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ORIGINAL ARTICLE

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A decision support system for rapid one-of-a-kind product development

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Abstract A decision support system (DSS) is a specific class of computerized information systems that support decision-making activities. Such a system has become paramount in supporting manufacturing activities with the development of World Wide Web (WWW) technology in recent years. The research and development of a knowledge-based DSS dedicated to rapid one-of-a-kind products (OKPs), however, has, to the author's knowledge, rarely been directly studied. This work presents a knowledge-based DSS for supporting decision-making activities in developing OKPs using broad knowledge base content. The underlying architecture of the proposed system is a system that manages and optimizes the data, information and knowledge in the product development process. A knowledge structure model is proposed in this paper, and a comprehensive set of expert knowledge and analytical/numerical methods are integrated into the system to automate intelligent decision-making. Case studies have shown that the knowledge-based DSS is able to help OKP companies develop new products more quickly by sharing optimization tools, information and knowledge to reduce possible errors and rework.

Keywords Customer interface · Data modelling · Information technology · Knowledge base · Mass customization · One-of-a kind product

1 Introduction

Decision support systems are interactive computer-based systems and subsystems intended to help decision-makers use communications technologies, data, documents, knowledge and/or models to identify and solve problems and make decisions [1]. For many reasons [2], the logical architecture to use for building contemporary decision support applications is the Internet or a corporate intranet built using Web technologies. The dominant information technology platform in companies has changed from mainframes and LAN-based, client-server systems to Web and Internet technologies [3]. This technology change is expanding what is called "information reach" and "information range" [4]. The reach of information and decision support systems has expanded significantly to serve companies of different sizes. The range and variety of decision support information and tools that can be developed, delivered, and shared is also becoming much larger.

The development of OKPs, as discussed by Wortmann [5], Hirsch [6] and Tu [7], usually involves a large amount of uncertainty from the market, customers and partners, which consequently results in a large amount of rework. Therefore, the product development (PD) cost is normally higher and the development lead-time is longer than in product-focused manufacturing companies. In order to respond rapidly to market pressure, many OKP companies have adopted a virtual manufacturing concept, which can be simply understood as a global collaboration business through subcontracting and through technology transfers between a company and its global partners. This virtual manufacturing concept helps a company to quickly and often economically meet its customers' needs by combining its own strengths and those of its partners. These virtual companies usually need to manage and optimize product development processes through a whole product development cycle by employing or developing DSS tools and seamlessly integrating these tools with the whole product development process. These tools should be able to support product development processes including customer requirement interpretation to decide how to address the customers' needs, product design to address the customer's needs, conceptual and functional prototyping to prove the effectiveness of the design, manufacturing process planning to determine how the product is to be made, design manufacture of tools, preproduction trial, production, and final delivery of the product to the customer or launch of the product into the market.

This article proposes a DSS for supporting rapid development of OKP or customized products. The main objective of the DSS is to provide and integrate tools for supporting optimal OKP

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development. The main goal of designing such a system is to conceive an optimal product under the given circumstances in the shortest time and at a minimum cost.

In this paper, the structure of the proposed knowledge-based DSS is described in Sect. 3. To build such a system, this paper proposes a product knowledge structure model, which will be detailed in Sect. 4. Section 5 considers the mapping of the proposed information model into the database structure and creating the engineering database. Case studies of the DSS are provided in Sect. 6. Finally, discussions and conclusions are made in Sect. 7 and Sect. 8.

2 Literature review

OKP was intensively researched under the ESPRIT research program on the theory of the factory of the future (FOF) in the late 1980s and early 1990s [8]. Most of the research efforts were placed on the OKP production management because operation efficiency was believed to be one of the major bottlenecks in OKP production. Rolstadas [8] proposed a framework for managing OKP in which an adaptive scheme for changing the production resource structure to meet the changes of product structure was suggested. However, the limitations and static nature of this adaptive factory managing structure were also noted. Up to now, the research in OKP is still heavily focused on managerial problems. Little work has been carried out on how to support rapid and economical OKP development.

The increasing complexity of OKPs and one-of-a-kind processes require early decision-making. Hence, the tools that can help decision-making at the early stages are essential. Knowledge modelled on design, process planning, quality, etc. and AI to support decision-making has become an important research field of rapid OKP development. In recent years, work has been carried out to develop Internet-based intelligent systems to support product development. For example, Pan et al. [24] integrated AI and knowledge technologies to improve the agility of product design and manufacturing. The integration of these technologies with Internet technology leads to an enabling technology for a distributed manufacturing company to achieve short PD cycle time and to quickly capture sudden market opportunities. Cheng et al. [9] and Pan et al. [2] proposed a Java- and AI-based system for the implementation of design agility and manufacturing responsiveness. Xue et al. [10] presented methods to model a knowledge base and a database for intelligent concurrent design. A system that combines knowledge-based reasoning and optimization was also introduced to automatically generate aspect models and identify the optimal design using optimization. Cheng et al. [11] presented a novel approach for implementing agile design and manufacturing concepts by using Internet-based technology. The underlying philosophy of this approach is to use Web-based design and manufacturing support systems as “smart” tools from which design and manufacturing customers can rapidly and responsively access the system’s built-in design and manufacturing expertise. Xu and Liu [12] proposed a Web-enabled PDM system in the collaborative design environment. Its architecture is based on the use of open data standards to allow users on a wide variety of platforms access to the product data and information. Integral elements of the proposed architecture include an object-oriented database (OODB), an object-oriented database management system (OODBMS), CGI script and visualisation applications.

