A Web-based Process Planning Optimization System for Distributed Design

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ABSTRACT

In this paper, a process planning module, which can optimize the selection of machining resources, determination of set-up plans and sequencing of machining operations to achieve optimized process plans, has been wrapped as services and deployed in the Internet to support distributed design and manufacturing analysis. The module includes four intelligent approaches, and a Tabu search-based approach is chosen to be explained to illustrate the optimization process. A Web-based prototype system has been setup for users to carry out visualization-based manipulations and process planning of design models by invoking the services remotely. Through effective utilizations of the Web and Java technologies, this system is operation system-independent, scalable and service-oriented, and can be used for a design team geographically distributed to organize a concurrent engineering design activity effectively.

Keywords: Process planning, Web-based system, distributed design

1. INTRODUCTION

As one of the most popular Internet tools, the Web aims to provide a light-weight and an operation system-independent platform for users to search, browse, retrieve and manipulate information disseminated and shared remotely. Based on the Web, design models can be dynamically shared and updated in an Internet environment and conveniently accessed and manipulated by remote people from the design team, management, marketing, maintenance and customers for efficient design collaboration, design process monitoring, product pre-review and evaluation. Application services in product design, process planning, engineering analysis and simulation, can be conveniently embedded in a Web environment as Application Service Providers (ASPs) for remote invoking and manipulation. Realizing the merits of the Web technology, recently researchers and developers are actively exploring and developing Web-based design and manufacturing systems, and the work can be summarized from the following two aspects.

(1) Web-based visualization systems

Web-based visualization systems [Cimmetry Systems Autovue™ (www.cimmetry.com); Actify SpinFire™ (www.actify.com); Adaptive Media Envision3D™ (www.adaptivemedia.com); Autodesk Streamline™ (www.autodesk.com/streamline-trial); etc.] have been developed to support visualization, annotation and inspection of design models to provide assistance of distributed design and manufacturing activities. These visualization systems are light-weight, easy-deployed and platform-independent, and they can facilitate an on-line team to take on design review, discussion, remark, customer survey to enhance collaborative product design and analysis. In order to deliver and manipulate interactive 3D objects effectively in the Web, some concise formats specially designed for Web applications, such as VRML, X3D, W3D and MPEG-4, have been launched to represent the geometry of 3D models as visualization-used triangular meshes, trimming lines and some attributes [Web3D Consortium (www.web3d.org); Roy and Kodkani, 1999; Huang and Mak, 2001; Kan, et al., 2001; Zhang, et al., 2004]. VRML is fundamental for the series of the standards to represent geometric elements and scenes, whilst X3D and MPEG-4 are extended to support XML-based representation and video/audio application in compressed binary formats, respectively. Some formats such as OpenHSF [Hoops™ (www.openhsf.org)] and ZGL [Autodesk Streamline™ (www.autodesk.com/ streamline-trial)] are functionally equivalent to VRML in geometric representation whilst they define data and algorithms for effective 3D streaming transmission over the Internet through data compression, mesh simplification and object prioritizing.

(2) Web-based design and manufacturing systems

Due to the diversified functions and applications, the appeared works in this category have different characteristics and implementation strategies. However, from the system infrastructures and information communication mechanisms, they share some similar development features and trends.

