A PDM-based Framework for Design to Manufacturing in Mold Making Industry - A Case Study of Business Process Integration

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ABSTRACT

As the product market lifecycle is becoming shorter, molding companies are forced to reduce the time to market. At the same time, the pressure of time-to-market is also conveyed to mold making companies. To rapidly respond to molding companies and retain customers, mold making companies have to improve their overall business performance. At present, mold making companies are faced with an inefficient Information Technology (IT) environment that lacks of integration and is not capable of effectively supporting information sharing and exchange. As a result, the overall business performance can not be improved as expected though the efficiency of individual activities has increased by the corresponding software systems. This paper presents the design and development of a PDM-based system for the integration of critical business processes, including design, planning and production, to enable higher business performance. The PDM system is first extended to manage non-engineering data and support business activities of planning and production. Then, the integration-supported models, including design model, routing planning model and task model, are presented from the perspectives of information association and process automation. The integration of workflow management to streamline business processes is also investigated. Finally, the system implementation is briefly introduced.

Keywords: Integrated Manufacturing, Process Integration, Enterprise Integration.

1. INTRODUCTION

Mold making companies, which are typical small and medium-sized enterprises (SMEs), usually operate in a make-to-order fashion. They are faced with the challenge of frequently changing customer requirements and have to rapidly respond to customers to gain business opportunities in competitive market [9]. As the product market lifecycle is becoming shorter, mold making also have to shorten their business cycle to rapidly respond to molding companies. Nowadays, many mold making companies have indicated that they are often requested to deliver molds to molding companies in three months. To survive in such a competitive market, mold making companies are seeking solutions to improve their overall business performance by integrating critical business processes, i.e. design, planning and production.

Design is the process of converting the needs and requirements for a product into specifications about a product, such as structures, functions and behaviors [10]. The design process mainly attempts to manage information and documents about products, parts and subassemblies, such as engineering drawings, solid models, product structures, product specifications and engineering changes, etc, for the excellence of design in terms of quality and efficiency. Planning, which is a bridge to link design and production, aims to make designs be realized cheaper, faster and better. Main activities in the planning process include routing planning, master planning and production scheduling. Production is the process to realize designs by managing workshop tasks according to the schedule generated at the planning stage. These three processes are closely interrelated and need to communicate with each other frequently. However, many mold making companies are faced with outdated and inefficient IT environment which can not effectively support information sharing and exchange between these business processes. Their adopted software systems work autonomously and independently. It leads to information islands which are one of the factors that hamper the enhancement of the overall business performance [8]. Information sharing and exchange between the systems still rely on paper-based documents and electronic files. Therefore, though the working efficiency of individual activities has increased, the overall business effectiveness is not improved as expected [13]. In addition, these standalone systems manage various types of information in different databases. Relevant information can not be linked together to form continuous information flows to support the integration of related business processes.

At present, to manage the entire business process, enterprises have to adopt a PDM system for managing product design and development, and an ERP system to support order processing and production planning. Both PDM systems and ERP systems are every expensive and difficult to implement, with potential failures. In this case, enterprises have to maintain two systems. In addition, information sharing between two systems is still a problem faced with enterprises. A significant industrial need is that one system can offer both functionalities of traditional PDM systems and ERP systems. The observation is that PDM vendors are intending to develop the functions conventionally offered by ERP systems into PDM systems. Meanwhile, ERP vendors also attempt to incorporate design management functions to ERP systems. This paper presents the design and development of a system for integrating design, planning and production processes based on the PDM framework. The system seamlessly integrates various types of information together to form continuous information flows to facilitate the interaction and automation of design, planning and production processes.

2. PDM-BASED INTEGRATION FRAMEWORK

Driven by the need of easy, quick and secure accesses to valid data throughout the design process, Product Data Management (PDM) systems appeared to control and manage product design [1]. The main objective of early PDM systems was to provide users with required data by managing a centralized design repository. At present, to synchronize data creation and modification and enable concurrent engineering, the PDM framework has been extended with new functionalities, such as change management, documents management and workflow management [3]. Although PDM systems effectively streamline the design process through the management of design data and documents, they are incapable of managing information related to non-engineering areas, such as sales, planning and production, due to the limited scope in terms of data. However, process integration can only be achieved when information can be shared and exchanged across different business processes. Thus, in process integration, it is essential to manage and associate various types of information according to the needs of different business processes. To enhance PDM systems for the integration of design, planning and production processes, the PDM repository is extended for managing non-engineering data. On the top of the informational extension, the PDM functionality is also expanded as PDM-based integration framework to assist planning and production activities, as shown in Fig. 1.

