Contextual knowledge management contains two key fundamental elements: knowledge and context. In this paper, context refers specifically to product development processes or scenario. It presents two parts of implications. One is the processes that the knowledge are used, the other is the contextual attribute of knowledge itself.

2.2 Context of knowledge management in PLM

The context of knowledge being used is presented by product development process, which is the environment of a step or a task that a product engineer undertakes in a product development process. The processes in nature construct the context of knowledge reuse.

In general, each mature organisation has its product development architecture and relevant documentation. Some of them have consolidated as Advanced Product Quality Plan (APQP) which defines the necessary steps and deliverables that needed to satisfy the customer's requirements. Product and Cycle-time Excellence (PACE) is a well known reference model that can be used to structure product development processes (McGrath et al., 1992).

In PACE, development activities are arranged in a hierarchy: stages (top and macro level), steps, task and activity (lowest and detail level). Stage presents decision level with milestones as its end; steps are used to plan and control the progress of product development; each step comprises several tasks which provide guidelines on how to complete a step;

and a task can be divided into several activities (shown in Figure 2a). Usually, stages and steps are always the same in different projects, while activities vary among projects.

In PLM system, there are two ways can be used to present process of product development. One is Work Breakdown Structure (WBS) embedded in project management, which presents the high level and somewhat flexible processes. The other is workflow in data management, which presents the somewhat rigid and automated processes. If taking PACE as a reference, WBS maps to the stage and step level, while workflow maps to task and activity level. Actually, there is not a definitive boundary between WBS and workflow. Which technology and approach should be chosen to map the PACE level depends on the situation case by case, especially for the task level.

Therefore, context construction for the contextual knowledge management in PLM can be divided into two levels (shown in Figure 2b): WBS driven high level product development context and workflow automated low level product development context. Regardless of which level of context, participants in each product development task or activity will be pushed rich and enough knowledge to facilitate to get the work done.

2.3 Contextual attribute of knowledge in PLM

Contextual attribute of knowledge is the conditions for the creation of the knowledge. Whenever knowledge is reused, its usage constraints should be carefully checked. Otherwise, knowledge can become falsehood. In PLM, relationship between data penetrates everywhere and becomes a key characteristic of PLM. Every data can be linked to others. Figure 3 illustrates a part which relates to documents that pertains to it, such as requirements, CAD model, data sheet, analysis report and test plan. If any of them was revised, the change history and change results will also be maintained and related to it, including knowledge of why revise, under what conditions and how change is embedded in those traceable histories. Besides, the part will also be related to the project, activities and deliverables that assigned to create it. All these data and information establish an integral and ultimate form of the context for knowledge reuse.

Figure 2 Product development context levels in PLM (see online version for colours)

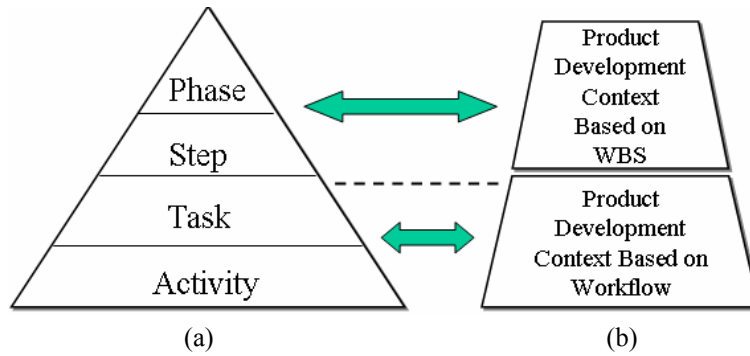
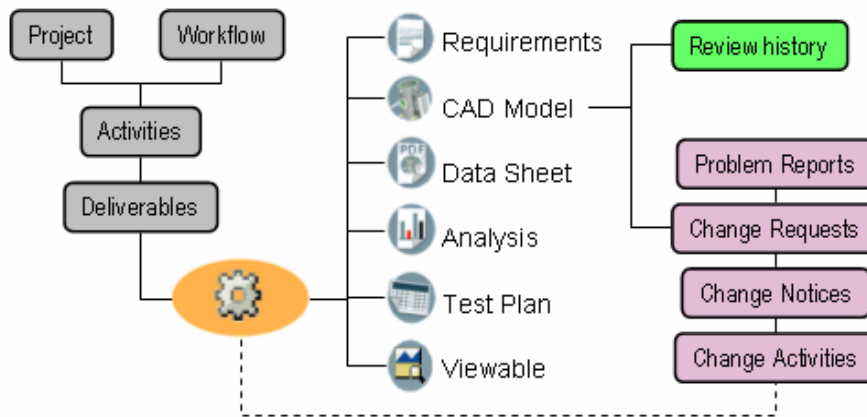


Figure 3 Example of contextual attribute of knowledge in PLM (see online version for colours)



3 Contextual knowledge management in PLM

To meet the requirement of contextual knowledge management in PLM, a C-B-A reference model was worked out. In this section, the key elements of this model are defined and analysed, and then the key technologies for the model are pointed out and discussed, which includes the approach for construction of context, the rules for knowledge classification and the mechanism of knowledge acquisition engine.

3.1 Elements of C-A-B model

C-A-B model of PLM-based contextual product development knowledge management contains three key elements and two engines which are demonstrated in Figure 4. Three elements are Knowledge Context (KC), Knowledge Aspects (KA) and Knowledge Base (KB). Two engines are KA mapping engine and KB acquisition engine.

WBS and workflow will be taken as knowledge carrier for KC. Each project task or activity constructs a specific context of knowledge application. For example, the market analysis activity in product concept design stage, and part design activity in product detail design stage.

KBs are the collections of all the data, information and knowledge libraries based on IT infrastructure. Knowledge base can be catalogued by functional application, such as business processes, standard parts, design standards, change

experiences, education courses, technical innovation collections and document templates.

KA defines the necessary and possible knowledge areas that linked to each product development activity. It acts as the bridge between KC and KB. Since KB just provides the collection of all possible knowledge, KA acquires and filters the knowledge from all the repositories of KB based on the KC and pushes them to the end user in friendly manner. As for a design activity, the possible aspects of knowledge may cover work steps, standards and regulations, templates, references, Frequent Asked Question (FAQ), basic skills and external information.

KA mapping engine can recognise what aspects of knowledge is required for a specific product development activity based on the characteristics of its context.

Knowledge acquisition engine searches and collects all the corresponding records of knowledge related to the KA from all the knowledge bases across organisation.

Figure 5 illustrates an example of extended picture of C-A-B model for product development under PLM environment.

Knowledge management in an organisation is a dynamic loop process of knowledge accumulation, share, reuse and update. Therefore, to use IT system to turn C-A-B to reality, the flexibility and scalability of knowledge maintenance should be taken into account. The flexibility and scalability means not only the aspects of knowledge, but also the knowledge base itself and knowledge records within each knowledge base.

Figure 4 C-A-B contextual KM model

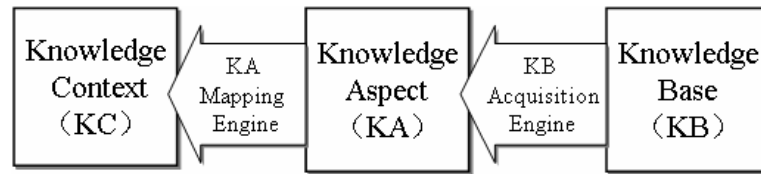
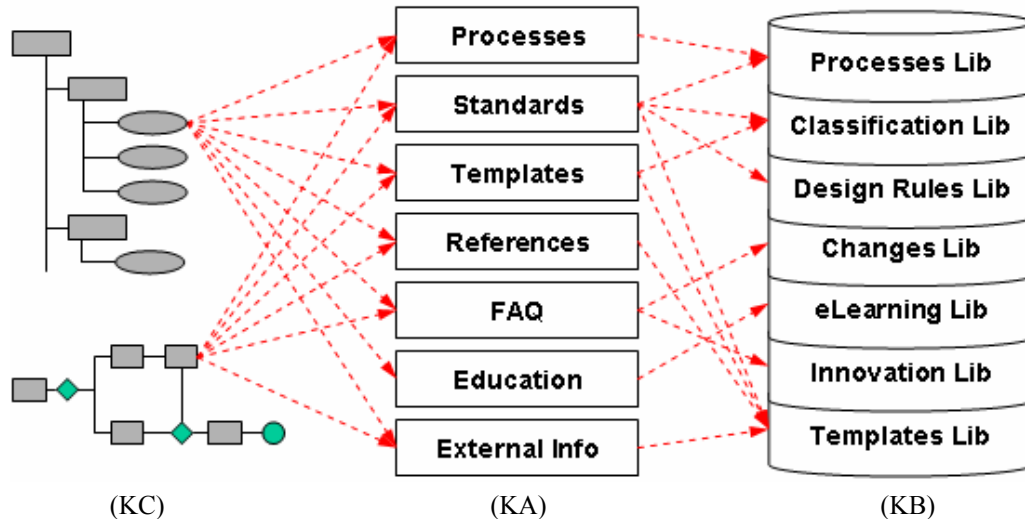


Figure 5 Example of extended C-A-B model (see online version for colours)



3.2 Structured context construction

Structured context is the key to ensure the success of contextual knowledge management upon C-B-A model. Figure 2 has showed that the context of knowledge management in PLM can be leveraged in two levels: project management level and workflow level. So the context construction on both levels is the most important.

WBS is a general method to define and structure project plan in project management. WBS defines the project scope by break the activities into hierarchical tree in the direction of tangible deliverables. WBS is the basis for project schedule, cost, quality and communication. In this paper, it takes another role to act as a carrier of knowledge capture, share and acquisition.

In PLM, the most efficient way to structure WBS is project templates. Project templates can reduce difficulty to control and monitor projects, and turn the project management process itself as a part of organisation knowledge to be reused. In addition, templates can make the product development more stable so that it is possible to link the knowledge aspects to project activities with proper project development context. In this way, application of IT technology will also become easier.

To generate WBS templates is a big challenge for most manufacturing enterprises, because most of the domestic organisations are still staying on the level of documentation. The product development procedure is not well-structured and applied using IT technology. Another reason may be the process difference among industries, products and product development types. PACE model can help organisations to build up their structured product development processes.

In PLM, workflow is a lower structured product development context for knowledge management, which emphasises on the

logic linkage and automation between development activities. Sometimes, it is also called Design Navigator when the workflows merged with contextual knowledge management.

Regardless of WBS or workflow, knowledge management will be reflected through product development activities or tasks. Each project has a unique identifier and several attributes, and each activity also has its unique identifier and attributes. These identifiers and attributes will be passed to knowledge acquisition engine as contextual information to facilitate knowledge search and retrieval.

3.3 Classification of knowledge

There are kinds of knowledge across product lifecycle. With a contextual knowledge management system, classification of knowledge should meet the requirements of knowledge acquisition and usage for designers in context.

As for a component design activity, the requirement of contextual knowledge includes constraint knowledge (boundaries of scenario), process knowledge (detail design steps), experience knowledge (including case studies, quality feedbacks, FAQ, et al.), reference knowledge (including templates, design standards, benchmark library, competitive information) and others (such as marketing information, education materials, brainstorm collections).

It is strongly suggested that organisations set up a department to take charge of knowledge management.

At present, PLM is good at managing explicit knowledge. Under the condition of lack of the support of intelligence, it is strongly recommended to translate the tacit knowledge to the description or definition of explicit knowledge (Bilello, 2006).

3.4 Knowledge acquisition engines

When the product development engineers click a knowledge aspect to retrieval knowledge, knowledge acquisition engine will search the knowledge records from different kinds of pre-defined knowledge bases based on current scenario (can be defined by a set of key attributes) and knowledge aspect itself (also can be defined by a set of key attributes), and then show it to the engineers in a friendly format. This also is called pushed knowledge acquisition engine (Wang et al., 2007) due to its nature that the engineers are not required to manually search different knowledge bases.