Chen and Liang [2000] proposed a Web-based system to integrate and share engineering information to support design and manufacturing activities such as domain investigation, functional requirement analysis, and system design and modelling. Functional modules in the system are wrapped and supported by CORBA for communication. The CyberCut system developed in University of California at Berkeley [Sung, et al., 2001] is a Web-based system integrating product design and process planning as a Java Applet program to include three primary modules: (1) a Web-based feature-based design tool to model prismatic 2.5D parts using a destructive solid geometry (DSG) way; (2) a new geometric representation based on the DSG for information exchange between the design and process planning modules, and (3) an automated process planning system based on two steps: macro planning and micro planning. The FIPER (Federated Intelligent Product EnviRonment) system [FIPER Project (www.fiperproject.com/fiperindex.htm); Bailey and Verduin, 2000; Beiter and Ishii, 2003] funded by NIST is to develop a new product design and analysis technology. The main objective of the system is to develop a Web-based distributed framework for design analysis and product lifecycle support based on component mechanisms and workflow mechanisms. It can provide open and flexible capabilities to incorporate existing analysis and design tools/methods through Java-based wrapping mechanisms including Java Native Interface (JNI) and the FIPER SDK toolkit. A workflow for a design process can be conveniently organized and configured by users through assembling components in the distributed environment. Shyamsundar and Gadh [2002] developed a new geometric representation named as AREP and a collaborative prototyping system based on the representation to perform real-time geometric modification for components/sub-assemblies in an assembly model. Mervyn et al. [2003] proposed a Web-based fixture design system, in which an XML format was designed for the transfer of information and knowledge between functional modules in the distributed environment. In the work of Choi et al. [2003] Web service architectures was utilized to establish the new generation of distributed design and manufacturing platform based on XML schemas and a communication protocol SOAP (Simple Object Access Protocol) to provide a neutral data exchange format and effective capabilities in interoperability, integration and Internet accessibility of services.

Based on the technical characteristics of the previous work, the following research issues reflect the current development features and trends:

- The concepts of services and ASPs are getting more popular in Web applications. To install application modules in remote servers as services and run them from Web browsers has many advantages such as avoiding complicated installations for individual computers, easily upgrading application modules and lowering the acquisition costs for Small and Middle Enterprise (SMEs) through renting services. One of the crucial research issues is to propose a light-weight wrapping mechanism for application systems to be used as services in the Web.
- Most of the current CAD systems are facilitated to export a proprietary model to a VRML model. However, during the conversion process, the organization and relevant property information based on features, which are quite important in CAD/CAPP/CAM systems for the high-level aggregations and interpretations of geometric and topological information, is lost. Due to this limitation, most of the Web-based visualization systems cannot effectively support some on-line manipulation operations on features such as selecting a feature or its properties for manipulation, highlighting or hiding a feature, or dynamically attaching attributes to a feature in a design model for evaluation and analysis. Meanwhile, as an emerging standard in the Internet and a system-independent way of representing exchange data, XML is being actively explored to support complex engineering information so as to take advantages of its design features and effective functions in the Internet applications. Therefore, it is imperative to develop an XML-based format that is suitable for Web applications, can represent engineering data based on features, and has strong interoperability and cross-platform capabilities.
- In order to facilitate the product design and realization processes in the Web, a visualization-based system and remote application services need to be integrated. The former can provide a Web-based environment for users to retrieve, view and manipulate a design model for design review, analysis or simulation conveniently. The latter deployed in the Internet can be invoked by users dynamically through the Web to evaluate and optimize the design so as to implement a collaborative concurrent engineering methodology.

In this paper, a Web-based system has been developed to support the establishment of a distributed design and manufacturing environment. The system can play as a platform for distributed users to carry out process planning activities through optimizing the selection of machining resources, determination of set-up plans and sequencing of machining operations of a design model. Four intelligent approaches have been developed to solve this optimization problem, and a Tabu Search (TS)-based approach will be illustrated to explain the process. The optimization module has been deployed in the Internet as Java Servlet-based application services based on a multiple-layer wrapping mechanism. Java Applet, Java2D and 3D technologies have been utilized in the system to develop a visualization-based manipulation environment of design models and optimization results. Through a XML-based data exchange format based on features and VRML, this system can exchange information with a distributed feature-based design system to form an integrated design and manufacturing analysis environment across the Internet.