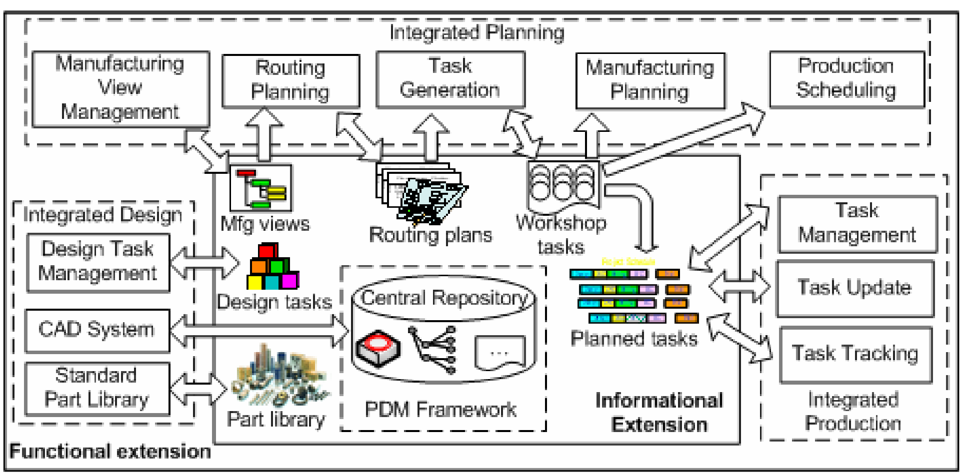

Fig. 1. PDM-based integration framework.

Fig. 1 shows the extension of the PDM central repository to accommodate three types of non-engineering information, which are manufacturing views, routing plans and workshop tasks. The extension put emphasis on the associations of these types of information to streamline business processes. Product structures are key information created in the design process. In general, PDM systems are capable of managing solid models, product structures and other documents. A product structure represents the constitution of a product by providing a hierarchical classification of parts and subassemblies that forms the product. Product structures are a means to reflect product constitution from the structural and functional viewpoints. In planning, the focus is on how to get the parts needed and which parts should be assembled together first. Therefore, at this stage, constitutional parts and subassemblies are classified into two groups: made internally and purchased from suppliers. In production, only items that are to be made internally are of interest. It means that different business processes look at the constitution of products from different perspectives. In the context of planning and production, the manufacturing view is another means that is used to reflect the constitution of products. Similar to a product structure, a manufacturing view also adopts a hierarchical structure to reflect the manufacturing precedence and assembly relationships of constitutional parts and subassemblies in a product. To facilitate integration, it is necessary to extend the PDM framework to manage manufacturing views.

Process plans are critical documents that provide instructions for operators to carry out machining operations. There exist two types of process plan documents that can be used to guide operators to machine parts: routing sheets and operation sheets. Due to the difference in production organizations and batch sizes, some companies use operation sheets and others use routing sheets. In general, operation sheets contain more detailed information about individual machining operations than routing sheets, which usually provide information about a group of machining operations. Routing sheets usually do not provide cutting parameters of machining operations. Operators need to decide cutting parameters based on experiences or manufacturing manuals, which are usually dedicated to the company. Routing sheets are often used in single or small batch production while operation sheets are more suitable for batch production to achieve high productivity. As molds are usually produced in single batch based on customer orders, the current PDM central repository is extended to manage routing plans.

Machining operations in routing plans need to be scheduled and assigned to proper time slots. Then, workshop supervisors assign machining operations to operators for execution. At workshops, machining operations are managed as tasks. Workshop tasks play a role of linking the planning process and the production process. They need to be represented in a unified way and managed in a central database to make them sharable to planning and scheduling as well as assigning and tracking.

Manufacturing views, routing plans and workshop tasks are three key types of information that flow through the processes of design, planning and production. Manufacturing views should be constructed based on product structures and synchronized with product structures. As the production process is only interested in parts/subassemblies that produced internally, routing plans need to be created based on manufacturing views, which contains information about make-buy decisions made by the production manager. Therefore, manufacturing views are the linkage of the design process and the planning process. Workshop tasks are determined based on routing plans and manufacturing views. Workshop tasks need to be scheduled before being released to workshops for execution. Obviously, workshop tasks are commonly shared by planning and production. It is imperative to manage these types of information in the central database and make them sharable and exchangeable between business processes. As a result, continuous information flows can be achieved to support business activities carried out by people with different disciplines.