The key to make the engine work efficiently is to standardise and consolidate the best practice search strings that engineers used to retrieval knowledge. The search string may be a comprehensive logic expression which is approved by practices. In this way, the difficulty to get the

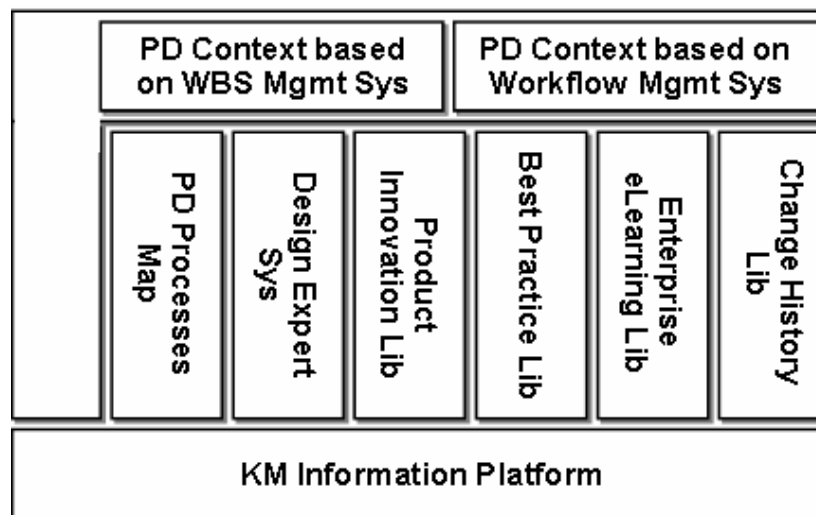
right contextual knowledge will be significantly reduced, especially for those new employees who are not full trained and with little experiences on product development work.

4 Application

4.1 System architecture

Figure 6 shows a system architecture of contextual knowledge management in PLM, which is based on above constructed model and several years of PLM implementation. The architecture was constructed with KM information platform, WBS-based product development context management system and workflow-based product development context management system, and several subject-oriented knowledge bases.

Figure 6 System architecture of C-A-B model application



Knowledge management information platform is web-based with features of scalability, robustness and security. It provides a basic framework to maintain knowledge base, knowledge records and knowledge aspects and make it easy to expand.

Context management systems are based on project management and workflow. Structured WBS templates and automated workflow are the key which can facilitate levelled product development management which can meet different management requirements from top level to bottom level. Project or workflow activities link to knowledge bases through knowledge aspects. They also link to deliverables, which may become the knowledge for later reuse.

Different kinds of knowledge bases include process knowledge map which provides product development process steps, work instructions and deliverable templates; design expert system which provides specifics of design standards, parameters and instructions on modelling; innovation library provides collections of BBS, external information, competitive information and advices from call-centre; best practice library provides parts classification, design cases; enterprise e-learning

library contains all electric multimedia training materials and capability assessment; change history library stores all the design changes, quality feedback and change solutions.

4.2 Development and deployment

Above system architecture has been applied and approved in engine research and development department of one of the most famous automotive OEM in China. The system was built on Windchill which is the PLM solutions provided by PTC (Parametric Technology Company), and PDMLink (mainly for data and workflow management), ProjectLink (mainly for project management) and PartsLink (mainly for data classification) were synthesised to give an integral solution for contextual knowledge management.

After one year of development and deployment, the effect was tangible. The knowledge either from the cooperation with external partner or from self research and development was accumulated and consolidated through systematic method and IT system, and has been continuously improving afterwards.

Figure 7 demonstrates a user interface of contextual knowledge management based on WBS. The top and left frame shows work breakdown of engine design, including the stages and main steps; the right top frame provides the detail tasks/activities that needed for piston and connecting rod design, which comes from process steps library; and the right bottom shows the detail instructions on how to complete the design activity, which also contains link engines to benchmark library and output templates which are both based on PartsLink.

Figure 8 demonstrates a user interface of contextual knowledge management based on workflow. The right top shows a workflow that built upon Windchill workflow manager; the main interface shows the details of a workflow task/activity, which contains the instructions, inputs which may be the outputs of former task/activity, reference information such as guideline manuals and deliverables that should be output. Reference information can link to any knowledge aspects that are helpful for completion of this task/activity.

Figure 7 Example of WBS-based C-A-B model (see online version for colours)

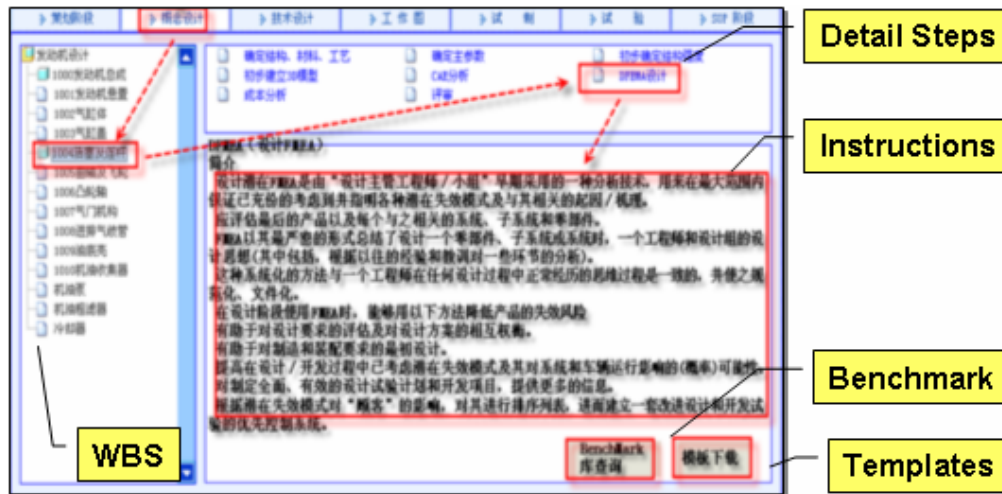


Figure 8 Example of workflow-based C-A-B model (see online version for colours)



5 Conclusion and future work

Differentiated from original literature or research which is focused on attributes definition of context of product development knowledge, in this paper a multi-level contextual knowledge management model, named C-A-B model, for product development based on WBS and workflow and its related system architecture was promoted and discussed. This model takes knowledge aspects as a linkage to pass product development

context information to knowledge bases to retrieval of related contextual knowledge to designers, which results in less search time and higher productivity to complete a product development activity.

C-A-B model combines project management, data management and knowledge management, which is a beneficial extension of PLM implementation and can bring more value to the clients by adoption of PLM.

There is a limitation to introduce contextual knowledge management based on WBS and workflow. Due to its standard and inflexible product development style, it may prevent enterprise innovations to some degree. Therefore, a mechanism of innovation should also be established along with the deployment of C-A-B model and the system based on it.

The further research may focus on the automation and intelligence of knowledge aspects extraction and knowledge acquisition engine. Tacit knowledge mining and definition is another area that is worthy of investigation.

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A hybrid decision support system for slow moving spare parts joint replenishment: a case study in a nuclear power plant

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Abstract: This paper presents a hybrid Decision Support System (DSS) for slow moving spare parts joint replenishment in a nuclear power plant. In this study, we integrate the fuzzy and grey theory-based spare parts criticality class evaluation model to confirm the target service level, and the web-based joint replenishment DSS to obtain reasonable purchase parameters that can be helpful for reducing total inventory holding costs. The proposed DSS was successful in decreasing inventories holding costs significantly by modifying the unreasonable purchase applications while maintaining the predefined target service level.

Keywords: spare part; criticality class; fuzzy; grey; joint replenishment; hybrid decision support system.

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1 Introduction

Increased efficiency of production plants requires the minimisation of machines downtime. Inventory control of Spare Parts (SPs) plays an increasingly important role in modern operations management. The trade-off is clear: on one hand a large number of spare parts ties up a large amount of capital, while on the other hand too little inventory inevitably results in poor supply service level or extremely costly emergency actions (Aronis et al., 2004). There are about 5000 SPs that are vital for safe production in one of the most successful nuclear power plants in China that was constructed based on the technology from France. About 50% of them are non-standard slow moving SPs and purchased from France with a lead-time ranging from

10 to 25 weeks. The company is obliged to carry inventories consisting of over 45 millions dollars of SPs to meet the need of maintenance.

Generally speaking, the usage amount of a slow moving SP is no more than 12 every year and the prediction is very hard. The inventory management policy of these SPs in this plant is holding plenty of inventories to meet the demand of safe operation at the peak load. After several years, inventory management policy can be optimised on the base of the statistics data and detail analysis to inventory history activities. So, maintenance engineers on the base of their experience, which was not analysed scientifically, decided the variety and amount of SPs. Inevitably, this led to relatively high inventory cost at the same time, the potential inventory-out cost had been found to increase

rapidly because there were more low-price SPs and fewer high-price SPs than necessary. Therefore, the way to identify the reasonable amount of SPs became one of the key problems in inventory management.

The criticality of an item is a very important factor associated with the service level that is defined as the probability of no shortage per replenishment from shelf. Then, we can identify the optimal control parameters according to all kinds of constraint condition. Therefore, identifying criticality class for a new SP in an accurate and efficient way becomes a challenge for inventory management. The best way to manage an inventory is through the development of better technique for identifying the criticality class of a SP, which can also be regarded as a classification problem, and management inventories from the point of view of their necessity in production and maintenance operation. Moreover, it is a fact that most of them are purchased from the same suppliers and fixed purchase cost is rather high. In that case, joint replenishment may allow use of 'group' discount and share the same facility or reduce cost associated with purchase. The joint replenishment problem involves determining a replenishment policy that minimises the total cost of replenishing multiple items from a single supplier (Silver, 1974). But this decision procedure is rather complex. However, Decision Support System (DSS) which has the capability of easy storage and retrieval of the required information would be a powerful tool to support decision-makers in making strategic decisions (Xie et al., 2005). So, there is a need to design and develop a DSS to assist managers to control inventory costs effectively while achieve the required service level.

There are many papers about SPs inventory control (Kennedy and Patterson, 2002; Kalchschmidt et al., 2003; Kukreja and Schmidt, 2005). However, there is currently no integrated DSS that combines the fuzzy and grey theory-based classification model and web-based decision implementation to joint replenishment decision-making. We, therefore, propose an integrated framework that can implement the identifying of criticality class that will be used to specify the target service level and present optimal inventory purchase advices. Our approach is as follows: first, the SPs Criticality Class Evaluation System (SPCCES) provides the evaluation results of criticality class. Second, the web-based joint replenishment DSS (WJRDSS) is developed to provide some joint replenishment suggestions. Moreover, the integrated Spare Parts Joint Replenishment DSS (SPJRDSS) is designed to provide managers with daily purchase suggestions. The remainder of this research is organised as follows. The model for identifying the criticality class of SPs is put forward in Section 2. Section 3 discusses the model for joint replenishment. In Section 4, we show the implementations of the SPJRDSS. Finally, some conclusions are given.

2 The SPs criticality class evaluation methodology

2.1 Reviews on evaluating of the criticality class

Factors such as costs of spares, availability, storage considerations, probability of requirement of a SP, machine downtime costs, etc. are generally considered while managing

SPs inventories. Many analytical models of different inventory control systems have been discussed. However, there is no evidence that any of the works have attempted to raise the question of evaluating the criticality of SPs using systematic and well-structured procedures (Braglia et al., 2004). Moreover, the various models described in the literature feature many assumptions that remain violated in real life. Simple and straightforward procedures such as ABC analysis and Analytic Hierarchy Process (AHP) analysis have been widely used in practice for confirming the criticality class of the SPs (Gajpal et al., 1994). But the indices considered, named lead time, type of spare and stock out implication, are so simple that they may give inaccurate results. An artificial neural networks approach was used to evaluate the criticality class of SPs (Wang et al., 2006), but the prediction accuracy should be improved.

A better way to manage an inventory is through the development of better technique for identifying the criticality class of a SP and management inventories from the point of view of their necessity in maintenance operation. However, the criticality of SPs needs to be evaluated and this is a difficult task which is often accomplished using subjective judgments. It has been found that no systematic procedure exists for classifying SPs as I, II, III and IV. Therefore, identifying criticality class for a new SP in an accurate and efficient way becomes a challenge for inventory management.

2.2 Confirm the evaluation index set

This study uses the modified Delphi technique to confirm the index set for criticality class evaluation. Delphi integrates the judgment of a number of experts who cannot come together physically, but also facilitates feedback, debate and comment. The overall objective of this technique is to achieve consensus among a diverse group of participants. For the success of such a study, it is critical to secure the participation of the right kinds of experts, who understand the issues, have a vision, and represent a substantial variety of viewpoints. The expert selection criteria are: active career in related business for at least ten years with rich experiences of production management and equipments maintenance; a global vision beyond local and temporary concerns; and accessibility and willingness to engage in intellectual dialogue.

By using group-discussing and anonymous questionnaire methods at the same time, necessary information is gathered and the 35 experts' ideas are analysed. According to the principle of rationality and maneuverability, we select the following factors. These factors can express the inherent relation among all the indexes that affect the criticality class of a SP.

- 1 *The specificity of a SP (P_1)*. Among the wide spectrum of spare parts are typically both standard parts, which are widely used by many users, and a certain amount of parts specifically tailored for and used by a particular user only. For standard parts the availability is usually good, there are stocks of these parts at different levels of the supply chain, and the suppliers are willing to cooperate with the users. For the user-specific parts: suppliers are unwilling to stock the special, low volume parts and the responsibility of availability and control remains with the user himself.