2. PROCESS PLANNING OPTIMIZATION

As the crucial activities in a CAPP system, selecting suitable set-up plans, determining machining resources such as machines and cutters, and optimizing sequencing machining operations are quite important to ensure satisfactory solutions with lowest machining costs. Considering the decision processes for these aspects are sometimes contradicting, and the evaluation criteria with different consideration angles are also conflicting in some cases, some developed reasoning methods such as knowledge-based reasoning [Chang, 1990; Wong and Siu, 1995; Chu and Gadh, 1996], graph manipulation [Irani, et al., 1995; Lin, et al., 1998], Petri-nets based approach [Kruth and Detand, 1992] and fuzzy logic reasoning [Ong and Nee, 1994] cannot effectively solve this problem with a global optimized result. Recently, evolutional and heuristic algorithms have been applied to the process planning research, and multiple objectives, such as the minimum use of expensive machines and tools, minimum number of set-ups and tool changes, and achieving good manufacturing practice, have been incorporated and considered as a unified model to achieve a global optimal target [Zhang, et al., 1997; Li, et al., 2002]. Four approaches, including Genetic Algorithm (GA), Simulated Annealing (SA), hybrid GA/SA and TS, have been applied to solve this problem. Here, the optimization model is to consider five aspects: (1) cost of machines utilization, (2) cost of cutting tools utilization, (3) number of tool changes, (4) number of set-ups, and (5) number of violated constraints (penalty function). The optimization objective is to reduce the total machining cost. An improved TS-based approach has been developed to generate process plans with near-optimal or optimal results according to the optimization model and objective.

2.1 Representation of the process planning problem

A part consists of a series of features, and each feature can be mapped as a set of machining operations as elements for a process plan. A process plan usually needs to determine the sequence of the operations, set-ups, and the machine and cutter for each operation. The objective is to generate the most economical plan evaluated from the numbers of the required set-ups and the utilization of machining resources. In each operation, there is a set of alternative machines, cutting tools and set-ups (here simplified and represented as Tool Approach Directions (TADs)) under which the operations can be executed. The proposed TS approach is used to determine the optimized sequence of the operations and the utilized machine, cutting tool and TAD chosen from their corresponding candidates according to certain optimization criteria.

The information for an operation is defined in Tab. 1. A process plan can be represented as n operations - $Oper[n]$, in which the sequence of the operations is arranged sequentially in the array, and the chosen machine, tool and TAD for an operation $Oper[i]$ from the candidate list are represented as $Oper[i].Machine\_id$, $Oper[i].Machine\_tool$ and $Oper[i].TAD\_id$ respectively. The optimization criteria can be computed as follows.

- <u>T</u>otal <u>M</u>achine <u>C</u>ost (*TMC*)

$$TMC = \sum_{i=1}^{n} (Oper[i].Machine\_id * MC[Oper[i].Machine\_id])$$

where MC is the <u>M</u>achine <u>C</u>ost of a machine

Variables	Descriptions
Operation_id	The id of the operation
Machine_id	The id of a machine to execute the operation
Tool_id	The id of a cutting tool to execute the operation
TAD_id	The id of a TAD to apply the operation
Mac_time	The machining time of the operation
Candidate_list[ ]	The list of the candidate machining resources list for executing the operation

Tab. 1. Definitions of data for an operation - $Oper[i]$.

- *Total Tool Cost (TTC)*

$$TTC = \sum_{i=1}^{n}(Oper[i].Tool\_id * TC[Oper[i].Tool\_id])$$

where TC is the Tool Cost of a tool

- *Number of Set-up (NS), and Total Set-up Cost (TSC)*

$$NS = 1 + \sum_{i=1}^{n-1}\Omega_2(\Omega_1(Oper[i].Machine\_id, Oper[i+1].Machine\_id), \Omega_1(Oper[i].TAD\_id, Oper[i+1].TAD\_id))$$

$$TSC = \sum_{i=1}^{NS} SC$$

where $\Omega_1(X,Y) = \{\begin{matrix} 1 & X \neq Y \\ 0 & X = Y \end{matrix}$, $\Omega_2(X,Y) = \{\begin{matrix} 0 & X = Y = 0 \\ 1 & otherwise \end{matrix}$