As shown in Fig. 1, the extension of functionality is proposed in accordance with the three business processes to assist business activities and information management. PDM systems put focus on the management of engineering information in design. However, few PDM systems stress the management of design tasks. Effective design task management can greatly enhance the traceability of the design process, improve the effectiveness of task assignment and help to achieve the balanced progress of design. Therefore, design task management is proposed to assist task assignment and design task tracking. In the planning process, routing planning is to assists the routing planner to create routing plans for parts. Task generation is designed to generate workshop tasks based on routing plans. Manufacturing planning and production scheduling are functions for the production planner to do planning and scheduling. In the production process, task management is provided for workshop supervisors to do tasks assignment and tracking. Tasks update is for operators to log the progress of task execution. Task tracking assist eligible people to capture the progress of production.

3. INTEGRATION OF DESIGN

To further improve the management of design process and facilitate the integration with other business processes, the design integration model shown in Fig. 2 has been developed on the top of thee product structure management of a PDM framework.

In the manufacturing view management, an essential requirement is that the manufacturing view of a product should be independent of the product structure and, at the same time, it should be easily synchronized with the product structure. In other words, the product structure of a product should be kept unchanged while constructing the manufacturing view of the product. Changes of the product structure of a product should be reflected to the manufacturing view of the product. For example, when a part is removed from a product, the manufacturing view management should be able to detect this change and keep the view consistent with the product structure. To fulfill this requirement, the model adopts product references, represented by the class *ProductRef*, and part references, represented by the class *PartRef*, as the means for constructing manufacturing views. A reference is a pointer pointing to a product or a part. According to the model, a manufacturing view consists of a set of instances of *PartRef*, which are organized in a hierarchical structure and an instance of *ProductRef* acts as the master of a manufacturing view. Apparently, the manufacturing view of a product can kept independent of the product structure because the manufacturing is constructed using references. A reference of a part or a product is does not contain the actual data of a part or a product. Therefore, no duplications of data exist and data consistency can be easily maintained. When a part is removed from a product structure, the association between the part and its reference will not exist. The part reference in the manufacturing view becomes a floating reference. When a part is added to a product, the part is an unreferenced part. These can be easily reflected to the manufacturing view management. The synchronization between a manufacturing view and the corresponding product structure can be achieved.

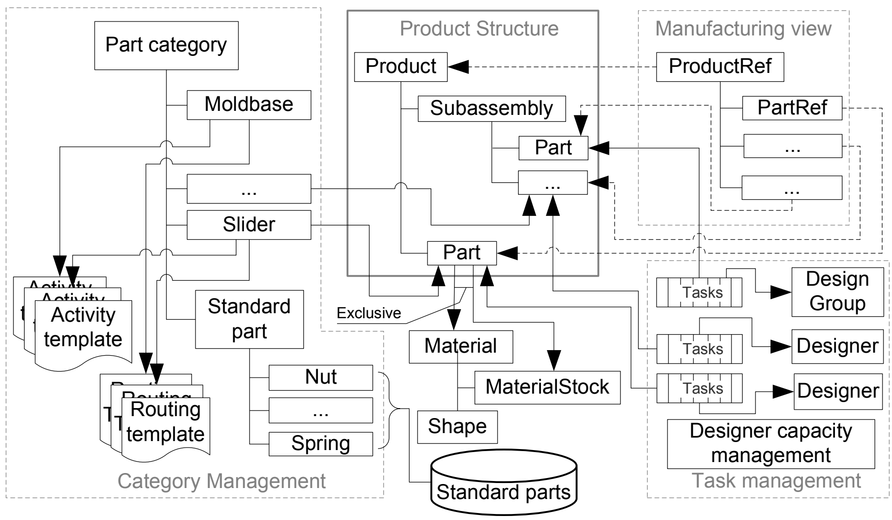

Fig. 2. Design integration model.

The model manages part categories to automate the generation of routing planning. As shown in the model of Fig. 2, part categories are represented in a tree structure. Each part should be assigned a category and each part category, except standard part and its sub-categories, has a routing template associated. A routing template can be understood as a typical routing plan for the parts of a category. When a design is completed and the part is being released for planning, the routing template for the category of the part can be used to automatically generate a routing plan for the part as its default routing plan.