- 2 *Predictability of demand (P_2)*. It is useful to divide the parts in terms of predictability into at least two categories: parts with random failures and parts with a predictable wearing pattern. The predictability of demand has an effect on the choice of the control principle between provisioning and time-phased maintenance. The possibilities to estimate failure patterns and rates by statistical data have some thing to do the difficulty to manage spare part.
- 3 *Status of availability of the production facility (P_3)*. When an original part fails and a SP is required, status are as follows: alternative production facility available; alternative production facility available if suitable modifications are made in machine or process and no alternative production facility available. So, a SP may have different criticality.
- 4 *The functional necessity of facility in the production (P_4)*. Different facilities may have distinct function. Some may be auxiliary while other may be vital to production. A SP is more crucial when it is pivotal to production or safety problem.
- 5 *Lead-time of procurement (P_5)*. The difficulty to obtain a spare part is related to lead-time of procurement. Obviously, it is difficult to obtain a SP quickly when the lead-time is long. According to specialists' experiences, the score can be given as follows: 1~3 while lead-time is less than 12 weeks, 4~6 while lead-time is varying from 12~24 weeks and 6~10 while lead-time is more than 24 weeks.
- 6 *Reparability character (P_6)*. If a SP cannot be repaired or the time for repair is so long for enterprise, the difficulty to manage a SP is high.
- 7 *The stage of lifecycle (P_7)*. If a SP is in its initial or decay stage, the difficulty to obtain a SP in a short time will become higher. It is not reasonable to hold too many spare parts when a certain part is in its initial stage because of uncertainty. However, we must hold a few more spare parts when a certain part is in its decay stage because of the possibility to be unable to obtain this part.
- 8 *Supply market (P_8)*. When a SP is always readily available from several suppliers, the difficulty to manage the SPs is low.

From what has been discussed above, we can identify index set $P = \{P_1, P_2, \dots, P_n\}$.

2.3 The evaluation method

It is a fact that criticality class evaluation is relatively difficult to most companies, and only limited information is available. The application of fuzzy and grey theory to criticality class analysis seems appropriate, as such analysis is highly subjective and related to inexact and grey information.

Fuzzy sets and possibility theories were introduced by Zadeh in 1965 as an extension of the set theory by the

replacement of the characteristic function of a set by a membership function whose values range from 0 to 1. It is now a wide field of study that has seen the development of different tools over the last ten years. Fuzzy mathematics pays more attention to objects that intension clear while extension vague. It depicts fuzzy phenomenon abstractly with mathematics ways and provides an effective bridge between classic mathematic and realistic fuzzy world.

Grey theory was developed (Deng, 1987) based upon the concept that information is sometimes incomplete or unknown. The intent is the same as with factor analysis, cluster analysis, and discriminant analysis, except that those methods often do not work well when sample size is small and sample distribution is unknown (Hsu and Wen, 2000). Grey theory pays more attention to objects that intension vague while extensions clear. It adopts the way to provide a supplement to the small sample data and have important practical value while the sample cannot meet the requirement of statistic. In the following model, we will use different theory to learn from fuzzy theory's advantage to offset grey theory's weakness. So, the evaluation result will be more reasonable. The meta-synthesis method will be discussed as follows.

Step 1: Confirm the weight of each index:

The weight of each index can be confirmed by many ways, such as entropy value, DELPHI and AHP. The AHP allows for inconsistency because in making judgments people are more likely to be cardinally inconsistent than cardinally consistent (Byun, 2001). At the same time, the AHP also uses a principle of hierarchic composition to derive composite priorities of alternatives with respect to multiple criteria from their priorities with respect to each criterion. In fact, AHP is an effective multi-criteria decision-making tool to find out the relative priorities to be assigned to different criteria and alternatives which characterise a decision. We can identify the weight of each index using AHP, i.e. $W = \{w_1, w_2, \dots, w_n\}$.

Step 2: Confirm the sample matrix:

Though a certain index may be quantitative, it is also difficult to judge its effect on the criticality of a SP directly. So, we can give a score (1–10) to evaluate the criticality class of a SP according to the practical condition for every index. The score should be given for every index according to the difficulty to obtain a SP or the analysis of its influence to production when a SP is unavailable. Subsequently, we will evaluate the criticality of a part based on those scores. Supposing the number of experts is r , so $E = \{E_1, E_2, \dots, E_r\}$. Assuming the value of index i that given by expert k is d_{ki} , then the sample matrix for all the experts can be expressed as following:

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1n} \\ d_{21} & d_{22} & \dots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{r1} & d_{r2} & \dots & d_{rn} \end{bmatrix}$$

Step 3: Confirm the evaluation class:

According to scientific estimate theory and the advice of the specialists, we confirm the criticality class of SPs as m . So, the comprehensive evaluate standard matrix is: $V = \{V_1, V_2, \dots, V_m\}$.

In this study, the criticality classes are divided into I, II, III and IV according to the advices of experts in order to deal with this problem easier where satisfying the necessary managerial requirement.

Step 4: Confirm the evaluation grey number:

- 1 Upper end level, grey number $\otimes \in [0, \infty]$, the corresponding Whitening Function (WF) is:

$$f_1(d_{ki}) = \begin{cases} d_{ki} / d_1 & d_{ki} \in [0, d_1] \\ 1 & d_{ki} \in [d_1, \infty] \\ 0 & d_{ki} \in (-\infty, 0) \end{cases} \quad (1)$$

- 2 Middle level, grey number $\otimes \in [0, d_1, 2d_1]$, the corresponding WF is:

$$f_2(d_{ki}) = \begin{cases} d_{ki} / d_1 & d_{ki} \in [0, d_1] \\ 2 - d_{ki} / d_1 & d_{ki} \in [d_1, 2d_1] \\ 0 & d_{ki} \notin (0, 2d_1] \end{cases} \quad (2)$$

- 3 Low end level, grey number $\otimes \in (0, d_1, d_2)$, the corresponding WF is:

$$f_3(d_{ki}) = \begin{cases} 1 & d_{ki} \in [0, d_1] \\ \frac{d_2 - d_{ki}}{d_2 - d_1} & d_{ki} \in [d_1, d_2] \\ 0 & d_{ki} \notin (0, d_2] \end{cases} \quad (3)$$

Step 5: Calculate grey statistics:

We can obtain $f_j(d_{ki})$ which represents the degree of d_{ki} belongs to index j ($j = 1, 2, \dots, m$) by grey theory, then n_{ij} and n_i can be calculated by equation (4) and equation (5).

$$n_{ij} = \sum_{k=1}^r f_j(d_{ki}) \quad (4)$$

$$n_i = \sum_{j=1}^m n_{ij} \quad (5)$$

Step 6: Calculate grey evaluation value and fuzzy matrix:

Then, r_{ij} can be calculated by formula $r_{ij} = n_{ij} / n_i$, thus:

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \quad (6)$$

Step 7: Calculate fuzzy comprehensive matrix:

$$B = (w_1, w_2, \dots, w_n) \cdot \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \quad (7)$$

Step 8: Calculate the result of evaluation:

Firstly, we should confirm the score of criticality class for a SP: $C = (V_1, V_2, \dots, V_m)^T$. Thus, Z can be obtained by formula $Z = (W \cdot R) \cdot C$, that is the result of criticality class evaluation.

2.4 Result analysis

In order to study the effectiveness of the proposed model, we must test the evaluation accuracy by reference to expert judgement. The test for the criticality class evaluation of 1600 SPs at a nuclear power plant shows the accuracy is about 98.2%. That is to say, the criticality classes of 90 items are confirmed according to expert judgement instead of the results of the proposed model. Some errors may be inevitably and have a negative impact on replenishment decision-making. So, it is necessary to check the classification result before using them.

3 Spare parts joint replenishment model

3.1 Method and algorithm

Generally speaking, these models can be divided into two parts. The first part deals with deterministic joint replenishment problem while the second part deals with stochastic joint replenishment problem. There are many papers that have discussed deterministic joint replenishment problem (Silver, 1976; Kaspi and Rosenblatt, 1991; Olsen, 2005), but the assumptions of those models are so rigorous that they cannot be used widely. Recognising the probabilistic nature of demand, Balintfy (1964) was the first to advocate the use of (s, C, S) policy. However, he did not propose a practical means of specifying the values of the control variables. Related papers include Chan et al. (2004) and Li (2004). In this paper, we will discuss the application of a practical model for joint replenishment based on the work of Silver (1976).

To be more explicit, we assume that there is a fixed cost associated with each replenishment, as well as a variable cost associated with each item involved in the replenishment. Related assumptions are as follows: (1) We pay attention to the case of Poisson demand. Of course, each item can have a different demand rate; (2) The replenishment lead-time is of constant length; (3) The entire cost is assigned to the item that triggers the replenishment; (4) Inventory cost is proportional to the average inventory level; (5) For each item, service level is defined as the probability of no shortage per replenishment from shelf.

In order to introduce this decision procedure, the following notations are defined:

λ_i , Poisson demand rate for item i , in pieces/yr;

L_i , lead-time for item i ;

Q_i , the economic order quantity of item i ;

P , target service level;

h_i , inventory holding cost per item per year;

r_i , price of item i ;

k_1 , fixed cost per replenishment;

k_{2i} , cost per item involved in replenishment for item i ;

S_i , order-up-to-level of item i ;

C_i , can-order point of item i ;

s_i , must-order point of item i ;

\bar{I}_i , average on hand inventory level of item i ;

n , number of items in the family under consideration;

$p_{p0\leq}(x_0/z)$, probability that a Poisson variable with parameter z takes on a value less than or equal to x_0 .

NT_i , expected number of replenishment triggered by item i per year;

EC_i , expected related costs per unit time for item i .

(1) *Independent control policy* (s, S)

$$\min EC_i = \frac{S_i - s_i + 1}{2} + (s_i - \lambda_i L_i) h_i r_i + \frac{(k_1 + k_{2i}) \lambda_i}{S_i - s_i} \quad (8)$$

Subject to

$$\frac{1}{-s_i} \sum_{x_0=s_i+1}^{\infty} (x_0 - s_i) p_{p0\leq}(x_0 | \lambda_i L_i) \geq p \quad (9)$$

Strictly speaking, the pair (S_i, s_i) which minimise equation (8) while satisfying equation (9) should be found. A simple approach we first select the order quantity which minimise EC_i , ignoring the constraint [equation (9)]. Then, given this value of $S_i - s_i$, the constraint is used to find the lowest value for s_i , the first step leads to the usual economic order quantity expression

$$Q_i^* = S_i - s_i = \sqrt{2(K_1 + k_{2i}) \lambda_i / h_i r_i} \quad (10)$$

In general this will not be an integer. Therefore, we test the two integer values Q_i of around Q_i^* , the one giving the lowest value of EC_i in equation (8) is the one to use.

Then, the lowest s_i which satisfies the following inequality should be used.

$$\lambda_i L_i - s_i - \lambda_i L_i p_{p0\leq}(s_i - 1 | \lambda_i L_i) + s_i p_{p0\leq}(s_i | \lambda_i L_i) \leq Q_i (1 - P) \quad (11)$$

(2) *Joint replenishment policy* (s, C, S)

The total expected relevant costs per year of the group of items are given by

$$EC_i = \bar{I}_i h_i r_i + NT_i K_1 + NT_i K_{2i} \quad (12)$$

$$EC = \sum_{i=1}^n (\bar{I}_i h_i r_i + NT_i K_1 + NT_i K_{2i}) \quad (13)$$

$$\mu_i = \sum_{j \neq i} NT_j \quad (i \neq j, j = 1, 2, \dots, n) \quad (14)$$

where μ_i is the expected number of orders triggered per year by all other items in a group.

And

$$\beta_i = NT_i / (NT_i + \mu_i) \quad (15)$$

The total expected relevant costs per year for item i are given by

$$EC_i = \{S_i - C_i + \beta_i (1 - \beta_i^{C_i}) / (1 - \beta_i)\}^{-1} \{ (S_i - C_i)(S_i + C_i + 1) h_i r_i / 2 + \beta_i [C_i - \beta_i (1 - \beta_i^{C_i})] h_i r_i / (1 - \beta_i) + \lambda_i \beta_i^{C_i} K_1 + \lambda_i K_{2i} \} \quad (16)$$

The total expected costs per year of the group of items are given by $TEC = \sum EC_i$.