- *Number of Machine Changes (NMC) and Total Machine Change Cost (TMCC)*

$$NMC = \sum_{i=1}^{n-1}\Omega_1(Oper[i].Machine\_id, Oper[i+1].Machine\_id)$$

$$TMCC = \sum_{i=1}^{NMC} MCC$$

- *Number of Tool Changes (NTC) and Total Tool Change Cost (TTCC)*

$$NTC = 1 + \sum_{i=1}^{n-1}\Omega_2(\Omega_1(Oper[i].Machine\_id, Oper[i+1].Machine\_id), \Omega_1(Oper[i].Tool\_id, Oper[i+1].Tool\_id))$$

$$TTCC = \sum_{i=1}^{NTC} TCC$$

- *Number of Violating Constraints (NVC) and Additional Penalty Cost (APC)*

$$NVC = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\Omega_3(Oper[i].Operation\_id, Oper[j].Operation\_id))$$

A fixed Penalty Cost (PC) is applied to each violated constraint. Thus

$$APC = \sum_{i=2}^{NVC} PC$$

where $\Omega_3(X,Y) = \{\begin{matrix} 1 & X \text{ and } Y \text{ violates constraints} \\ 0 & X \text{ and } Y \text{ is in accordance to constraints} \end{matrix}$

- *Total Weighed Cost (TWC)*

$$TWC = w_1 * TMC + w_2 * TTC + w_3 * TSC + w_4 * TMCC + w_5 * TTCC + w6 * APC$$

where $w_1 - w_6$ are the weights

Based on these concepts, the process planning optimization model can be represented as follows:

$$\min_x \quad TWC(x)$$
$$x \in \{\text{Trial process plans}\}$$

The geometric and manufacturing interactions between features as well as technological requirements in a part can generate some preliminary precedence constraints between machining operations. These interactions and technological requirements can be summarized as several types: (1) fixture interactions, (2) tool interactions, (3) datum interaction, (4) thin-wall interactions, (5) feature priorities, (6) material-removal interactions, (7) fixed order of machining operations [Li, et al., 2002].

2.2 TS-based optimization algorithm

A typical algorithm of TS can conduct an searching process for a near-optimal or optimal solution through avoiding entrainment in cycles by forbidding or penalizing moves which take the solution, in the next iteration, to points in the solution space previously visited (hence "Tabu") [Glover, 1997]. It consists of three main strategies, i.e., the forbidding strategy, freeing strategy and aspiration strategy [Glover, 1997]. During a search process, a Tabu list to record the recently past moves is established and dynamically maintained. The forbidding strategy controls the solution that enters the Tabu list. The freeing strategy is used to manage the solution that exits the Tabu list and when. The aspiration strategy is the interplay between the forbidding and freeing strategies for selecting trial solutions. Based on this algorithm, the workflow of the process planning optimization approach has been designed (shown in Fig. 1). Some basic elements in the algorithm are briefly stated as follows.

(1) Initial plan, current plan and elite plan. An initial plan is generated by randomly sequencing the machining operations and selecting the machine, tool and TAD for the execution of each operation in the plan from the corresponding candidate resource lists. A current plan is the best solution selected in each iteration and it is used to start a new iteration through generating some neighborhood trial solutions. An elite plan records the best solution found so far.

(2) Neighborhood strategies. A set of process plans can be generated from a current plan for trials using neighborhood strategies. The neighborhood strategies include two basic manipulations. The first mutation manipulation randomly replaces the set of machine, tool and TAD from the candidate list in the operations of a plan. The second manipulation changes the sequence of two operations in a plan using shifting (selecting an operation from an plan to insert into a new place), swapping (selecting two operations for position exchange) or adjacent swapping (selecting two adjacent operations for position exchange) operations, which are the same to those described in [Li, et al., 2002].