Design is one of the critical phases in the product lifecycle as decisions made at this stage not only directly affect the characteristics and quality of products but also cause impacts to other phases. For example, materials and structures that have been decided at this phase can be the factors that primarily determine the cost of manufacturing the parts. A research revealed that 70 percent of product cost throughout product lifecycle is determined by decisions made at the design phase although design itself accounts for only 5 percent of the total costs under traditional cost accounting methods [7]. Effective task management in design is imperative and critical in the control of design quality and progress. In general, task management involves task generation, task assignment, task execution and task tracking [6]. In mold design, the first step is layout design which is to determine the overall structure of a mold and the specifications of key parts, such as mold base and ejection mechanism, by analyzing molding parts and customer requirements. This step results in a preliminary mold structure. Fig. 2 also shows that each part category has associated with an activity template. An activity template defines the detail steps of the design of the part of a category, such as structure analysis, pressure verification or simulation. Based on the preliminary structure and activity templates, design tasks can be automatically generated. Then, the design manager can assign the tasks to individual designers or design groups. The available capacity of designers are managed to assist the design manager to do task assignment. With the help of the available capacity, the effectiveness of tasks assignment can be improved to balance the work load of each designer to ensure the overall progress of a mold design.

In addition to the support of manufacturing view management, part category management and design task management, material information is also integrated with the product structure management to support design. The material of a part can be specified either as a material or a material stock as shown in Fig. 2. It has to be pointed out that materials in the model are characterized by chemical and physical properties while material stocks, which are usually managed in inventory, are characterized by various sized shapes of materials, such as round bars of steel. The information of materials and material stocks is managed in the central database and made sharable to design, planning and production. As a result, material information can be kept consistent throughout three business processes.

4. INTEGRATION OF ROUTING PLANNING

Different companies have different sets of manufacturing resources. In other words, different companies have different manufacturing capabilities. Routing plans should be developed in accordance with the manufacturing capability of a company. Otherwise, a routing plan may be theoretically correct but not reasonable to a company. A means to enable a company to define its specific manufacturing capability for routing planning is essential to create routing plans that are reasonable to the company. The manufacturing capability of a company can be represented by a set of machining operations that can be carried out by the company. In some sense, the manufacturing capability of a company is the summation of the capability of all the machines of the company. The customization of the manufacturing capability of a company is achieved by defining the capabilities of the machines of the company, as shown in Fig. 3. In manufacturing companies, machines are usually organized into different logic groups, which are called work centers. The capability of a work center is the aggregation of the capability of machines in the work center.

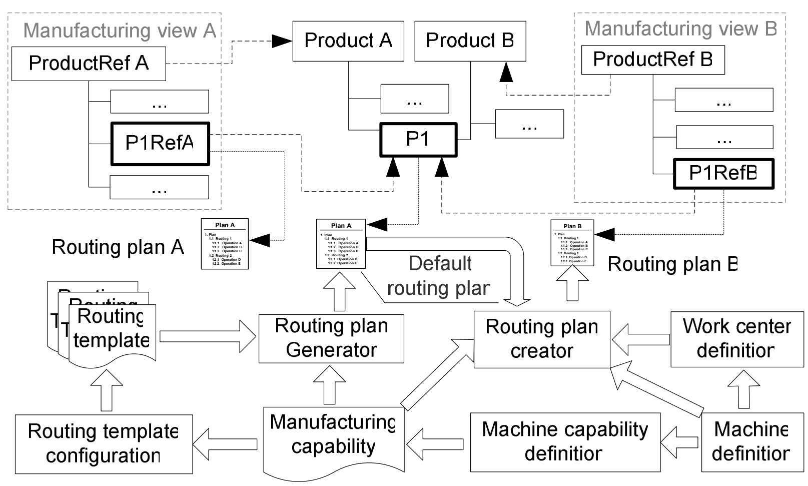

Fig. 3. Routing planning model.

The objective of routing planning is to achieve the design specifications of products in an economic and efficient way. In general, key parts are not sharable between molds. Therefore, routing planning usually needs to be done for key parts of each mold. To take advantage of the similarity of parts and improve the working efficiency of routing planners, a template-based routing method is developed, as shown in Fig. 3. A routing template is a master routing plan for a part family. Master routing plans can be developed based on composite parts, which are hypothetical parts that are used to represent all of the design and manufacturing attributes of each part in individual part families. As discussed above, each part category can have a routing plan template associated. The routing plan generator can automatically generate a default routing plan for the parts of the category at the time of release. Routing templates are also integrated into the routing planning creator, which is graphical environment for the routing planner to manually create routing plans. While creating a new routing plan, the routing planner can manually specify a routing template to generate an initial routing plan. In this way, routing planners do not have to create routing plans from scratch and their work efficiency can be improved.