The algorithm to find the s_i , C_i and S_i is as follows:

Step 1: initiation ($i, j = 1, 2, \dots, n$)

$$C_i^{(1)} = 0, Q_i = S_i^{(1)} = \sqrt{2(K_1 + K_{2i}) \lambda_i h_i r_i};$$

$$NT_i = \lambda_i / Q_i, \mu_i(k) = \sum_{i \neq j} NT_j; \beta_i(k) = NT_i / (NT_i + \mu_i).$$

Step 2: for C_i , select the small S_i to make EC_i become minimum

$$\hat{S}_i(C_i) = C_i - \frac{\beta_i (1 - \beta_i^{C_i})}{(1 - \beta_i)} + \sqrt{\frac{2 \lambda_i (K_{2i} + K_1 \beta_i^{C_i}) + 2 C_i \beta_i^{C_i+1}}{h_i r_i} + \frac{2 C_i \beta_i^{C_i+1}}{(1 - \beta_i)} \frac{\beta_i (1 - \beta_i^{C_i}) (1 + \beta_i^{C_i+1})}{(1 - \beta_i)^2}} \quad (17)$$

Then,

$$\hat{E}C_i = h_i r_i [\hat{S}_i(C_i) + 0.5]$$

If

$$\left[\frac{2 \lambda_i}{h_i r_i} (K_{2i} + K_1 \beta_i^{C_i}) + 2 C_i \beta_i^{C_i+1} / (1 - \beta_i) - \frac{\beta_i (1 - \beta_i^{C_i}) (1 + \beta_i^{C_i+1})}{(1 - \beta_i)^2} \right] < 0$$

then $\hat{S}_i(C_i) = C_i$,

$$EC_i = \left\{ \beta_i \frac{1 - \beta_i^{C_i}}{1 - \beta_i} \right\}^{-1} \left\{ \beta_i [C_i - \beta_i (1 - \beta_i^{C_i})] \frac{h_i r_i}{(1 - \beta_i)} + \lambda_i \beta_i^{C_i} K_1 + \lambda_i K_{2i} \right\}.$$

Step 3: vary C_i from $C_i^{(1)}$ to $s_i^{(1)}$, and calculate corresponding S_i^* . Select the integer S_i that around S_i^* giving the lowest value of EC_i .

Step 4: Repeat steps 1–3 until all of S_i and C_i ($i=1, 2, \dots, n$) are gained.

Step 5: Compute NT_i

$$NT_i = \frac{\lambda_i \beta_i^{C_i}}{S_i - C_i + \beta_i(1 - \beta_i^{C_i}) / (1 - \beta_i)} \quad (18)$$

where β_i , S_i and C_i can be gained from Step 1 to Step 4.

Step 6: If S_i and C_i remain the same during the next two iterative procedures, we terminate and the current values of S_i and C_i are the appropriate once to use. Otherwise, we compare current value of EC_i with its value on last iteration. If a decrease of less than 0.01% has occurred, we terminate. If not, we set $k = k + 1$ and return to the start of Step 2.

Step 7: Identify s_i by service level constraint, select the smallest s_i such that:

$$\left[\frac{1}{\beta_i^{C_i}} p_{p0 \leq} (s_i + C_i | \lambda_i L) - p_{p0 \leq} (s_i + 1 | \lambda_i L) - \beta_i^{s_i+1} \sum_{x_0=s_i+2}^{s_i+C_i} p_{p0} (x_0 | \lambda_i L) / \beta_i^{x_0} \right] \geq \frac{P}{\beta_i^{C_i}} \quad (19)$$

where $S_i^* = S_i + s_i$, $C_i^* = C_i + s_i$.

Then S_i^*, C_i^*, s_i are the appropriate decision parameters to use.

3.2 Numerical examples

Consider the following example involving four items:

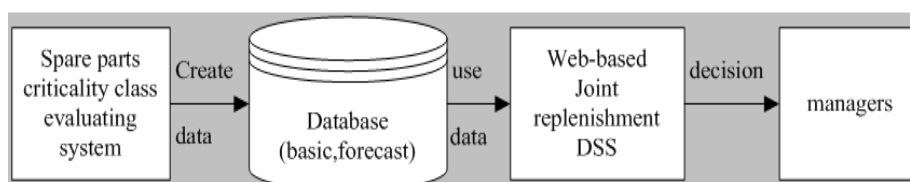
Item	λ_i	r_i	L_i	k_{2i}
i	pieces/yr	\$/yr	yr	\$
1	3.5	36.7	0.7	50
2	9.5	12	0.7	50
3	5.4	82	0.7	50
4	12.2	20.3	0.7	50

where $k_1 = 200$ and the corresponding control parameters and results of different control policy are given in Table 1.

Table 1 Results of independent control and joint replenishment

No	Q_i^*	Q_i	s_i	EC_i	s_i	C_i	S_i	EC_i
	$P = 0.95$				$P = 0.95$			
1	15.4	15	5	135.77	4	10	17	111.39
2	44.5	44	11	118.42	10	26	47	97.21
3	12.8	13	7	271.45	7	13	19	256.71
4	38.8	39	14	181.57	12	28	46	154.59
Σ	707.21				619.90 (-12.34%)			

Figure 3 The general integrated framework



In the following, we will discuss the sensitivity analysis for the related changes of decision factors.

- 1 When $k_1 + k_2 = 250$, the influence of the changes of k_1/k_2 on the saving of Total Costs (TC) are shown by Figure 1.
- 2 When $k_1=200$ and $k_2=50$, the influence of the changes of P on the saving of TC are shown by Figure 2.

Figure 1 The influence of the changes of k_1/k_2 on the saving of TC (see online version for colours)

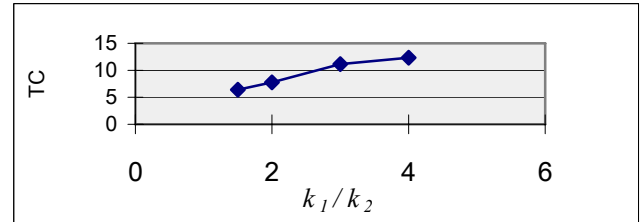
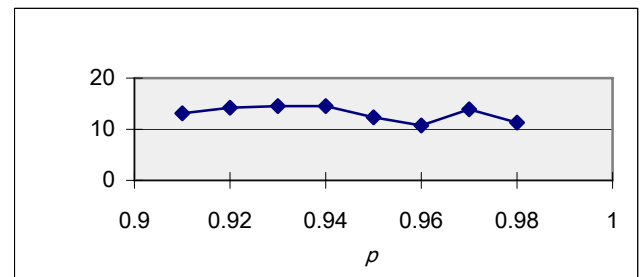


Figure 2 The influence of the changes of p on the saving of TC (see online version for colours)



In summary, the following statements can be made. (1) The total costs saving of joint replenishment increase as k_1/k_2 increase, certainly intuitively appealing; (2) The total costs saving of joint replenishment are quite insensitive to the changes of the service level P .

4 System development methodology

4.1 The general integrated framework

The integrated framework of SPJRDSS proposed will be developed to support decision-making in SP inventory control with the use of the criticality class evaluating results and other constraint conditions. Based on this framework, we develop an SPJRDSS that can be used by many companies. SPJRDSS consists of two subsystems: one is SPCCES, which is the off-line forecasting unit; the other is WJRDSS, which is the daily on-line decision unit. The former can provide classification data for the latter. The general framework is shown in Figure 3.

4.2 User interface

The design of the user interface is a key element in DSS functionality. The DSS interface should provide easy communication between the user and the system. Web browser serves as the user interface component of the DSS, which make the technology easy to understand and use. According to the

previous WJRDSS architecture, we develop corresponding system using the browser/server mode, which contains a three-tier structure. WJRDSS partial user interfaces are shown in Figure 4. In the interface, the corresponding optimal purchasing strategies will be generated by the WJRDSS that can be used as an individual system.

Figure 4 WJRDSS partial user interface

Spare Parts Joint Replenishment Decision-Making		
Number of items for joint replenishment | 2		
	Item1	Item2
Lead Time(weeks)	| 37	| 23
Holding cost per item per year(%)	| 20	| 20
Price(\$)	| 153	|
Number of usage per year	|	|
Fixed cost per perplishment	|	|
Cost per item involed in replenishment	|	|

| Start Computering

4.3 Build the prototype system

Based on the general framework and the description of two subsystems, we construct an SPJRDSS for users' convenience. The formation of SPJRDSS is the integration of the SPCCES and WJRDSS. The integration process is that the SPCCES is embedded into the WJRDSS. The SPCCES is developed by Powerbuilder8.0 and adopts the client/server mode here. The advantage of this mode is that the server's function can be exerted as it can in terms of either program execution efficiency or program interaction. In SPCCES, the input data are transformed into appropriate input vectors by corresponding rules and heuristic algorithms. Empirical results reveal that the classification result is relatively accurate and acceptable. In order to translate those results into corresponding joint purchasing advice, the WJRDSS is constructed. In the same way, the SPCCES is considered to be an embedded system and has been a part of WJRDSS. Based on some models and knowledge bases and databases, we develop WJRDSS with a three-tier structure using the popular browser/server mode. The advantage of this mode lies in easy operating and easy maintenance. Moreover, programmes can be revised remotely in the client site with authorised access.

Based on SPCCES and WJRDSS, the SPJRDSS is generated naturally in order to overcome the drawbacks of the two subsystems. SPCCES is seen as an embedded system and has already been combined with WJRDSS in the integrated system. When entering the WJRDSS, we can click the 'SPCCES' button; then the SPCCES will run in the server site, and meanwhile the results obtained will be transmitted into the corresponding database of the database server. Figure 5 shows an SPJRDSS interface when we query the joint replenishment suggestions. [Asl: actual service level by simulation; Tsl: target service level; Total costs saving: (s, C, S) model vs. traditional (s, S) inventory model.]

By implementation of SPJRDSS and practical application in LA Nuclear Power Plant in China, we find that the DSS is integrated, user-oriented; their purchase decision suggestions are reliable by practical testing. It can help inventory managers to make scientific decisions by adopting the joint replenishment advices provided by SPJRDSS. Compared with the total inventory holding costs in 2006, about 4.6% was saved by cutting out unnecessary purchase applications and modification the incorrect plan in 2005 while maintaining the target service level.

Figure 5 The implementation of SPJRDSS (see online version for colours)

Integrated Spare Parts Joint Replenishment Decision Support System

[Chinese](#) [Data management](#) [Purchase suggestions](#) [Vendor Information](#) [Logistics service](#) [Link](#)

[ISPJPDSS](#)>>Suggestions for joint replenishment items

		Suggestion							
		StockNo	s	C	S	ASL (%)	TSL(%)	EC	Total costs saving(%)	Vendor
4 items	MRM10481	4	10	17	95.23	95.00	1113.9	-12.34	NCD0401
	MSM10499	10	26	47	95.34	95.00	972.1		NCD0312
	MSM10512	7	13	19	95.12	95.00	2567.1		MST0102
	MRM10544	12	28	46	95.02	95.00	1545.9		MST0412

[More data please click.....](#)

5 Conclusions

This study briefly introduces an integrated framework for SPs joint replenishment decision and implementation of the framework. Based on the proposed framework, we construct an integrated SPs joint replenishment DSS that can improve the overall performance of forecasting and decision process for inventory managers. The use of the criticality class evaluation model can be a persuasive analytical tool in deciding whether the criticality of a SP should be classified as a category I, II, III or IV. At the same time, a numeric illustration shows its effectiveness and feasibility. In the future, we plan to make more progress in establishing more practical inventory models to improve the decision support ability of SPJRDSS.

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Appendix A Numerical example for criticality class evaluation

The criticality class of a widely-used bearing used in a power plant must be evaluated before the confirmation of its inventory level. The criticality is utilised to estimate an appropriate amount of this SP for the initial provisioning so that the optimal maintenance plan can be achieved. Relative data associated with the evaluation are as follows:

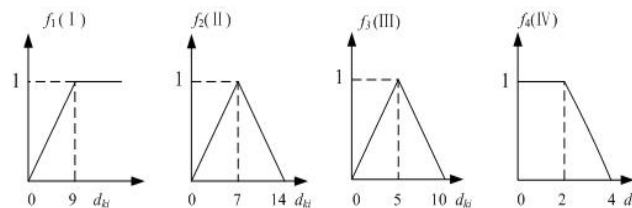
$$W = \{0.133, 0.141, 0.131, 0.119, 0.121, 0.133, 0.115, 0.107\};$$

Sample matrix:

$$D = \begin{bmatrix} 6 & 7 & 8 & 6 & 7 & 7 & 7 & 6 \\ 7 & 8 & 6 & 7 & 8 & 6 & 7 & 7 \\ 7 & 7 & 8 & 7 & 7 & 7 & 6 & 5 \\ 8 & 6 & 8 & 8 & 9 & 8 & 5 & 6 \\ 8 & 7 & 8 & 6 & 7 & 7 & 7 & 5 \\ 7 & 8 & 9 & 7 & 8 & 5 & 6 & 5 \\ 6 & 7 & 9 & 7 & 6 & 8 & 8 & 6 \\ 7 & 7 & 8 & 6 & 7 & 8 & 7 & 6 \\ 8 & 6 & 7 & 6 & 6 & 6 & 7 & 7 \\ 7 & 8 & 9 & 7 & 8 & 7 & 6 & 7 \end{bmatrix}$$

According to the specialists' advices, we divide the criticality class into four class: I, II, III and IV and confirm corresponding $V = \{9, 7, 5, 2\}$. The second step is to identify corresponding grey number and white functions as Figure A1.