The main problem in developing DSS has focused upon how design knowledge should be captured, modelled and presented. The nature of engineering design requires knowledge representation schemas to be as flexible and robust as possible [13]. The search for a flexible and robust knowledge representation is inherently related to the design researchers seek to model. OKP development process support applications need complex data models because they manipulate simulations of the real world. The critical issues in managing and sharing engineering information in the design process are [14]:

- forming product data structures and query mechanisms for accessing information about the product;
- developing a design environment that promotes information sharing that is unobtrusive to the designer.

The EXPRESS information model defined by ISO 10303, the STandard for Exchange of Product model data (STEP), describes the information models for applications in design, manufacturing and other engineering areas. An EXPRESS information model of product data structure can be mapped into a database system and can be used to define database support for concurrent engineering. Databases built around STEP models are essential because they provide content that integrated systems for supporting the design process can understand [15]. Novice designers can also use those engineering databases to query information about designed products.

The next important issue for knowledge management systems is an emerging trend of the decentralization of design teams, functionally and geographically. This perspective leads to a model of network design [16] that represents a method for managing engineering information from a number of sources. Other issues include the integration of various technologies and tools with different enterprise data models [17] , worldwide knowledge and resource access among heterogeneous computer systems, remote access to algorithms or large application tools that run on different platforms [18], etc. A comprehensive review of the recent developments in developing Internet-based systems for rapid OKP development was carried out by Xie et al. [19]

To solve these issues, this paper proposes a DSS system for supporting rapid OKP development in the global environment. The underlying architecture of the proposed system is a knowledge-based system that manages and optimizes the data, information and knowledge in the product development process. A knowledge modelling framework is proposed, and a comprehensive set of expert knowledge and analytical/numerical methods are integrated into the system to automate intelligent decision-making. Case studies will be carried out on how the knowledge-based DSS is able to help OKP companies develop new products more quickly by sharing optimization tools, information and knowledge to reduce possible errors and rework.

3 System architecture

The DSS is shown in Figure 1. This system aims to create an Internet-based software platform for OKP companies to accumulate OKP development experience or knowledge; support collaborative, integrated and concurrent product development; capture dynamically and respond to customer requirements and cut down product development cost. This system is used to develop interoperability standards needed by the company to integrate the product design, planning and manufacturing processes.

The actual architecture implemented is simple. Most Web-based DSS are built using a three-tier or four-tier architecture as shown in Fig. 1. A person using a Web browser sends a request using the hypertext transfer protocol (HTTP) to a Web server. The Web server processes the request, using a program or script. The script may implement or link to a model, process a database request, or format a document.

The results are returned to the user's Web browser for display (see Fig. 1). Web applications are designed to allow any authorised user with a Web browser and an Internet connection to interact with them. The application code usually resides on a remote server, and the user interface is presented at the client's Web browser.

The system contains several common modules and tools, as well as special modules and tools for specific OKP development. As shown in Figure 1, the system contains the following basic modules and tools: 1) an Internet based software platform, 2) global customer interfaces, 3) an Internet-based integrated PD environment [19], 4) an Internet-based product design environment for supporting product design, 5) an Internet-based virtual process planning/assembly environment, 6) an Internet-based virtual simulation platform, 7) an Internet-based virtual manufacturing platform, 8) Internet-based design/manufacturing product data /knowledge bases and tools, and 9) a global cost optimisation tool.

A systematic approach to the DSS is important. Simply making an existing DSS accessible by using a Web browser to managers, customers or other stakeholders will often lead to unsatisfactory results. A systematic development approach must be explicitly chosen, and managers must be involved in the development process. Developing the user interface, models, data storage and the tools above for knowledge-based DSS remain major tasks. For example, a user interface remains important in