(3) Forbidding, aspiration and freeing strategies. The forbidding strategy, which is used to manage a plan to enter a Tabu list, can avoid cycling and local minimums by forbidding certain moves during the

most recent computational iterations. The Tabu list is based on a "first-in-first-out" (FIFO) queue rule to store recently searched plans. An aspiration strategy can enable a plan that has been forbidden by the Tabu list to become acceptable if it satisfies a certain criterion, so as to provide some flexibility to the forbidding restrictions by leading the search in a desirable direction. A common criterion is to override a tabooed plan if its machining cost is lower than that of the elite plan. The freeing strategy is used to control which plan exists from the Tabu list and when. This strategy is applied in one of the following two cases: (a) When the Tabu list is full and a new plan needs to join, the earliest forbidden plan in the Tabu list should be freed so that they can be reconsidered in the future search; (b) When an evaluated current plan satisfies the above forbidding strategy but it passes the aspiration criterion test, this plan should be considered as admissible (in this case, the aspiration strategy is equivalent to the freeing strategy in function). More details for applying these three strategies are illustrated and highlighted in Fig. 1.

(4) Stopping criteria. Termination conditions for the searching algorithm can be set using one of the following criteria: (a) the iterations reach a pre-defined number; and (b) the elite plan is kept unchanged for a pre-defined number of iterations.

3. DESIGN OF THE WEB-BASED SYSTEM

3.1 Structures of the Web-based system

The Web-based system is based on a multiple-layer client/server architecture to consist of four functional modules mainly: (1) a front-end client embedded in a Web browser to support the visualization of design models, invocation of remote process planning optimization services, and display and manipulation of optimization results, (2) a look-up service to register, manage and search for services deployed in the Internet, (3) the process planning services deployed in the Internet, and (4) a database system [MySQL™ (www.mysql.com)] for storing information about available machines, cutters and their costs. This system can communicate with a distributed feature-based design system [Li, et al., 2004] to retrieve design models represented in an XML format (will be explained in Section 3.2). The scenario is shown in Fig. 2.

The front-end client has four basic functions: (1) a visualization environment for manipulating design models represented as a light-weight format and optimization results, (2) an interface to register services dispersed in the Internet for remote calling and operations, (3) an interface to the database to retrieve and store information, and (4) an interface to the distributed feature-based design system to exchange design models and relevant information for visualization and analysis in this system. Based on the Java Applet, Servlet and Java2D and 3D technologies, this client include the following components: (1) a Tomcat Web server, (2) an Applet for visualization-based manipulations of design models and optimization results based on Java 3D and 2D respectively, and (3) communication facilities in the Applet to exchange information with the process planning services, database and distributed feature-based design system.

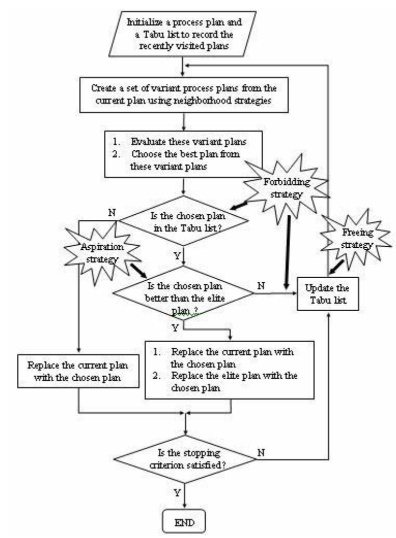


Fig. 1. Workflow of the TS-based process planning.

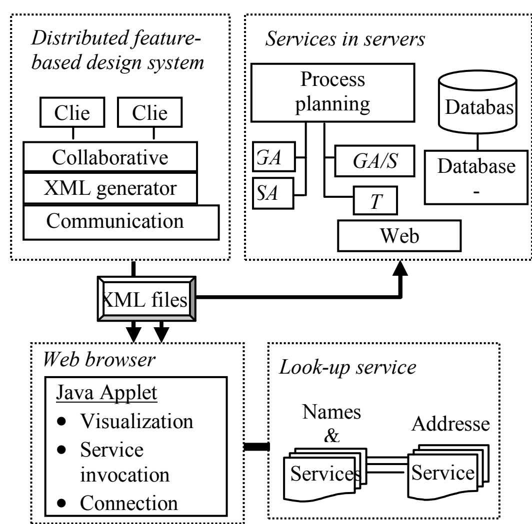


Fig. 2 Scenario and some functions of the Web-based system.