Figure A1 Four white weight functions



Thus, n_i and r_{ij} ($i=1, 2, \dots, 8; j=1, 2, \dots, 4$) can be calculated step by step, and R can be obtained.

$$R = \begin{bmatrix} 0.3434 & 0.4042 & 0.2525 & 0 \\ 0.3434 & 0.4042 & 0.2525 & 0 \\ 0.4189 & 0.3913 & 0.1889 & 0 \\ 0.3191 & 0.3980 & 0.2829 & 0 \\ 0.3603 & 0.3998 & 0.2399 & 0 \\ 0.3353 & 0.3926 & 0.2711 & 0 \\ 0.3153 & 0.3928 & 0.2921 & 0 \\ 0.2869 & 0.3689 & 0.3443 & 0 \end{bmatrix}$$

Then, we can obtain $B = (0.3552, 0.3977, 0.2471, 0)$ and $Z = B \cdot C = 7.216$. So, the criticality class of this SP can be regarded as the 'II' class.

R&D partnership contract coordination of information goods supply chain in government subsidy

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Abstract: Information goods supply chain partnership is the contract relationship of co-opetition (Brandenburger and Nalebuf, 1996) innovation in nature. The main findings are as following: in the threat of strategic substituting from industrial competitor of information goods, the government subsidy policy for information goods supply chain makes up the lack of incentives to original innovation due to innovation externalities, improves information goods supply chain partners' incentives to cooperative innovation, reduces industrial competitor's incentives to imitative innovation, and makes supply chain system profit of information goods and social welfare improvement in the incentive policy of government subsidies. The perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the strengthening of the innovation basis and the extent to which partners absorb and transform technological innovation knowledge, and the improvement of intellectual property protection environment and the degree of intellectual property protection.

Keywords: information goods; information goods supply chain; cooperative innovation; government subsidy; non-linear transfer payment contract; perfect sharing contract.

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1 Introduction

While the rapid development of internet and information technology has pushed the human economy and society into the network economy era, the dependence on economic resources has been transformed from the enormous depletion of natural resources to the valid exploitation and utilisation of information resources. As the specifics of network economy, information goods with essential input factors on the contribution of information resources can be in intangible digital form, which are produced, distributed and consumed with zero gravity in the virtual world. And they have been profoundly changing the way of production, trade, living and study of human society. Meanwhile, the inherent characteristics of information goods market caused by network economy embedded with winner-take-all, technology innovation competition and creative destruction (Wang and Ji, 2008), endow the consumers of information goods with the unprecedented options. The base of competitive advantage for the information goods firms has been beyond the capability and resources of single company, and the competition among companies has extended to the competition among supply chains. Cooperation is the core of supply chain management. The information goods supply chain partners will create more cooperative innovation surplus and relational rents beyond the single company and get the Parato optimal and improvement of information goods supply chain, which is essential incentive to establish information goods supply chain partnership.

Information goods supply chain partnership is the contract relationship of co-opetitive (Brandenburger and Nalebuf, 1996) innovation in nature. The information goods market with natural monopoly is essentially different from traditional physical goods market. Above all, the monopoly status of information goods market derives mainly from technology innovation competition rather than monopoly behaviour. The life-cycle curve of information goods is much sharper with exponential changing trend. In general, the life-cycle curve of physical goods can be divided into four stages consisting of introduction, growth, maturity, saturation. Whereas the life-cycle curve of information goods is approximately linear with fuzzy boundary among the four stages (Wang and Ji, 2008). Simultaneously, in comparison with the traditional physical goods, there are distinguished economic uniqueness of information goods emerging in production, consumption and distribution, ranging from the high-investment and high-uncertainty of the first unit in production, the culture consumption behaviour in essence and non-rivalrous consumption, and asymmetry of value and ownership transfer in distribution, which determine that the spillover effect in cooperative innovation and the strategic substituting effect among the information goods industrial competitors will lead to cooperative innovation competence weakened and even lost.

And then it will lead to harassment, maladjustment and even destruction of cooperation. Based on the government subsidy, this paper aims to study the R&D partnership coordinated contract of information goods supply chain.

From the economics of welfare, Pigou (1999) proposes the government, as a natural-born representative of public benefits, can internalise externalities through taxation and subsidisation schemes. The government should impose taxation on the enterprises whose marginal private cost is less than social marginal cost, that is, the government should implement the taxation scheme in the case of external diseconomies. Whereas the government should give subsidisation to those enterprises whose marginal private benefit is less than social benefit, that is, the government should implement the scheme of subsidisation in the case of external economies. Basley and Suzumura (1992) establish comparative statics results for an oligopoly model with strategic commitment, taking an excise tax and subsidy as two shift factors to study the influence on short-run as well as long-run effects of outputs, cost-reducing R&D investment incentives and social welfares. Yi and Shin (2000) examine the endogenous formation of R&D coalitions with high spillovers among symmetric firms. They suggest that government subsidies to R&D consortia for basic research with high spillovers can improve social welfare by encouraging wider participation to a research consortium, that is, by alleviating free-rider problems in coalition formation. Lach (2002) finds evidence suggesting that the R&D subsidies granted by the Israel Ministry of Industry and Trade greatly stimulated company-financed R&D expenditures for small firms but had a negative effect on the R&D of large firms, although not statistically significant. One subsidised New Israeli Shekel (NIS) induces 11 additional NIS of own R&D for the small firms. However, because most subsidies go to the large firms a subsidy of one NIS generates, on average, a statistically insignificant 0.23 additional NIS of company-financed R&D. Huo et al. (2003) study the government's R&D subsidising policy to a monopolistic upstream firm in a two-tier supply chain. The upstream firm provides an input to the downstream firms, which engage in output competition on the market. Before producing the input, the upstream firm conducts cost-reducing R&D. The study shows that the R&D subsidy is related only to the number of downstream firms and is unrelated to other parameters, with a larger number of downstream firms requiring smaller subsidies. Laincz (2005) further studies how the R&D subsidies impact on market structure. In this paper, the government subsidy refers to the policy of government economic incentives in virtue of direct investment or taxation reduction on R&D innovation incentives. On the basis of Grossman's proposal on the proportional subsidisation (Eaton and Grossman, 1986), here defines the government subsidy rate to cooperative innovation of information goods supply chain partners as a decision variable of government subsidisation incentive policy.

After formalising the basic model and assumptions in Section 2, in the incentive policy of government subsidies, two incomplete contract coordinated mechanisms are established to impact on the information goods supply chain partners' incentives to cooperative innovation and respective optimal contract clauses are designed in Section 3 and Section 4, respectively. Section 5 discusses the comparisons of effective contract coordination in government subsidy. The study results show that: (a) in the threat of strategic substituting from industrial competitor of information goods, the government subsidy policy for information goods supply chain makes up the lack of incentives to original innovation due to innovation externalities, improves information goods supply chain partners' incentives to cooperative innovation, reduces industrial competitor's incentives to imitative innovation, and makes supply chain system profit of information goods and social welfare improve; (b) in the incentive policy of government subsidies, the perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the strengthening of the innovation basis and the extent to which partners' absorb and transform technological innovation knowledge; (c) the government subsidy-based perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the improvement of intellectual property protection environment and the degree of intellectual property protection.

2 Basic model and assumptions

In dual-oligopoly market environment, consider a two-tier supply chain of information goods consisting of two contracting partners, a downstream producer of information goods, denoted by D_1 , and only one upstream supplier of information resources, denoted by U. The information goods supply chain partnership, denoted by U- D_1 , is essential for the output of the original information goods in virtue of cooperative R&D for original innovation. The independent downstream firm, which means the downstream industrial competitor, denoted by D_2 , is essential for the output of the imitative information goods in virtue of imitative innovation via purchasing and reverse engineering.

Assume each firm is rational and risk neutral, whose eventual objective is to maximise profit. Due to linear life-cycle curve of information goods (Wang and Ji, 2008), following Bowley (1924), the inverse demand functions of final information goods for firms D_1 and D_2 are, respectively:

$$\begin{cases} p_{D_1} = a - (q_{D_1} + \theta q_{D_2}) \\ p_{D_2} = a - (\theta q_{D_1} + q_{D_2}) \end{cases} \quad (1)$$

where p_{D_1} and p_{D_2} are the oligopoly prices, q_{D_1} and q_{D_2} are the final information goods quantities of firms D_1 and D_2 , respectively. Let a be the reserve prices of firms D_1 and D_2 and $a > 0$. Let the product substitutability parameter, denoted by θ ($0 < \theta < 1$), represent the degree of innovation differentiation of the final information goods of firms D_1 and D_2 .¹

Based on d'Aspremont and Jacquemin (1988), let the R&D investment cost functions for firms D_1 and D_2 to get innovation rents (denoted by x_{D_i} , $i = 1, 2$) be $\frac{1}{2}\gamma_{D_i}x_{D_i}^2$, where γ_{D_i} are the parameters of R&D investment cost for firms D_1 and D_2 , and γ_{D_i} reflect the innovation basis of a firm such as information resource and knowledge stock, as well as the extent to which a firm absorbs and converts technological innovation knowledge. In this paper, for analytical convenience, considering the reserve prices of firms D_1 and D_2 depending on the valuations from final consumers, the final reserve price functions may be derived from the above the innovation rents x_{D_i} for firms D_1 and D_2 :

$$a_{D_i} = a + x_{D_i} \quad i = 1, 2 \quad (2)$$

Meanwhile, in the information goods supply chain partnership U- D_1 , if the upstream supplier U invests $\frac{1}{2}\gamma_U x_U^2$, the final reserve price of firm D_1 will be increase x_U . Here, γ_U is the parameter of R&D investment cost for firm U, which reflects the innovation basis of firm U (such as information resource and knowledge stock), as well as the extent to which firm U absorbs and converts technological innovation knowledge.

For further consideration of cooperative innovation with horizontal spillover effect, in the information goods supply chain partnership U- D_1 , the final reserve price function for firms D_1 can be shown as following:

$$a(x_{D_1}, x_U, \delta) = a + (x_{D_1} + x_U) - (\delta_{D_1} \cdot x_{D_1} + \delta_U \cdot x_U) \quad (3)$$

where δ_U ($0 \leq \delta_U \leq 1$) and δ_{D_1} ($0 \leq \delta_{D_1} \leq 1$) are the parameters of the horizontal spillover effect which represent the degree of R&D innovation rents x_U and x_{D_1} spillover, respectively.²

3 Non-linear transfer payment contract coordination in government subsidy

In the incentive policy of government subsidies, consider non-linear transfer payment contract coordination of U- D_1 under dual-oligopoly market environment, which can be analysed as a three-stage game problem:

- 1 In the first stage of the game, the upstream supplier formulates the non-linear transfer payment contract clauses;
- 2 In the second stage, the information goods supply chain partners simultaneously determine on their cooperative R&D investment for original innovation;
- 3 Finally, in the third stage, the downstream producer outputs the final information goods and completes in quantities in the dual-oligopoly market.

Without loss of generality, assume that each firm of information goods has zero marginal cost and variable cost is not considered. Meanwhile, for simplicity, assume the parameters of the horizontal spillover effect of U- D_1 are

symmetric, that is, $\delta_U = \delta_{D_1} = \delta$ $0 \leq \delta \leq 1$. And assume the government subsidies for cooperative innovation of U-D₁ are symmetric, that is, $s_U = s_{D_1} = s$ $0 < s < 1$.

In what follows, use sub-game perfection as the equilibrium concept and solve the above three-stage game problem by backward induction.