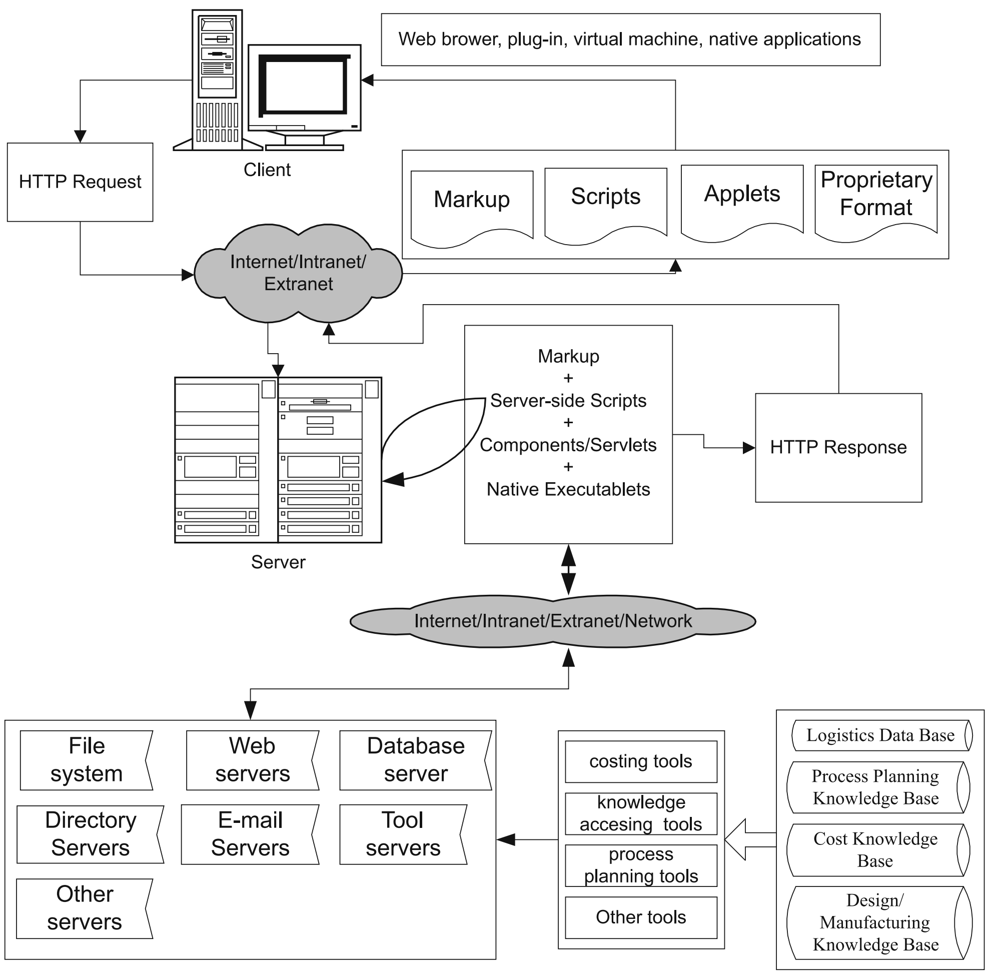

Fig. 1. The DSS architecture

a Web development environment, and it probably becomes more important because so many users of various levels of sophistication can potentially access some or all DSS capabilities.

In this paper, instead of discussing the structure of the entire system, the authors opt to discuss the knowledge base structure, modelling framework, product models and database implementation of the EXPRESS model. These modules and tools will be detailed in the following sections.

4 Product knowledge structure model

The knowledge structure model, as shown in Fig. 2, is the conceptual description of ideas, facts and processes that represent the model of the OKP to be designed. The knowledge structure model used in development of a presented concept is based on an EXPRESS information technology model that was accepted in 1994 as an international standard (ISO 10303) [20]. The knowledge structure model contains four layers, which include a knowledge layer, a parts layer, a feature layer and a parametric layer. The parametric layer contains the geometric data of the shape feature of the part and tool features. The feature layer contains all of the feature information, which includes not only the feature information (i.e. attributes) but also relationships with other feature-level information objects and objects defined by users. The part layer contains all of the part information that includes feature information and relationships among different part-level information objects. The knowledge layer contains not only the part information, but also "knowledge-related" information objects and an inference engine. The knowledge in the knowledge layer is extracted from part-level knowledge and feature-level knowledge, which are formed by information objects and relationships among them. The knowledge in the knowledge layer can be directly used to support intelligent concurrent design and manufacturing. The management feature is used to manage all of the information of a certain part, which can be saved and used as a part of a company database. Application objects defined by users according to the requirements of the project can be put in the feature and part layer.

The object created in the above knowledge structure model is defined based on common object concepts. There are groups of standard elements or information constructors that are used by every information model, which contain elements as follows:

- Entity: a construction that represents the appearances from the real world
- Property: a specific characteristic of the entity; it could represent a numerical value, constraints, behaviour, etc.
- Attribute: a certain property type that sets the restrictions on other properties or on whole entities
- Relation: implicit or explicit relationship between two constructions in the model
- Cardinality: the number of instances of one construction that can be linked with instances of other constructions.

The entities and relations among them are the bases of conceptual modelling. Also, the information models encompass an explicit group of the interpretation rules. The features that imply special demands on the information model are:

- uneven and variable structure of data,

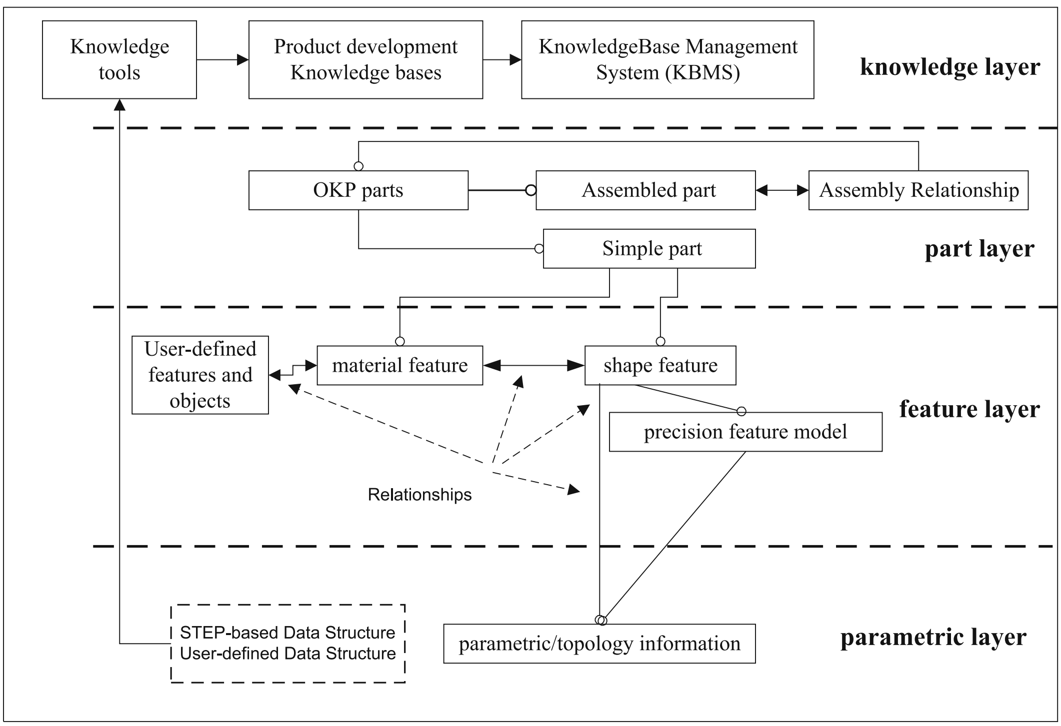

Fig. 2. The product knowledge structure model

- Web-like structure of the concept that is a result of multiple links and dependencies,
- dynamic nature of the data over the course of product development.

The basic part of the model is a “Part”. Such a part can be the piece that cannot be disassembled (called “SimplePart”) or the piece composed from two or more other pieces with defined relations between them.

On the above figure, four models in the knowledge structure model may be noticed: description model, geometric model, material definition and feature model. The task of the description model is to define descriptive, non-geometric information about the product or assembly element. The description module works with standard classes and types defined by the ISO 10303 standard. The entity product is the basic part of the description module and its purpose is to describe the physical object that emerges from the some process. The geometric definition of the product is the basic definition from which follows all the necessary information for analysis or product realisation. The feature module is the variation of the geometric modelling, but due to our specific approach, it is separated into different modules. The material definition module contains all of the information about materials that are necessary for the modelling or the product realisation. Figure 3 presents a subset of entities for the product structure description module.

This model is very complex because it contains an extremely large amount of information about a product. The majority of information is stored in the geometry and feature modules, and that is a reason for simplifying the model for product structure description. For the purpose of simplifying the model, this paper will not consider the details of the geometry or features and focuses on the description of a product. Figure 3 shows how a product object is defined and modelled. The product object will be filled in with information relevant to the product. The content of the object together with its relationships will be added into the DSS, which will be used in the product development process.

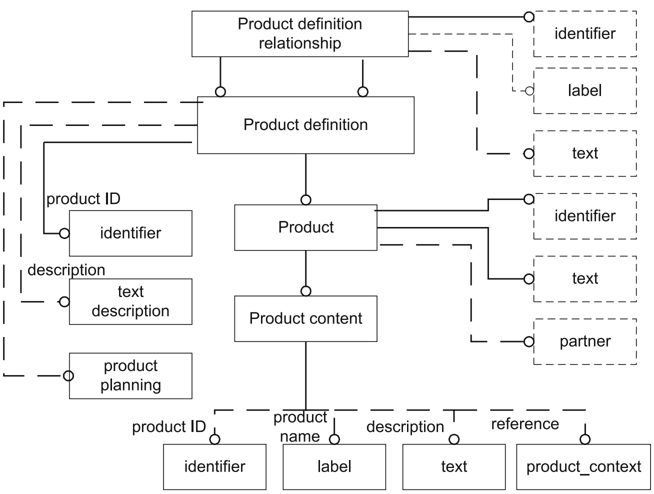

Fig. 3. The product structure description model

5 Database implementation of the EXPRESS model

The EXPRESS information models defined by ISO STEP describe a logical structure that must be mapped into database structures to create an information infrastructure. EXPRESS is technologically independent when developing information models for product data exchange. An EXPRESS model can be mapped to multiple data processing processes and can be used as the common basis for product data and design knowledge exchange between engineers and engineering systems. Four implementation levels have been proposed for EXPRESS information models [21] (Fig. 4):

- File exchange: product data is moved from a software tool into and out of a standard exchange format.
- Working form exchange: product data is moved from an application program into and out of a temporary working database through standard software calls. The access software has no database capabilities beyond data manipulation and navigation.
- Database exchange: product data is moved into and out of an Internet-based database management system [22]. The system must be accessible by standard exchange format files, standard access software function calls, and standard DML statements, such as SQL.
- Knowledgebase exchange: the product knowledge structure model is moved into and out of a knowledge base management system. The system will support all lower implementation levels and will enforce all of validity constraints specified in the implementation models.