The addresses of the process planning services located in the Internet are registered in the above look-up service for remote calling. In order to provide an extensible and flexible mechanism to integrate the application programs, a three layered architecture, including wrapper classes for the services, abstract classes for the services, and detailed class and method implementations, has been designed. A service wrapper, which is a Servlet class to have a standard “POST” communication procedure to link the front-end client with a Java or C++ program through exchanged XML-based objects, is used to integrate the program wrapped as a Servlet-based service without many changes to the native codes of the program itself. For a C++ program, the wrapper includes the JNI mechanism to link the C++ codes into the Java environment. With the abstract classes, the services that have not been integrated yet can be implemented and join the system later without needing the re-initialization of the whole system. Details of the architecture are given in Fig. 3.

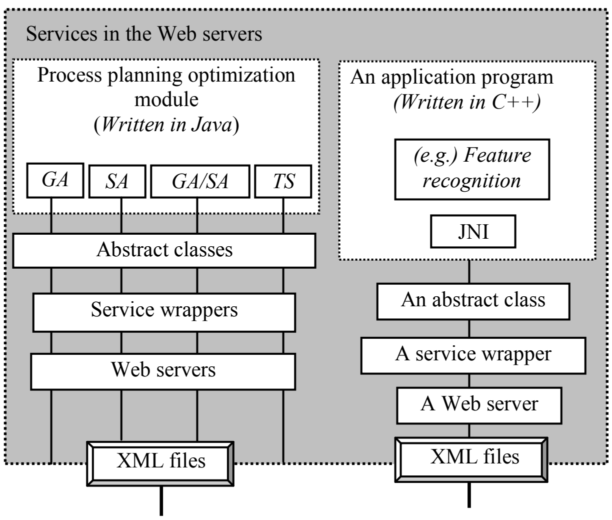


Fig. 3 The multiple-layer architecture for wrapping services.

The main class of the front-end client for the Web-based systme is *VisualizationApplet*, which can retrieve, display and manipulate the visualization data. This class can retrieve design models from the *PartHandleServlet* class in the distributed feature-based design system and machining resources from the database through the *DatabaseConnectionServlet* class, and pass the chosen machining operations and resources for features to the process planning services for further processing. Four the process planning optimization programs wrapped as *AnalysisServlet_GA, AnalysisServlet_SA, AnalysisServlet_GA_SA* and *AnalysisServlet_TS* are arranged in the Internet for on-line evaluation. Through the “POST” method, a communication channel can be established and objects can be exchanged between two Servlet classes or between an Applet class and a Servlet class. The workflow and exchange information are described below:

(1) *PartHandleServlet* (in the distributed feature-based system) -> *VisualizationApplet*. Passed object: an XML-based representation for features.
(2) *DatabaseConnectionServlet* -> *VisualizationApplet*. Passed object: machining resources such as available machines, cutting tools and their costs
(3) *VisualizationApplet* -> *AnalysisServlet_TS* (or one of the other three services). Passed objects: XML-based machining operations and resources selected for features, and precedence constraints for operations.
(4) *AnalysisServlet_TS* -> *VisualizationApplet*. Passed objects: XML-based optimized operations and cost.

3.2 An XML-based representation for design models

In order to organize the visualization data as a feature-based format to support some feature-based manipulations in the Web-based system, such as highlighting or hiding a feature in a part, dynamically retrieving some important parameters and attributes of a feature, or evaluating the creation history of the part, a new XML-style format based on features and VRML has been designed.