As shown in the routing planning model, routing planning is done based on the manufacturing view. When initializing a reference of the part, a routing plan can be created for the part reference by copying the default routing plan, which is automatically generated based on a routing template. Routing plans that are associated with part references are actually used in production. This enables a part which is shared by different products to have a different routing plan in each product. Put it in a simple way, a part can manufactured using different ways when it is used in different products. For example, say *Part P1* is shared by the products A and B. The reference *P1RefA* in the manufacturing view A has a routing plan associated and the part reference *P1RefB* in the manufacturing view B can have a different routing plan associated. It means that the model is capable of keeping different versions of routing plans for the same part in different products. This feature is very significant to mold making companies because of the particular characteristics of mold making. As mentioned, mold making companies usually operate in a make-to-order manner because molds have to be specifically produced based on the requirements of individual customers. Since molds are different from the merchandizes that are popularly traded in the market, few third parties produce exchangeable key parts of molds for the replacement of damaged ones. Molding companies usually have to order the replacements of damaged parts from the original maker of the mold. When a mold reaches the end of its life, the molding company also has to order a new mold from the same mold maker. The necessity is that mold making companies are able to quickly find the historical routing plans. The routing plan may need to be improved in the reproduction of some key parts or a whole mold. At the same time, the original routing plan should be kept unchanged as historical data for the auditing purpose. In these cases, a new manufacturing view can be created for the product and original routing plans are copied and associated with part references in the new manufacturing view. The improvement to the routing plans can be done based on the new manufacturing view to keep the original routing plans untouched.

5. INTEGRATION OF TASK PLANNING AND MANAGEMENT

In an environment without the integration of design and planning, software systems that work standalone can not share information with each other. Information exchange between systems can only be done via paper-based documents or electronic files. The production planner usually has to determine workshop tasks based on product structures and routing plans before carrying out planning and scheduling. The scheduled machining operations need to be documented and further passed to corresponding workshop supervisors. In such an environment, the coexistence of the same piece of information is inevitable and information synchronization is difficult. This would definitely cause inefficient information exchange and much time will be spent on data re-organization and re-enter. The developed system integrates design, planning and production and enables information sharable to all the activities in these business processes. Therefore, a unified task model that is capable of supporting task generation, planning and assignment and tracking has been developed, as shown in Fig. 4.

Designed parts are realized by carrying out a set of machining operations on raw materials. At workshops, machining operations are managed as a set of tasks. A task is a machining operation to be done on a part by an operator on a machine. Therefore, the model represents a task as aggregation of a part and an operation of a routing plan for a part. As indicated by the model, tasks are generated based on a manufacturing view and routing plans. A manufacturing view is constructed with two concerns: 1) whether a part is to be made internally or outsourced to externally partners due to the constraint of manufacturing capability and/or the lack of capacity; and 2) the manufacturing precedence of parts according to assembly relationships. Tasks should not be generated for standard parts and outsourced parts. Actually, purchase requests should be generated for the purchasing department to prepare purchase orders if purchase management is integrated.

To fulfill the due data of a customer order, the tasks related to a product should be well planned before being released to workshops for execution. In general, the schedule of tasks related to a product is achieved by two consecutive activities; that is, master planning and production scheduling. Master planning, which is usually done on the basis of individual products, is mainly to determine time periods during which individual parts of a product must be accomplished. Production scheduling takes one step further to allocate time slots to each task in accordance with available machines. To support planning and scheduling, four attributes are incorporated into the task model to record time periods using the pair of start date and end date and time slots using the pair of start time and end time. As a result, tasks can be directly used as the inputs of master planning and production scheduling without any transformation needed. The results of master planning and scheduling can be directly recorded in tasks.