The database implementation process can be divided into two stages [15]. The first stage is to convert an EXPRESS information model to a structure definition for target DBMS. The second stage is transfer EXPRESS-defined data into database and out of it. Although it is technology-neutral, EXPRESS is suitable for information models that challenge the capabilities of many existing database systems. A number of research groups have been recently reported to map EXPRESS to other data models like network, hierarchical, relational and object models.

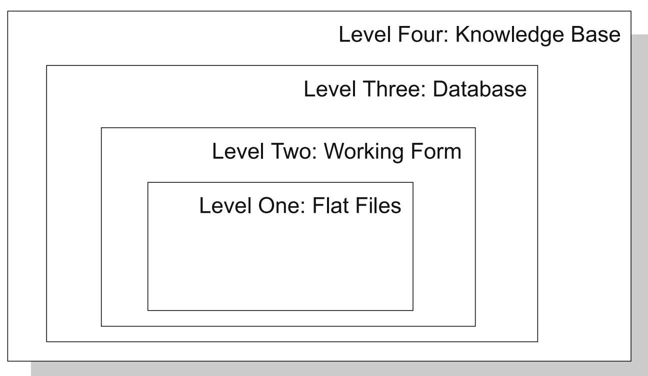

Fig. 4. STEP implementation levels for EXPRESS information models

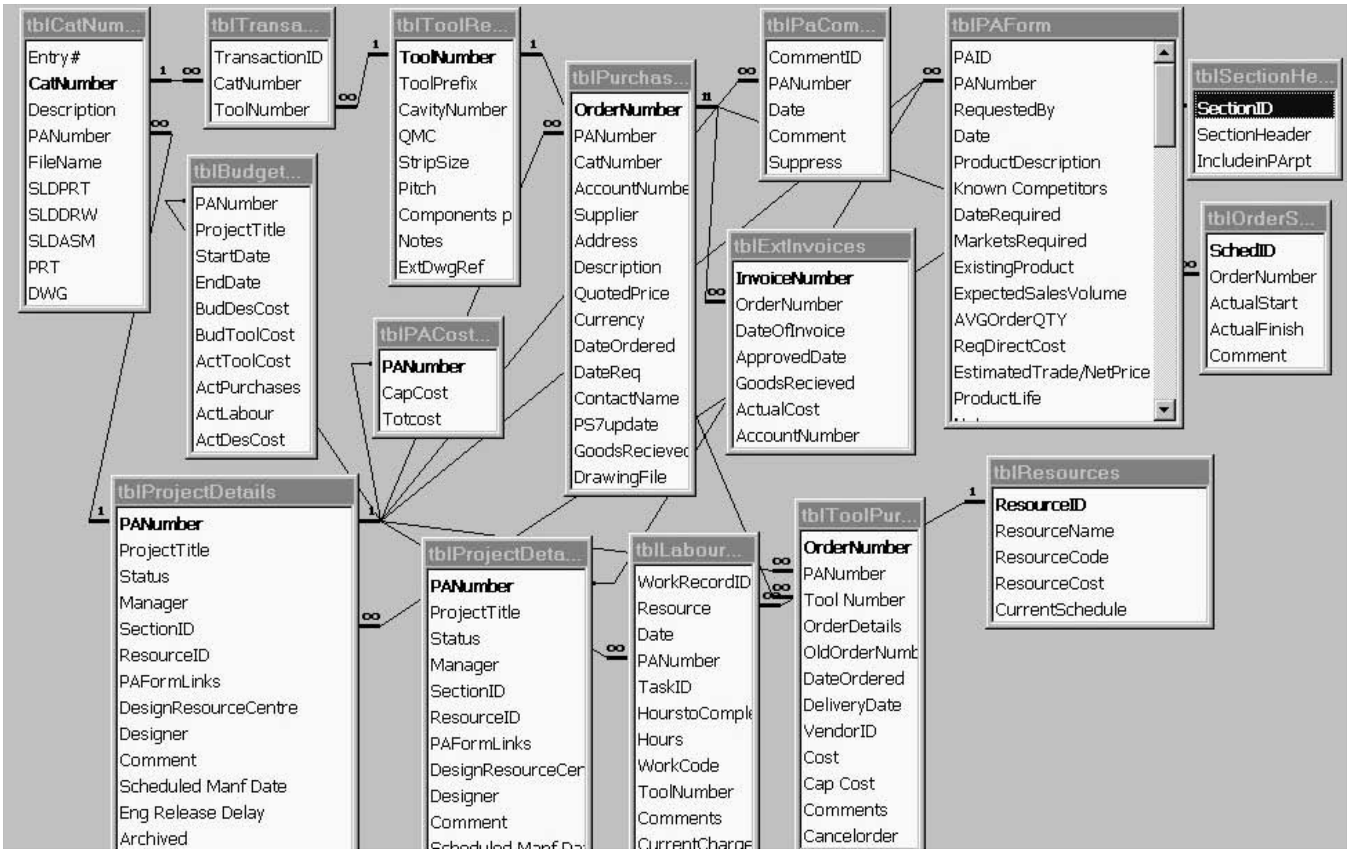

Fig. 5. A subset of EXPRESS model entities after mapping into a relational database structure

Implementations may require heavy encoding to represent the full range of EXPRESS structures within a target database system.