Firstly, analyse the equilibrium outputs of the downstream firms in the dual-oligopoly market in the third stage. Given the government subsidy rate, the cooperative R&D investment levels for original innovation of U-D₁ and the non-linear transfer payment clauses, the downstream producer D_1 determines $q_{D_1}^{(3)}$ to maximise its own profit:

$$\begin{aligned} \text{Max}_{q_{D_1}} \pi_{D_1} = & [a + (1-\delta) \cdot (x_{D_1} + x_U) \\ & - (q_{D_1} + q_{D_2})] q_{D_1} - (t \cdot q_{D_1} + T) - (1-s) \cdot \frac{1}{2} \gamma x_{D_1}^2 \end{aligned} \quad (4)$$

where t is the linear transfer payment parameter and T is the fixed transfer payment parameter. Simultaneously, the downstream industrial competitor D_2 determines $q_{D_2}^{(3)}$ to maximise its profit as well.

$$\text{Max}_{q_{D_2}} \pi_{D_2} = [a + x_{D_2} - (q_{D_1} + q_{D_2})] q_{D_2} - \frac{1}{2} \gamma x_{D_2}^2 \quad (5)$$

Solving the first-order and second-order conditions with respect to q_{D_1} and q_{D_2} of the above equations (4) and (5), we can obtain:

$$\begin{aligned} q_{D_1}^{(3)} &= \frac{a + 2[(1-\delta) \cdot (x_{D_1} + x_U) - t] - x_{D_2}}{3} \\ q_{D_2}^{(3)} &= \frac{a + 2x_{D_2} - [(1-\delta) \cdot (x_{D_1} + x_U) - t]}{3} \end{aligned}$$

Substituting the equilibrium outputs $q_{D_1}^{(3)}$ and $q_{D_2}^{(3)}$ into the equation (4), and then, in the second-stage, the profit maximisation problem for the downstream producer D_1 is rewritten as following:

$$\text{Max}_{x_{D_1}} \pi_{D_1} = \left\{ \frac{a + 2[(1-\delta) \cdot (x_{D_1} + x_U) - t] - x_{D_2}}{3} \right\}^2 - T - (1-s) \cdot \frac{1}{2} \gamma x_{D_1}^2 \quad (6a)$$

Also, the maximising profit of the downstream industrial competitor D_2 is expressed as

$$\text{Max}_{x_{D_2}} \pi_{D_2} = \left\{ \frac{a + 2x_{D_2} - [(1-\delta) \cdot (x_{D_1} + x_U) - t]}{3} \right\}^2 - \frac{1}{2} \gamma x_{D_2}^2 \quad (6b)$$

From equations (6a) and (6b), the first-order conditions with respect to x_{D_1} and x_{D_2} are, respectively,

$$\begin{cases} \frac{\partial \pi_{D_1}}{\partial x_{D_1}} = \frac{4(1-\delta) \{ a + 2[(1-\delta) \cdot (x_{D_1} + x_U) - t] - x_{D_2} \}}{9} - (1-s) \cdot \gamma x_{D_1} = 0 \\ \frac{\partial \pi_{D_2}}{\partial x_{D_2}} = \frac{4 \{ a + 2x_{D_2} - [(1-\delta) \cdot (x_{D_1} + x_U) - t] \}}{9} - \gamma x_{D_2} = 0 \end{cases}$$

In order to obtain the uniqueness and stability of Nash equilibrium, we should have $\gamma^{(2)} > \text{Max} \left(\frac{8}{9}, \frac{8(1-\delta)^2}{9(1-s)} \right)$. And

then, solving for the equilibrium R & D investment levels, we can obtain:

$$\begin{aligned} x_{D_1}^{(2)} &= \frac{4(1-\delta)}{K_0} \{ (3\gamma - 4)a + 2(3\gamma - 2)[(1-\delta) \cdot x_U - t] \} \\ x_{D_2}^{(2)} &= \frac{4}{K_0} \{ [3(1-s)\gamma - 4(1-\delta)^2]a - 3(1-s)\gamma[(1-\delta) \cdot x_U - t] \} \\ \text{And } K_0 &= 3(1-s)\gamma(9\gamma - 8) - 8(1-\delta)^2(3\gamma - 2) \end{aligned}$$

Accordingly,

$$\begin{aligned} q_{D_1}^{(2)} &= \frac{3(1-s)\gamma}{K_0} \{ (3\gamma - 4)a + 2(3\gamma - 2)[(1-\delta) \cdot x_U - t] \} \\ q_{D_2}^{(2)} &= \frac{3\gamma}{K_0} \{ [3(1-s)\gamma - 4(1-\delta)^2]a - 3(1-s)\gamma[(1-\delta) \cdot x_U - t] \} \end{aligned}$$

Meanwhile, in the information goods supply chain partnership (U-D₁), before obtaining optimal transfer payment, the upstream supplier must determine its optimal R&D cooperative investment to maximise its profit, that is

$$\text{Max}_{x_U} \pi_U^{(2)} = t \cdot q_{D_1}^{(2)} + T - (1-s) \cdot \frac{1}{2} \gamma x_U^2 \quad (7)$$

Substituting the equilibrium output $q_{D_1}^{(2)}$ into equation (7), then, from its first order condition, it follows that the optimal R&D investment of upstream cooperative partner U is

$$x_U^{(2)} = \frac{6(1-\delta)(3\gamma - 2)}{3(1-s)\gamma(9\gamma - 8) - 8(1-\delta)^2(3\gamma - 2)} \cdot t$$

Now, in the first-stage, the optimal transfer payment level, which determined by the upstream supplier to maximise its profit, must satisfy

$$\text{Max}_t \pi_U^{(2)} = t \cdot q_{D_1}^{(2)} + T - (1-s) \cdot \frac{1}{2} \gamma (x_U^{(2)})^2$$

Substituting $q_{D_1}^{(2)}$ and $x_U^{(2)}$ into the above equation, from its first-order and second-order conditions, the optimal linear transfer payment can be determined as

$$t^{T*} = \frac{(3\gamma - 4)[3(1-s)\gamma(9\gamma - 8) - 8(1-\delta)^2(3\gamma - 2)]}{4(3\gamma - 2)[3(1-s)\gamma(9\gamma - 8) - 11(1-\delta)^2(3\gamma - 2)]} a \quad (8)$$

where, $0 < s < 1 - \frac{11(1-\delta)^2(3\gamma - 2)}{3\gamma(9\gamma - 8)}$. Consequently, the

equilibrium profiles of non-linear transfer payment contract coordination in government subsidy are solved as follows:

1 Optimal Cooperative R&D Investment, Optimal Private Profit and Optimal System Profit of Information Goods Supply Chain

$$x_U^{T*} = \frac{3(1-\delta)(3\gamma - 4)}{2K_1} a \quad (9a)$$

$$\text{And } K_1 = 3(1-s)\gamma(9\gamma - 8) - 11(1-\delta)^2(3\gamma - 2)$$

$$x_{D_1}^{T^*} = \frac{2(1-\delta)(3\gamma-4)}{K_1} a \quad (9b)$$

$$\pi_U^{T^*} = \frac{3(1-s)(3\gamma-4)^2}{8(3\gamma-2)K_1} \gamma a^2 + T \quad (10a)$$

$$\pi_{D_1}^{T^*} = \frac{(1-s)(3\gamma-4)^2[9(1-s)\gamma-8(1-\delta)^2]}{4K_1^2} \gamma a^2 - T \quad (10b)$$

$$\Pi_{SC}^{T^*} = \frac{A_1}{8(3\gamma-2)K_1^2} (1-s)(3\gamma-4)^2 \gamma a^2 \quad (11)$$

$$\text{And } A_1 = 27(1-s)\gamma(5\gamma-4) - 49(1-\delta)^2(3\gamma-2)$$

Here, in order to satisfy the participation constraint (IR) of the downstream producer D_1 in the information goods supply chain, the optimal fixed transfer payment must be $0 \leq T^{T^*} \leq \frac{(1-s)(3\gamma-4)^2[9(1-s)\gamma-8(1-\delta)^2]}{4K_1^2} \gamma a^2$.

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$$x_{D_2}^{T^*} = \frac{9(1-s)\gamma(5\gamma-4) - 22(1-\delta)^2(3\gamma-2)}{(3\gamma-2)K_1} a \quad (12)$$

$$\pi_{D_2}^{T^*} = \frac{[9(1-s)\gamma(5\gamma-4) - 22(1-\delta)^2(3\gamma-2)]^2}{16(3\gamma-2)^2 K_1^2} (9\gamma-8) \gamma a^2 \quad (13)$$

3 Social Welfare

In non-linear transfer payment contract $\{t^{T^*}, T^{T^*}\}$, the social welfare is defined as the total sum of system profit ($\Pi_{SC}^{T^*}$) derived from cooperative innovation of information goods supply chain, private profit ($\pi_{D_2}^{T^*}$) derived from imitative innovation of downstream industrial competitor, and information goods consumer surplus (CS^{T^*}). Here, in the case of linear inverse demand functions, the information goods consumer surplus may be summarised as $\frac{1}{2}(q_{D_1}^{T^*} + q_{D_2}^{T^*})^2$ (Martin, 2003), that is

$$W^{T^*} = \Pi_{SC}^{T^*} + \pi_{D_2}^{T^*} + CS^{T^*}, \quad (14)$$

$$CS^{T^*} = \frac{A_2}{32(3\gamma-2)^2 K_1^2} 9\gamma^2 a^2$$

$$\text{And } A_2 = (1-s)(63\gamma^2 - 72\gamma + 16) - 22(1-\delta)^2(3\gamma-2)$$

4 Perfect sharing contract coordination in government subsidy

Based on incentive subsidies from government, the perfect sharing contract coordination of U- D_1 in dual-oligopoly market environment may be analysed as a full information three-stage game problem as well.

- *Stage 1:* The upstream supplier formulates the perfect sharing contract clauses;
- *Stage 2:* The information goods supply chain partners simultaneously determine on their cooperative R&D investment for original innovation;
- *Stage 3:* The downstream producer outputs the final information goods and completes in quantities in the dual-oligopoly market.

Also, assume that each firm of information goods has zero marginal cost and variable cost is not considered; assume that the parameters of the horizontal spillover effect of U- D_1 are symmetric, that is, $\delta_U = \delta_{D_1} = \delta$ $0 < \delta < 1$; and assume the incentive subsidies from government for cooperative innovation of U- D_1 are symmetric, that is, $s_U = s_{D_1} = s$ $0 < s < 1$.

To start with, discuss the equilibrium outputs of the downstream firms in the dual-oligopoly market in the third stage. Given the government subsidy rate, the cooperative R & D investment levels for original innovation of U- D_1 and the perfect sharing contract clauses, the downstream producer D_1 determines $q_{D_1}^{(3)}$ to maximise its own profit, that is

$$\text{Max}_{q_{D_1}} \pi_{D_1} = \phi[a + (1-\delta)x - (q_{D_1} + q_{D_2})]q_{D_1} - (1-s)\frac{1}{2}\gamma(\tau x)^2 \quad (15)$$

Here, τ ($0 < \tau < 1$) and ϕ ($0 < \phi < 1$) represent R&D investment sharing parameter and cooperative innovation revenue sharing parameter of U- D_1 , respectively. For analytical simplicity, define τ is the proportion of cooperative innovation rents x of the downstream producer and $1-\tau$ is the proportion of cooperative innovation rents x of the upstream supplier. For the cooperative innovation revenue, the downstream producer obtains a share of ϕ while the upstream supplier gets a share of $1-\phi$.

Simultaneously, the downstream industrial competitor D_2 determines $q_{D_2}^{(3)}$ to maximise its profit as well:

$$\text{Max}_{q_{D_2}} \pi_{D_2} = [a + x_{D_2} - (q_{D_1} + q_{D_2})]q_{D_2} - \frac{1}{2}\gamma x_{D_2}^2 \quad (16)$$

The first-order conditions with respect to q_{D_1} and q_{D_2} of equations (15) and (16) give rise to the following quantity reaction functions:

$$R_{D_1}(q_{D_2}) = \frac{a + (1-\delta)x - q_{D_2}}{2}$$

$$R_{D_2}(q_{D_1}) = \frac{a + x_{D_2} - q_{D_1}}{2}$$

Solving from the above both reaction functions, and then

$$q_{D_1}^{(3)} = \frac{a + 2(1-\delta)x - x_{D_2}}{3}$$

$$q_{D_2}^{(3)} = \frac{a + 2x_{D_2} - (1-\delta)x}{3}$$

In the second stage, via substituting $q_{D1}^{(3)}$ and $q_{D2}^{(3)}$ into equation (15), the profit maximisation problem for U-D₁ to satisfy the Incentive Compatibility (IC) constraints may be given below:

$$Max_x \pi_{D1}^{(3)} = \phi \left[\frac{a + 2(1-\delta) \cdot x - x_{D2}}{3} \right]^2 - (1-s) \cdot \frac{1}{2} \gamma (\tau \cdot x)^2$$

$$Max_x \pi_U^{(3)} = (1-\phi) \left[\frac{a + 2(1-\delta) \cdot x - x_{D2}}{3} \right]^2 - (1-s) \cdot \frac{1}{2} \gamma [(1-\tau) \cdot x]^2$$

Also, the maximising profit of the downstream industrial competitor D₂ is expressed as

$$Max_{x_{D2}} \pi_{D2} = \left[\frac{a + 2x_{D2} - (1-\delta) \cdot x}{3} \right]^2 - \frac{1}{2} \gamma x_{D2}^2$$