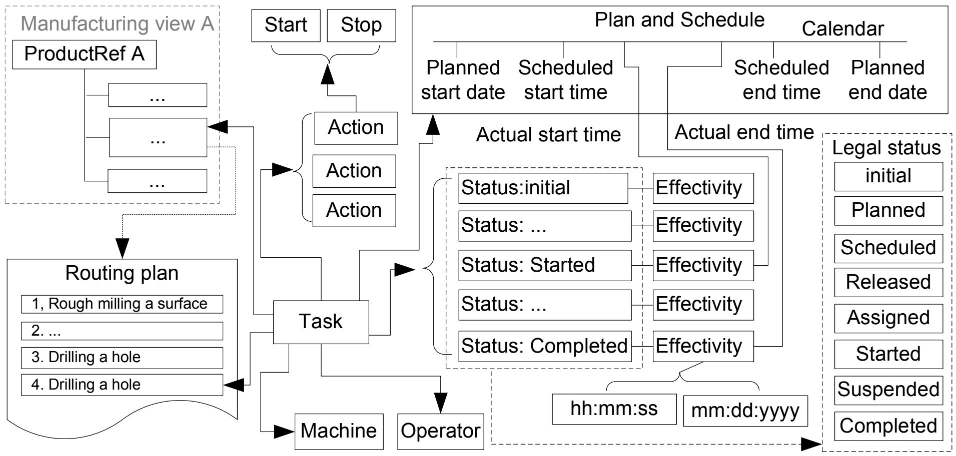

Fig. 4. Unified task model.

It can be seen that the model adopts status as a means to support task management and tracking. In business process integration, status represents the current issue of a state change of a data entity or a task [3]. Status management provides a "push" mechanism to share mature data with downstream activities of business processes [11, 12]. As a result, maturity criterion is provided for triggering downstream activities to enable better concurrency. According to the task model, after being generated, tasks are in the status of "initial" and waiting for planning and scheduling. Scheduled tasks are ready to be released to workshops for execution. Only released tasks can be assigned to operators by workshop supervisors. Assigned tasks will have operators and machines associated to indicate the task owner and the machine for use. The statuses "suspended" and "cancelled" are special ones for the management of exceptions and changes that take place at the production stage. The tasks have to be suspended in the following situations: 1) changes are requested by customers; and 2) the payment is delayed in terms of payment terms and the credibility evaluation of the customer is failed; and 3) design flaws are identified at the production stage. In these cases, some tasks may resume and others should be cancelled. These suspended and cancelled tasks should not be physically deleted from the database. They have to be kept for the purposes of cost analysis and auditing. Therefore, the model allows a task to have multiple statuses associated. Each status has effectivity to record the time when the task evolves to this status. The current status can be identified by using effectivity. The duration of a status can be calculated based on the effectivity of the status and the effectivity of the next status. The duration of the execution of a task can be calculated based on the effectivity of the status "started" and "completed". As such, the status evolution path of a task assists to track task progress and resource consumption, and helps to achieve more accurate cost analysis. It has to be pointed out that the time captured based status is the duration of activities. In the model, the action is modeled for capturing the actual time the operator spends on a task. Accordingly, the function "Task Update" shown in Fig. 1 is modeled for operators to log the start times and stop times of actions. The barcode technique may be used to integrate machines into the system to automatically capture the start times and stop times of actions.

6. WORKFLOW-DRIVEN PROCESS AUTOMATION

Workflow aims at the automation of procedures to pass documents, information or tasks between participants based on a defined set of rules. A workflow reference model has been defined by the workflow management coalition (WfMC) [5]. It provides a standard framework which describes a set of interfaces to enable the interaction between supporting tools, execution services, client applications and external applications. Based on this framework, the main characteristic of a workflow management system is that the workflow logics are decoupled from the workflow management program. In other words, a complete workflow management system consists of two components: 1) a modeling tool for creating workflow models; and 2) an execution service to run workflow instances created based on workflow models. Therefore, a workflow management system offers: 1) the flexibility to configure and reconfigure the flows of documents, information or tasks; 2) the automation of status evolution based on a defined flow model; and 3) an efficient environment to proactively push documents, information or tasks to participants. As such, some workflow management products have been quite successful in the market, such as *Staffwaree*™, *InConcerte*™ and *FlowMarkare*®. The PDM framework also defines workflow management as a basic function of PDM systems.