As a part of the ongoing project in development of the Internet-based rapid OKP development system [19], the implementation of the proposed product structure model into a relational database structure was put in place (see Fig. 5). This implementation maps EXPRESS to a relational model. Tables for each entity are created. Columns for each attribute of the entity are defined. Each table has a column with a unique identifier for each instance. Attributes with composite values like entity instances are stored as foreign keys containing the unique instance identifier. Relational database data types are substitutes for the EXPRESS primitive data types. Once a database is built, the connection to the knowledge-based DSS (see Fig. 1) is not a hard task.

6 Implementation

The DSS has been tested in an injection mould company in Christchurch. To develop different OKPs, the actual models in the system will be different. For example, the system for sheet metal product development included IT tools such as an information integration framework, a real-time computer-aided process planning module, a nesting tool for optimal cutting/punching, an optimal tool for tool selection and design/manufacturing knowledge bases. A similar DSS for rapid tool/mould making contains a different set of IT tools such as a design-for-cost/manufacturing module, a cost knowledge base and a product information management base for similar product development. This system has been implemented in a leading New Zealand electrical appliance manufacturing company. The company produces various industrial switches, control systems, and electrical appliances. In terms of the data structures and general information system framework, the product design/manufacturing knowledge bases for rapid OKP development and the STEP-based product databases have been built to support the company's rapid industrial switch development, inclusive of product development and mould/tool making.

In order to share the data and knowledge among the people in the company's branches that are located worldwide, the structure of the Internet-based DSS that has been developed for a manufacturing company in New Zealand. This system includes the Internet-based software tools for information management and sharing among different departments, the integrated data environment and interfaces, a CORBA-based distributed environment, customer interfaces and several knowledge bases. The Internet-based database publishing tool and object communication tool were developed to dynamic publish an Access database onto an Internet platform.

According to the customer's requirements for a particular type of electrical switch, the searching model in the system can find a prototype, i.e. a product produced by the company in history that has the maximum sum of endeavour rates. For this case, the prototype found by the system is a 626VC industrial switch in the 300 series. The output from the system is shown in Fig. 6.

Figure 6 shows a dynamic user interface on a Web page. From this interface, a user can quickly search the necessary information to produce the 626VC switch. As shown in Fig. 6, a list of buttons is designed for the user to access relevant information to develop the product. The user, for instance, can quickly get a CAD drawing of the product by double-clicking "626VC" in the "Drawing" box, an the assembly illustration by clicking the "Product Assembly Picture" button on the right hand side of the page. Table 1 shows some examples of the buttons and associated information links.

Figure 7 shows the assembly picture of the 626VC switch and a list of assembly parts of the product and their part descriptions are also built into the knowledge base. The associated tools for producing 626VC can be found by clicking the "Tools that make product" button. The designer's information will be displayed after clicking the "Product Designer(s)" button. As shown in Table 1, comments and discussions made at earlier product design stages can be accessed by clicking the "Product Design Questions" button. Project appraisal information such as order, delivery and cost information will be displayed by clicking the "Project Appraisal" button. All of the relevant data and information through a product development cycle are recorded.

Table 1. Examples of buttons and associated information links

Button	Information link(s)
Mould flow results	Mould flow test results
Tools that make product	Associated tool information
Product design questions	Comments and questions made at the product design stage
Product designers	Designer's name, experience, cost, etc.
Product appraisal	Order information, delivery time, cost

This Internet-based information management system automatically brings up the data relevant to 626VC from these computers (or databases) via a front-end user interface to the users who have the right to access this communication network from anywhere in the world.

Figure 8 shows a screen print of a manufacturing interface, which was designed to share manufacturing knowledge. From this interface, a user can quickly search the existing machine tool information for producing 626VC. Production engineers can quickly search the available machine tools in the manufacturing plant by clicking the "Machine Tools" button. For example, as shown in Fig. 8, a list of machine tools is shown when the "Machine Tools" button is clicked and the searching requirements are specified. The machining cost was also modelled and stored in the machine and tool database, which was used as a data resource for a cost optimisation algorithm. Further information is also accessible through a list of labelled buttons, which lead to