Conventionally, in CAD systems, a design model is directly converted to a VRML model, and the primary geometric data in a VRML model are triangular patches and boundary trimming lines between faces. During this process, the information for the high-level form features and the organization of their composition faces can not be preserved. In the new XML format, attributes include the following types:

(1) Identifications: part_id, feature_id and face_id.
(2) Assembly features. These features define some common relationships between design parts such as co-planar, co-axis, against, fitting, etc.
(3) Colors and materials of models. All form features in a design part usually share the same color and material.
(4) Form feature types and their parameters. Usually, there are three types of form features: parametric features with parameters for instancing, sweeping features with base shapes, sweeping manners and parameters, and non-parametric features. For the first two types of features, there are some sub-types. According to different types, a pair of tags (<tag>…</tag>) in the XML can be used for storing a single parameter or a block of data.
(5) Form feature relationships. Two manners are usually used to create models through form features – explicit Boolean operations and local operations (selecting entities from existing features to add or

subtract new features). Therefore, the relationships of two overlapping features can include combination (two features are combined through an explicit Boolean operation) and attachment (a new feature is added to an existing feature through a local operation).

(6) Face attributes such as types of faces (planar faces or surfaces), normals of planar faces and curvatures of surfaces.

(7) VRML patches for each face. The information is organized as two groups: a group for the coordinates of vertices and a group for their indexes.

The XML-based structure is shown in Fig. 4.

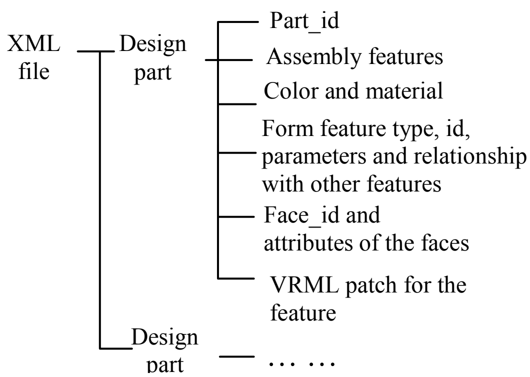


Fig. 4 An XML representation for a design model.

4. A CASE STUDY

A case study is illustrated here to show a process planning optimization process in the Web-based system.

(1) A model can be created in the feature-based design system (shown in Fig. 5). Due the manufacturing feature recognition service is not integrated in the Web-based system yet, the design is arranged with subtractive features removed from the initial building stock (manufacturing features). The model can be converted as an XML-based format and passed to the Web-based system.

(2) A user can observe the design model in the Web-based system shown in Fig. 6. He can change the visualization mode of the part, for example, hiding the meshes, highlighting a feature and retrieving its parameters, rotating and zooming the part, etc.

(3) He can select and invoke a process planning service from the Web-based system dynamically. He can select an optimization objective and relevant weights, parameters of the optimization service, a feature or a face to arrange constraints, and machining resources such as cutting tools and machines (in order to show the information clearly, the information of this part is displayed in Tab. 2). The final optimization results are shown in Fig. 7. Fig. 8 is a Java2D-based visualization and manipulation tool to observe, query, zoom and edit the intermediate results.

5. CONCLUSIONS AND FUTURE WORK

In this paper, a Web-based process planning optimization system has been developed to support distributed design. The Web-based system provides a convenient platform for users to view and evaluate a design model effectively through dynamically invoking remote process planning optimization services. A Tabu search-based approach is chosen from four intelligent approaches to be explained in detail to show the optimization process. Through a wrapping mechanism, the optimization module has been developed as services located in the Internet for remote invoking. A distributed feature-based design system can generate design models in an XML-style feature representation to provide for the Web-based system for viewing-based manipulations. The main contributions of this work are summarized as follows:

(1) By taking advantages of the effective utilizations of the Web and Java technologies, this system is operation system-independent, scalable and service-oriented. The services located in the Internet can provide an effective and centrally managed manners for a designer to conduct a process planning optimization process to evaluate his or other people's design effectively in a distributed design activity;

(2) A new XML-style feature representation has been proposed to carry out some feature-based visualisation manipulations in the Web-based system. This format incorporates the characteristics of VRML and features to support Web applications. The XML-based information representation can make the system to be effectively adaptable to meet the new development of the Internet technology such as the Web-service technology. The multiple-layer architecture designed for wrapping the process planning services ensures the system with the services to be extensible to integrate other legacy systems.