To take the advantage of workflow management and automate business processes, the workflow management capability is integrated to manage product design, route design tasks, control the release of parts and routing plans and govern the evolution of workshop task status, as shown in Fig. 5. The workflow for products is to control the stages of the product lifecycle from design, manufacturing view definition, routing planning, master planning and production scheduling. The part workflow is to control the flow of design tasks, such as requirement analysis, structure analysis, detail design, design reviews and release. When the part comes to the state "released", the product workflow is notified to determine whether the product lifecycle should be promoted to the stage of manufacturing view definition. In the model, a robot is a computer program to automatically control the promotion or demotion of a workflow. The robot between "Design" and "Manufacturing view" does not promote the product workflow to the manufacturing view state until all parts are released. Similarly, the robot between "Task release" and "Complete" only promotes the product workflow to "Complete" when all the tasks related to a product are completed. While generating workshop tasks, the task workflow is associated with each task to control the status of tasks. In the diagram, an or-split indicates that the workflow only move forward along one of the branches.

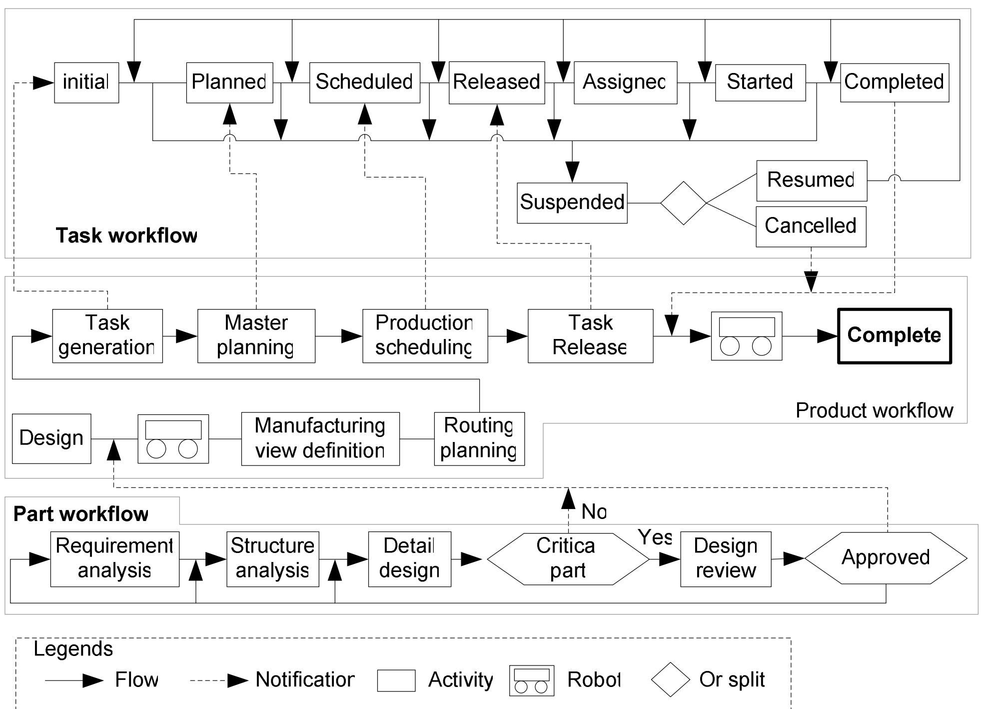

Fig. 5. Workflows for products, parts and tasks.

7. IMPLEMENTATION

The process integration involves in process analysis and redesign, integration platform selection and integration development to deliver a total solution to meet specific requirements [2]. Integration platform selection is very critical as it affects the solution performance and determines the effort and cost to be consumed in integration development. Two major concerns are stressed in the platform selection: 1) the system architecture of the platform should provide the powerful foundation for the integration of business processes; 2) the platform should offer "green areas" to make the integration clean and neat. A "green area" is referred to where the functionality required is almost fully provided and can be directly used in the integrated environment or does not exist at all. The "green area" offers a great freedom to incorporate new concepts and technologies into the integrated solution with few data consistent problems. After the evaluation of some PDM systems, Windchill by Parametric Technology Cooperation (PTC) is selected as the platform for integration development. Windchill provides powerful functions for managing design with little customization required. It provides an adaptor to integrate commercial CAD systems from different vendors. After integration, designers can directly check in and check out design models from the Windchill database. Windchill also has a built-in workflow engine that offers a friendly graphical environment for defining, tracking and monitoring workflows. In addition, it also provides an integrated development environment to support modeling, source code generation, programming, version control and testing.