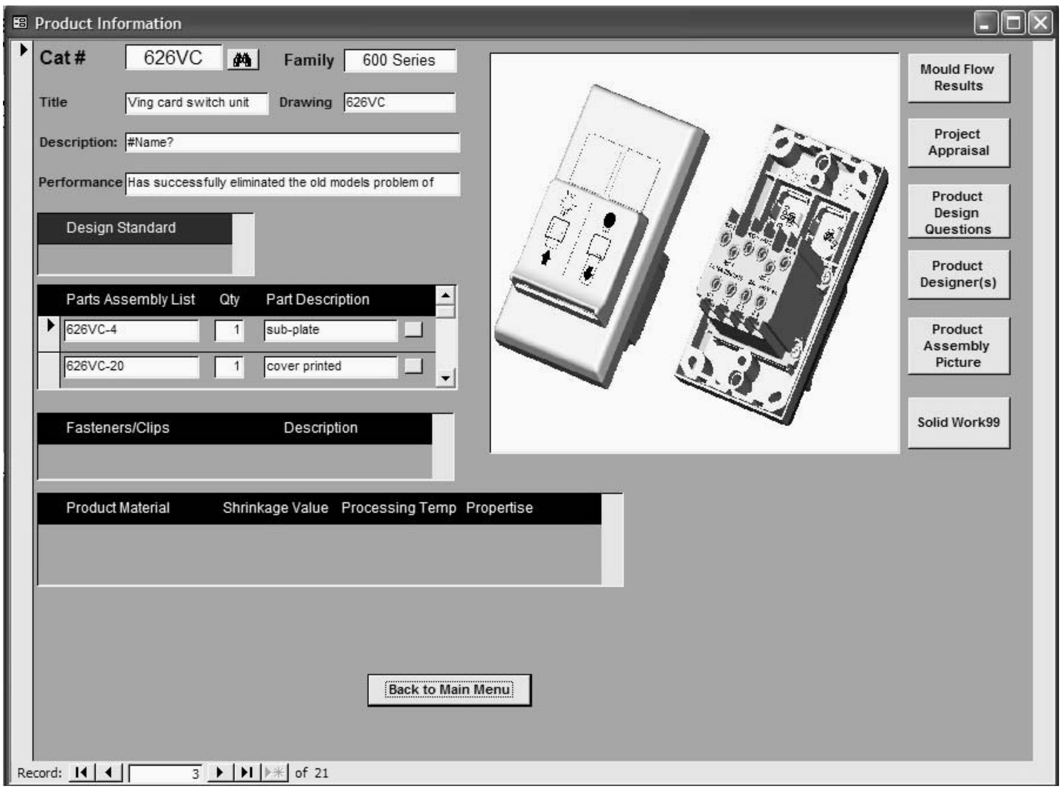

Fig. 6. The product interface

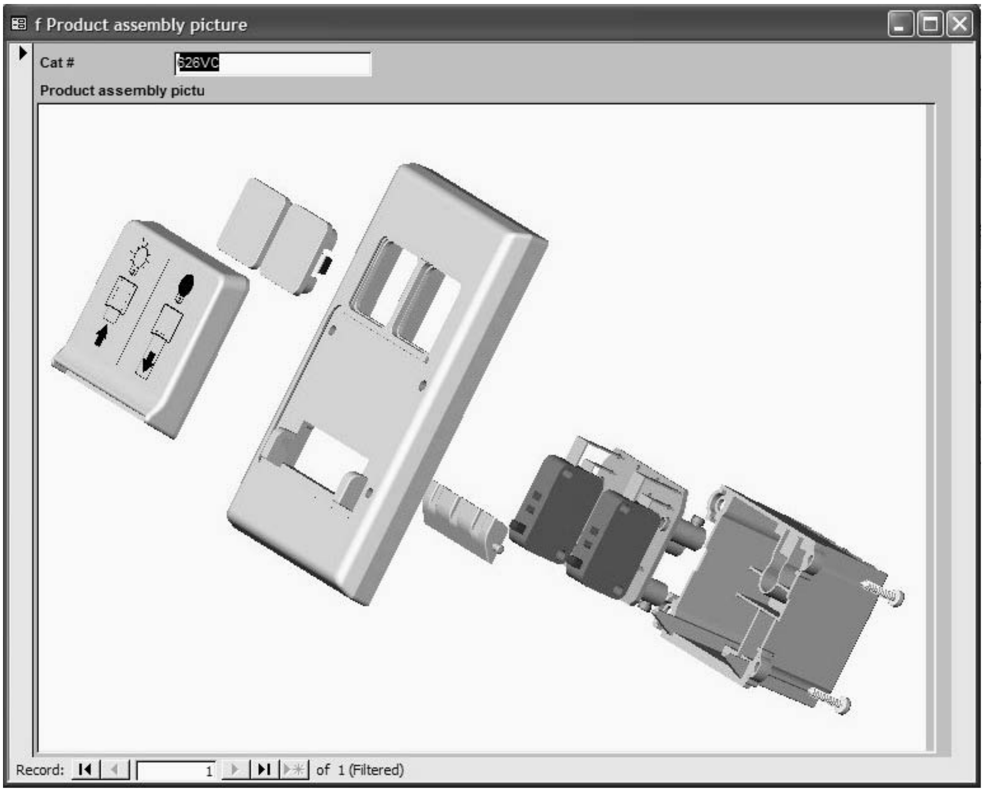

Fig. 7. Associated information links for producing a 626VC switch

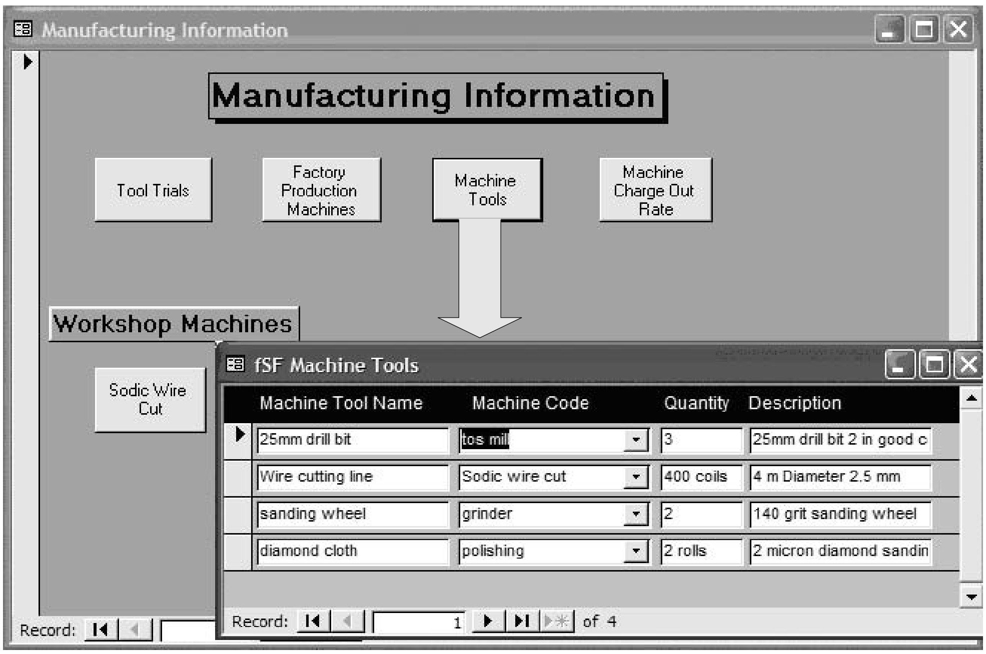

Fig. 8. Manufacturing interface

more tailored interfaces, including tool trial and production work request information, workshop machinery details, workshop machine tool information and production machinery details.

The DSS also contains a cost estimate and optimal control tool. This tool works in the following sequence: first, after receiving the requirements of a product, this tool searches the project appraisal database for the cost information of similar products. If there are similar products available, the cost of the most similar product will be picked up and used as a reference for early decision-making. Second, if there are no similar products in the database, the cost estimate and optimal control tool will search all of the relevant databases, fill in the dynamic programming network according to various process plans, and find the optimal cost and plans. Final cost information and process plans are reported to the product development team.

7 Discussion

Knowledge-based decision support systems have reduced technological barriers and have made it easier and less costly to make decision-relevant information and decision support tools available to managers and users in geographically distributed locations. Because of the World Wide Web infrastructure, an enterprise-wide DSS can now be implemented at a relatively low cost for geographically dispersed partners, including suppliers and customers. Using knowledge-based DSS, organizations can provide DSS capability to managers over an intranet, to customers and suppliers over an extranet, or to any partners over the global Internet.

The Web has increased access to DSS opportunities, and it should increase the use of a well-designed DSS in a company. Using a Web infrastructure to build a DSS improves the rapid dissemination of "best practices" analysis and decision-making frameworks, and it should promote more consistent decision-making on repetitive decision tasks across a geographically distributed organization. The Web also provides a way to manage a company's knowledge repository and to bring knowledge resources into the decision-making process. One can hope that Web-based delivery of DSS capabilities will promote and encourage ongoing improvements in decision-making processes.