Solving the first-order conditions with respect to x and x_{D2} of the above maximising profit problems, respectively:

$$\frac{\partial \pi_{D1}}{\partial x} = \phi \frac{4(1-\delta)[a + 2(1-\delta) \cdot x - x_{D2}]}{9} - (1-s) \cdot \gamma \tau^2 \cdot x = 0$$

$$\frac{\partial \pi_U}{\partial x} = (1-\phi) \frac{4(1-\delta)[a + 2(1-\delta) \cdot x - x_{D2}]}{9} - (1-s) \cdot \gamma (1-\tau)^2 \cdot x = 0$$

$$\frac{\partial \pi_{D2}}{\partial x_{D2}} = \frac{4[a + 2x_{D2} - (1-\delta) \cdot x]}{9} - \gamma x_{D2} = 0$$

Then,

$$\phi^{(2)} = \frac{\tau^2}{\tau^2 + (1-\tau)^2}$$

$$x^{(2)} = \frac{4(1-\delta)(3\gamma-4)}{K} a$$

$$\text{And } K = 3(1-s)\gamma(9\gamma-8)[\tau^2 + (1-\tau)^2] - 8(1-\delta)^2(3\gamma-2)$$

$$x_{D2}^{(2)} = \frac{3(1-s)\gamma[\tau^2 + (1-\tau)^2] - 4(1-\delta)^2}{K} 4a$$

In the first stage to formulate the perfect sharing contract clauses, satisfying the IC constraints, the profit maximisation problem for U-D₁ can be rewritten as following:

$$Max_{\tau} \Pi_{SC} = \left[\frac{a + 2(1-\delta) \cdot x^{(2)} - x_{D2}^{(2)}}{3} \right]^2 - (1-s) \cdot \frac{1}{2} \gamma (\tau \cdot x)^2 - (1-s) \cdot \frac{1}{2} \gamma [(1-\tau) \cdot x]^2$$

$$s.t.: \phi = \frac{\tau^2}{\tau^2 + (1-\tau)^2}$$

Substituting $x^{(2)}$ and $x_{D2}^{(2)}$ into the above expression and then,

$$Max_{\tau} \Pi_{SC}^{(3)} = \frac{A}{K^2} (1-s)\gamma[\tau^2 + (1-\tau)^2](3\gamma-4)^2 a^2$$

$$s.t.: \phi = \frac{\tau^2}{\tau^2 + (1-\tau)^2}$$

$$\text{And } A = 9(1-s)\gamma[\tau^2 + (1-\tau)^2] - 8(1-\delta)^2$$

Taking the first-order and second-order conditions with regard to τ , it can be obtained as three parameter solutions:

$$\tau_1 = \frac{3 + \sqrt{3}K_{\tau}}{6}; \tau_2 = \frac{3 - \sqrt{3}K_{\tau}}{6}; \tau_3 = \frac{1}{2},$$

where

$$K_{\tau} = \sqrt{\frac{8(1-\delta)^2(6\gamma-4)}{(1-s)\gamma(9\gamma-4)}} - 3.$$

Since $\Pi_{SC}(\tau_1 = \frac{3 + \sqrt{3}K_{\tau}}{6}) = \Pi_{SC}(\tau_2 = \frac{3 - \sqrt{3}K_{\tau}}{6})$ and $\Pi_{SC}(\tau_3 = \frac{1}{2}) > 0$.

$$= -\frac{(3\gamma-4)^2}{24(3\gamma-2)} \gamma a^2 < 0$$

Therefore, $\{\tau^{P*}, \phi^{P*}\} = \left\{ \frac{1}{2}, \frac{1}{2} \right\}$ and $0 < s < 1 - \frac{16(1-\delta)^2(3\gamma-2)}{3\gamma(9\gamma-8)}$.

Consequently, the equilibrium profiles of perfect sharing contract coordination in government subsidy are solved as follows:

- 1 Optimal Cooperative R&D Investment, Optimal Private Profits and Optimal System Profit of Information Goods Supply Chain

$$x_{D1}^{P*} = x_U^{P*} = \frac{4(1-\delta)(3\gamma-4)}{3(1-s)\gamma(9\gamma-8) - 16(1-\delta)^2(3\gamma-2)} a \quad (17)$$

$$\Pi_{SC}^{P*} = \frac{(3\gamma-4)^2 [9(1-s)\gamma - 16(1-\delta)^2]}{[3(1-s)\gamma(9\gamma-8) - 16(1-\delta)^2(3\gamma-2)]^2} (1-s)\gamma a^2 \quad (18)$$

- 2 Imitative Innovation Investment and Optimal Private Profit of Downstream Industrial Competitor

$$x_{D2}^{P*} = \frac{3(1-s)\gamma - 8(1-\delta)^2}{3(1-s)\gamma(9\gamma-8) - 16(1-\delta)^2(3\gamma-2)} 4a \quad (19)$$

$$\pi_{D2}^{P*} = \frac{(9\gamma-8)[3(1-s)\gamma - 8(1-\delta)^2]^2}{[3(1-s)\gamma(9\gamma-8) - 16(1-\delta)^2(3\gamma-2)]^2} \gamma a^2 \quad (20)$$

- 3 Social Welfare

In perfect sharing contract $\{\tau^{P*}, \phi^{P*}\}$, the social welfare is defined as the total sum of system profit (Π_{SC}^{P*}) derived from cooperative innovation of information goods supply chain, private profit (π_{D2}^{P*}) derived from imitative innovation of downstream industrial competitor, and information goods consumer surplus (CS^{P*}).

$$W^{P*} = \Pi_{SC}^{P*} + \pi_{D2}^{P*} + CS^{P*},$$

$$CS^{P*} = \frac{[(1-s)(3\gamma-2) - 4(1-\delta)^2]^2}{[3(1-s)\gamma(9\gamma-8) - 16(1-\delta)^2(3\gamma-2)]^2} 18\gamma^2 a^2 \quad (21)$$

5 Comparison of effective contract coordination in government subsidy

To start with, the equilibrium outcomes in non-linear transfer payment contract and perfect sharing contract show

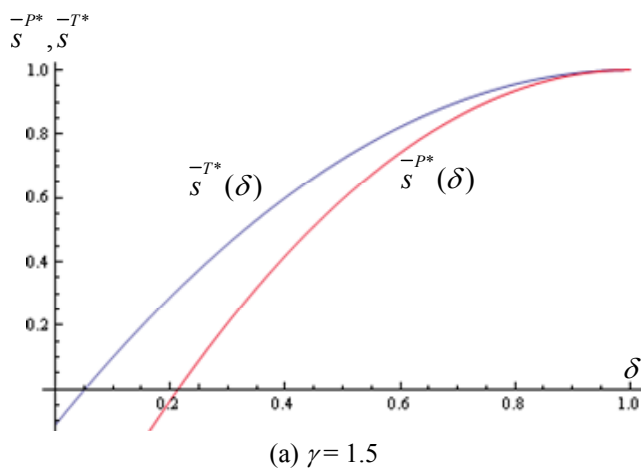
that the maximum subsidy rate (denoted by \bar{s}) for U-D₁ from government is accordingly:

$$\frac{-T^*}{s} = 1 - \frac{11(1-\delta)^2(3\gamma-2)}{3\gamma(9\gamma-8)} \quad (22)$$

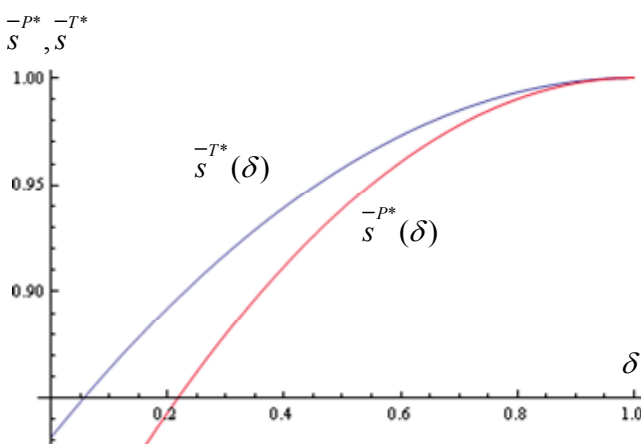
$$\frac{-P^*}{s} = 1 - \frac{16(1-\delta)^2(3\gamma-2)}{3\gamma(9\gamma-8)} \quad (23)$$

From equations (22) and (23), it is clear that the maximum government subsidy rate for U-D₁ in perfect sharing contract ($\frac{-T^*}{s}$) is obviously lower than non-linear transfer payment contract ($\frac{-P^*}{s}$). Furthermore, the difference between $\frac{-T^*}{s}$ and $\frac{-P^*}{s}$ increases as the parameter of the horizontal spillover effect δ decreases for $0 \leq \delta \leq 1$; and increases as the parameter of R&D investment cost γ decreases, see Figures 1 and 2, which show that government subsidy-based perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the strengthening of the innovation basis and the extent to which partners' absorb and transform technological innovation knowledge, and the improvement of intellectual property protection environment and the degree of intellectual property protection as well.

Figure 1 The relationship of \bar{s} and δ (see online version for colours)

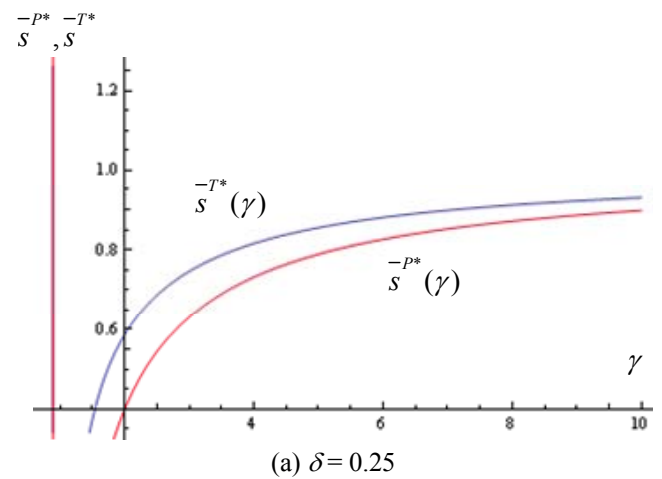


(a) $\gamma = 1.5$

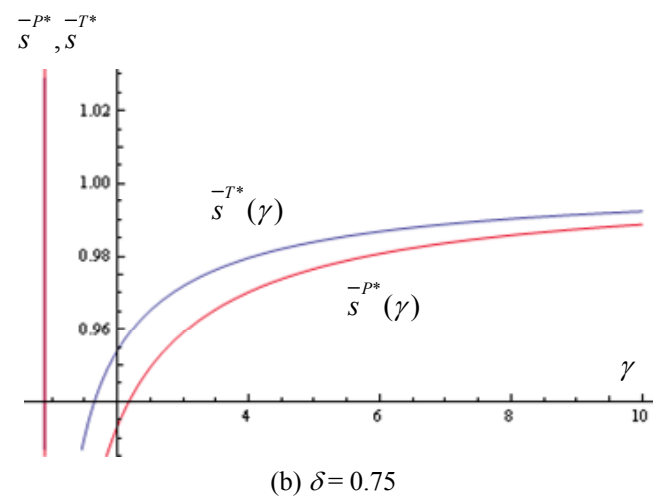


(b) $\gamma = 7.5$

Figure 2 The relationship of \bar{s} and γ (see online version for colours)



(a) $\delta = 0.25$



(b) $\delta = 0.75$

In the next part of this paper, let us use numerical simulation analysis to compare the effective coordination between non-linear transfer payment contract and perfect sharing contract in the incentive policy of government subsidies.