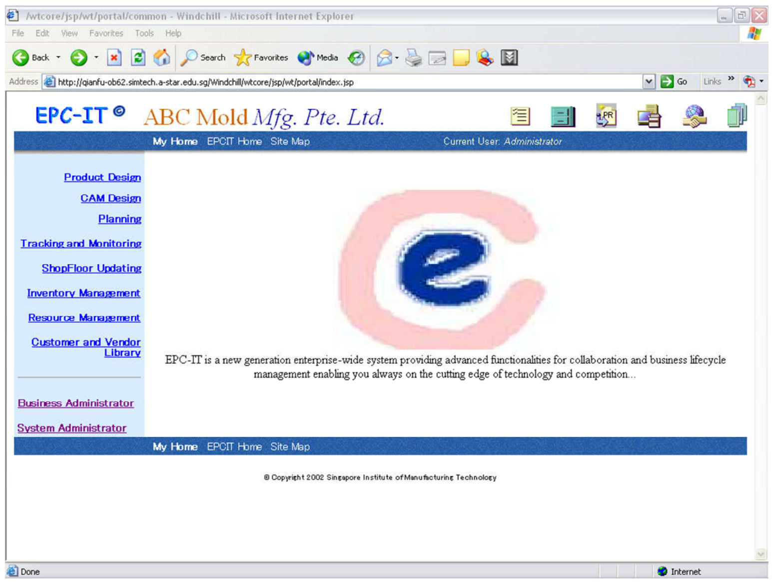

Fig. 6. Main GUI of the developed system.

Based on the business practices of mold making, system functions are grouped into different modules for different people from different departments. Fig. 6 shows the organization of modules in the developed system. The main modules include product design, CAM design, Planning, Tracking & Monitoring and Shop floor update. The module of "Tracking and Monitoring" is provided for workshop supervisors to assign, track and monitor tasks. The module of "ShopFloor Updates" is intended for operators to log the progress of tasks. Fig. 7 illustrates the functions of individual main modules. Apart from the main module, the system also provides functions for managing inventory, enterprise resources as well as the information of customer and other business partners to support the integration of three processes. The administrative functions are provided by the module of business administrator and system administrate. The business administrator is designed for configuring workflows and other settings related to business. The system administrate provides functions to support system maintenance.

8. CONCLUSION

Traditionally, PDM focuses on the management of product data to achieve the effectiveness of product design. Due to the increasing complexity and variety of products, a comprehensive computational framework is required to effectively enable capture, representation, retrieval and reuse of product knowledge. In addressing this need, the concept of PDM is extended to product lifecycle management (PLM), which is a business strategy for creating a product-centric environment to connect various product stakeholders over the entire lifecycle of the product [1]. Design, planning and production are three critical business processes in the product lifecycle. In the modern competitive business environment, the integration of these business processes is a strong industrial need [4]. To assist mold making companies to achieve this integration, the PDM framework has been extended from two aspects: repository and functionality. The repository extension is to enable PDM systems to manage non-engineering information and makes information sharable to planning and production. The functionality extension is to incorporate functions to support planning activities and production management. Based on the extended frame, extended design management model, view-based routing planning model and task management model have been developed to streamline information flows and connect business processes. The extended design management model incorporates the concepts of manufacturing view and routing template and is capable of supporting the management of design tasks. The routing planning model employs routing templates to automate the generation of routing plans. The manufacturing view-based management of routing plans is adopted to effectively support the reproduction and retain historical data. A unified task model has also been developed to support task generation, planning and scheduling. Workflow management has been employed to achieve the automation of business processes. The implementation of the system has been briefly presented and the main modules and their functions have also been introduced.

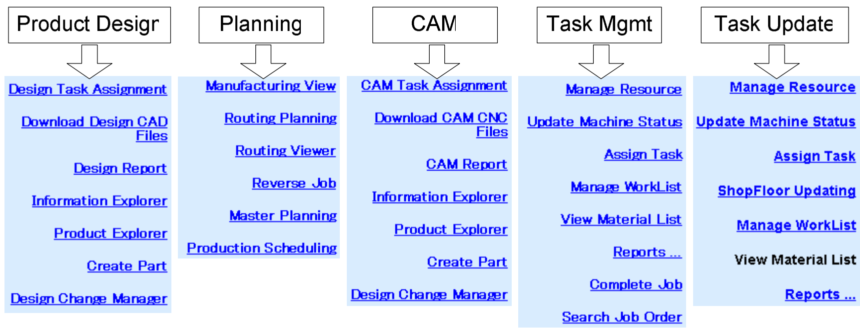

Fig. 7. Functions of individual modules.

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