What are the potential problems with the knowledge-based DSS? First, user expectations may be unrealistic, especially in terms of how much information they want to be able to access from the Web. Second, there may be technical implementation problems, especially in terms of peak demand and load problems. Third, it is costly to train decision support content providers and to provide them with the necessary tools and technical assistance. Fourth, Web-based DSS create additional security concerns. Finally, the integration of the knowledge-based DSS with other OKP development tools will be a main issue. According to a survey carried out in our research group in 1999, there are overall 30 different software tools employed in OKP companies in New Zealand [23]. A research project, funded by the Public Good Science Funding of New Zealand, is underway in our research group to propose an Internet-based open platform to further integrate the knowledge-based DDS with the tools used in those OKP companies.

8 Conclusions

This work presents a knowledge-based decision support system for supporting rapid development of OKPs. The knowledge-based system enables an OKP company to harness geometric definitions, through commercial CAD systems, along with the knowledge of its experts, product rules, performance data, legislative and safety codes, and design and manufacturing best practices. With the support of such a system, smart decisions can be made when the product to be developed is in different stages. The system can also provides advice on the real-time changes of customer requirements and design configurations. Case studies in Sect. 6 shows that the knowledge-based system has greatly reduced the possible errors and rework in a mould manufacturing company. The proposed DSS will help OKP companies in the following respects:

1. Supporting manufacturing optimisation and cost reduction: the knowledge-based DSS, together with other tools such as partner-selection tools, cost-analysis tools and planning tools, can dramatically affect the overall product development cycle time, quality and the company's reputation.
2. Integration of product life-cycle: Although the competitiveness of products primarily depends on their quality and cost, considerations of the efforts involved in other product life-cycle phases, such as service/maintenance, system maintenance, system upgrade, recycle/disposal, etc., have become very important in today's marketplace. The proposed knowledge-based DSS is readily extendable for integrating the tools/software used in other life-cycle phases.
3. The DSS supports the integration of an OKP company with its partners and customers: as OKP development process is no longer carried out by a single company, this system provides a knowledge-based platform for OKP companies to join efforts with others to fulfill the requirements of customized products demanded by the market.

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