5.1 Government subsidy-based optimal cooperative R&D investment analysis

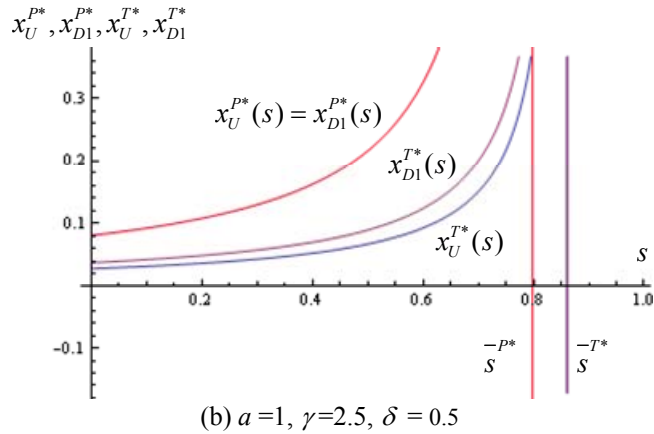
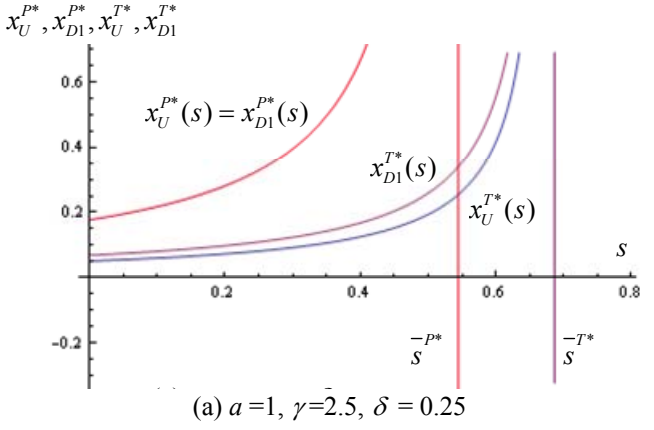
As to the minimum parameter of R&D investment cost (denoted by $\underline{\gamma}$) for U-D₁ in non-linear transfer payment contract and perfect sharing contract are

$$\underline{\gamma}^{T^*} = \frac{8r_1 + 11r_2 + \sqrt{(8r_1 - 11r_2)^2 + 88r_1r_2}}{18r_1} \quad (24)$$

$$\underline{\gamma}^{P^*} = \frac{4r_1 + 8r_2 + 4\sqrt{(r_1 - 2r_2)^2 + 2r_1r_2}}{9r_1} \quad (25)$$

where $r_1 = (1-s) \in (0,1)$ and $r_2 = (1-\delta)^2 \in [0,1]$. Therefore, without loss of generality, letting $a=1$, $\gamma=2.5$ while δ is given different levels and s is variable, for $0 < s < 1$, the respective numerical simulation results of equations (9) and (10) are illustrated in Figure 3 and the main findings can be summarised in the following proposition:

Figure 3 The relationship of optimal cooperative R&D investment and s (see online version for colours)



Proposition 1: For different level of horizontal spillover effect $\delta, 0 \leq \delta \leq 1$,

(a) the optimal cooperative R&D investments of $U-D_1$ increase as the government subsidy rate s increases, for $0 < s < 1$;

(b) however, the optimal cooperative R&D investments of $U-D_1$ in perfect sharing contract coordinated mechanism (x_U^{P*} and x_{D1}^{P*}) are higher than non-linear transfer payment contract coordinated mechanism (x_U^{T*} and x_{D1}^{T*}), with the incentive gap to cooperative innovation between these two mechanisms increases as the government subsidy rate s increases, for $0 < s < 1$.

5.2 Government subsidy-based imitative innovation investment analysis

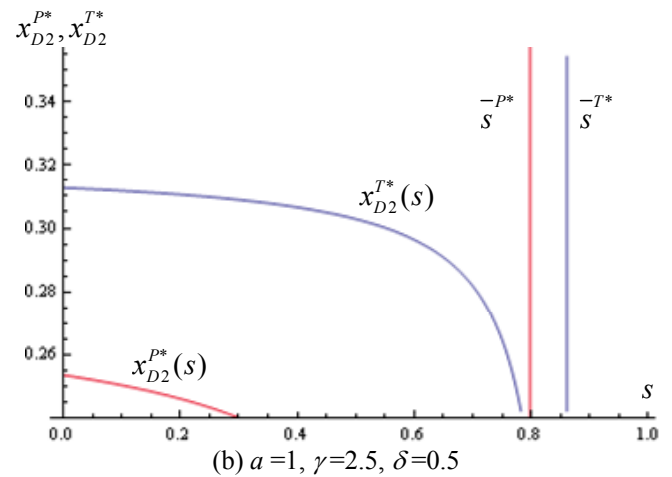
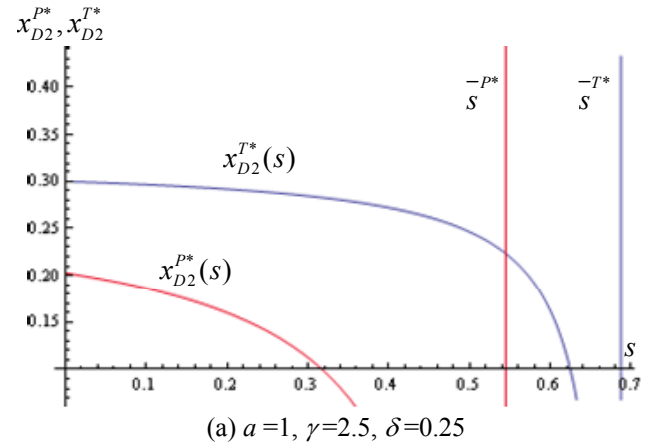
Simultaneously, letting $a=1, \gamma=2.5$ while δ is given different levels and s is variable, for $0 < s < 1$, the respective numerical simulation results of equations (12) and (19) are shown in Figure 4. Then, the main findings can be summarised as following:

Proposition 2: For different level of horizontal spillover effect $\delta, 0 \leq \delta \leq 1$,

(a) the imitative innovation investment of industrial competitor (D_2) reduces as the government subsidy rate s increases, for $0 < s < 1$;

(b) however, the imitative innovation investment of industrial competitor (D_2) in perfect sharing contract coordinated mechanism (x_{D2}^{P*}) are lower than non-linear transfer payment contract coordinated mechanism (x_{D2}^{T*}), with the incentive gap to imitative innovation between these two mechanisms increases as the government subsidy rate s increases, for $0 < s < 1$.

Figure 4 The relationship of imitative innovation investment and s (see online version for colours)



5.3 Government subsidy-based optimal system profit analysis of information goods supply chain

Accordingly, letting $a=1, \gamma=2.5$ while δ is given different levels and s is variable, for $0 < s < 1$, the respective numerical simulation results of equations (11) and (18) are illustrated in Figure 5. Therefore, we can further find:

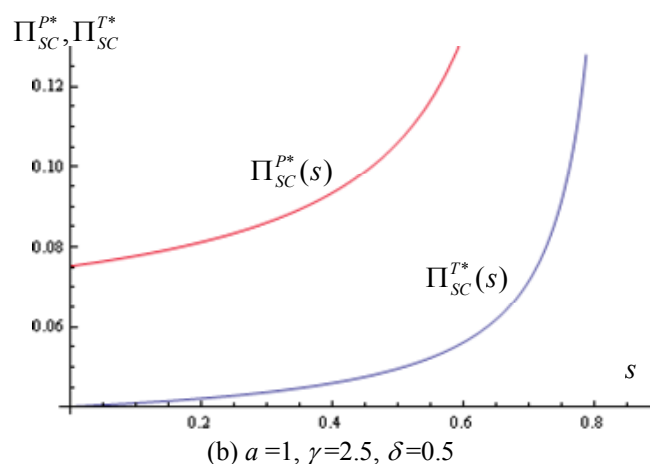
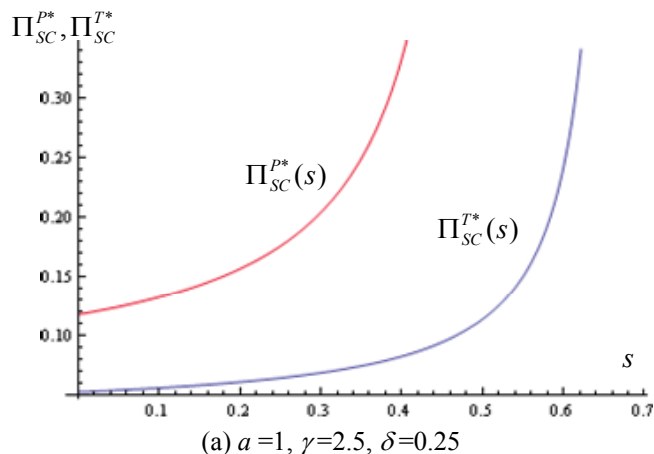
Proposition 3: For different level of horizontal spillover effect $\delta, 0 \leq \delta \leq 1$,

(a) the optimal supply chain system profit of information goods increases as the government subsidy rate s increases, for $0 < s < 1$;

(b) however, the optimal supply chain system profit of information goods in perfect sharing contract coordinated mechanism (Π_{sc}^{P*}) are greater than non-linear transfer

payment contract coordinated mechanism (Π_{SC}^{T*}), with the system profit gap of information goods supply chain between these two mechanisms increases as the government subsidy rate s increases, for $0 < s < 1$.

Figure 5 The relationship of optimal supply chain system profit of information goods and s (see online version for colours)



5.4 Government subsidy-based social welfare analysis

Now, letting $a=1, \gamma=2.5$ while δ is given different levels and s is variable, for $0 < s < 1$, the respective numerical simulation results of equations (14) and (21) are illustrated in Figure 6. Consequently, we can further find the following proposition:

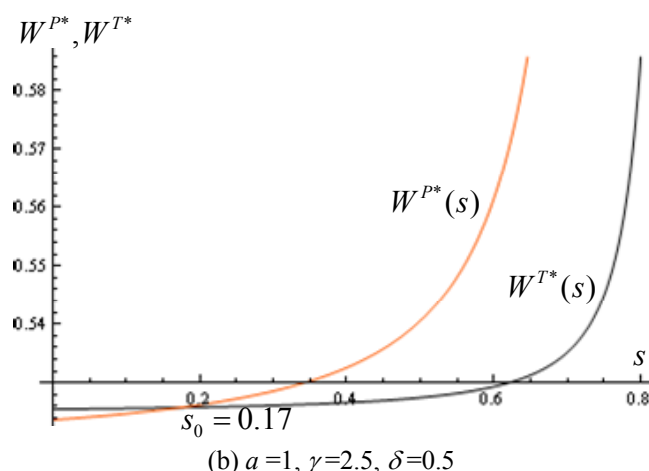
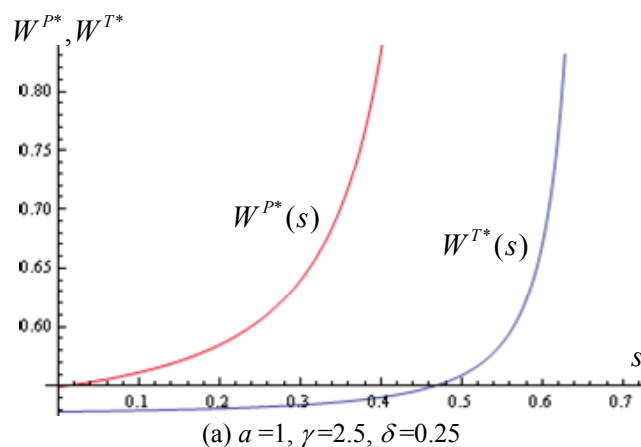
Proposition 4: For different level of horizontal spillover effect $\delta, 0 \leq \delta \leq 1$,

(a) the social welfare increases as the government subsidy rate s increases, for $0 < s < 1$;

(b) for low and no horizontal spillover effect, as well as for high horizontal spillover effect when the government subsidy rate s is sufficiently higher [$s \in (s_0, 1)$], the social welfare in perfect sharing contract coordinated mechanism (W^{P*}) are greater than non-linear transfer payment contract coordinated

mechanism (W^{T*}), with the social welfare gap between these two mechanisms increases as the government subsidy rate s increases, for $0 < s < 1$; Otherwise, for high horizontal spillover effect and the government subsidy rate s is lower enough [$s \in (0, s_0)$], the social welfare gap will be not obvious.

Figure 6 The relationship of social welfare and s (see online version for colours)



6 Concluding remarks

In this paper, two government subsidy-based incomplete contract coordinated mechanisms are established to impact on the information goods supply chain partners' incentives to cooperative innovation. The three main findings are obtained as: firstly, in the threat of strategic substituting from industrial competitor of information goods, the government subsidy policy for information goods supply chain makes up the lack of incentives to original innovation due to innovation externalities, improves information goods supply chain partners' incentives to cooperative innovation, reduces industrial competitor's incentives to imitative innovation, and makes supply chain system profit of information goods and social welfare improve; secondly, in the incentive policy of government subsidies, the perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the strengthening of the innovation basis and the extent to

which partners' absorb and transform technological innovation knowledge; thirdly, the government subsidy-based perfect sharing contract may achieve greater effective coordination than non-linear transfer payment contract, along with the improvement of intellectual property protection environment and the degree of intellectual property protection.

Acknowledgements

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Notes

- 1 If $\theta = 1$, the original and imitative information goods are perfect substitutes, which means that final consumers have the same valuations for the original and imitative information goods.
- 2 If the horizontal spillover effect parameter is 0, it means that the cooperative R&D innovation is being in perfect intellectual property protection. Whereas the horizontal spillover effect parameter is 1, it means that the cooperative R&D innovation is without intellectual property protection.

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