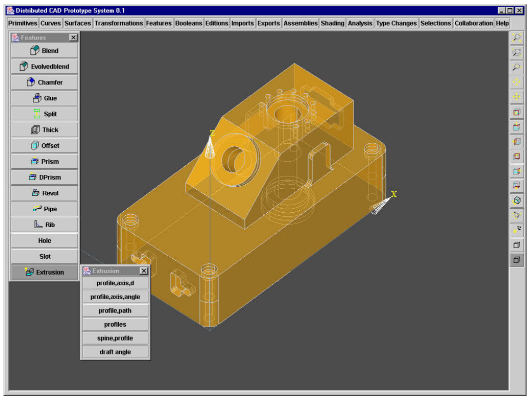
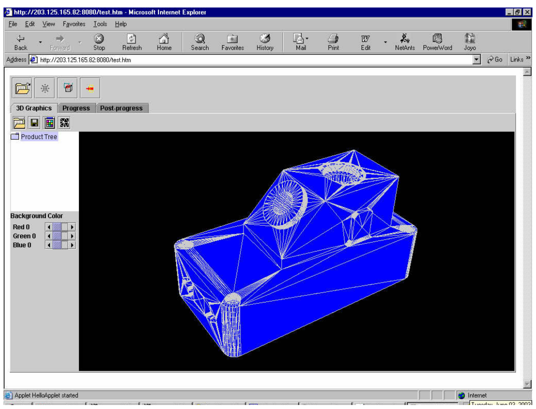
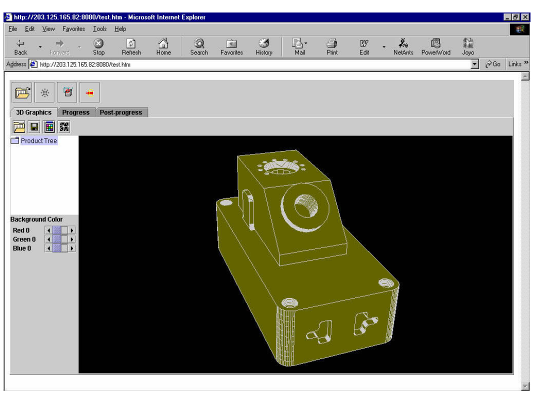


Fig. 5 A design part created in the feature-based system.



(a) *The model with meshes is shown in a Web browser*



(b) *The visualization mode of the part is changed in the Web browser (without meshes)*

Fig. 6 The part is shown and manipulated in the Web-based system.

The future improvement work for the system includes the following four aspects:

(1) In order to enhance the performance for transferring and visualizing complex design models or assemblies, a 3D streaming technology is considered to be integrated into the Web-based system to reduce the bandwidth requirement of using 3D design content and enhance the visualisation effect.

(2) The current system and services are mainly based on the Java Servlet mechanism. With the development and popularity of some new Internet integration technologies such as the Web-service, it is necessary to explore plans to integrate the current functions and functional modules under the new system infrastructure.

The optimization algorithms will be enhanced and improved further. For example, the determination and optimization of the machining parameters for features and machining operations will be studied. Meanwhile, new manufacturing analysis services such as a scheduling service for optimizing the utilization of multiple machining resources for multiple design models at the same time, and an assembly service for organizing collaborative assembly design in the Web, are being investigated and developed.

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Features	Feature Descriptions	Operations (Oper_id)	TAD Candidates	Machine Candidates	Tool Candidates
F_1	A planar surface	Milling ($Oper_1$)	+z	M_2, M_3	C_6, C_7, C_8
F_2	A planar surface	Milling ($Oper_2$)	-z	M_2, M_3	C_6, C_7, C_8
F_3	Two pockets arranged as a replicated feature	Milling ($Oper_3$)	+x	M_2, M_3	C_6, C_7, C_8
F_4	Four holes arranged as a replicated feature	Drilling ($Oper_4$)	+z, -z	M_1, M_2, M_3	C_2
F_5	A step	Milling ($Oper_5$)	+x, -z	M_2, M_3	C_6, C_7
F_6	A protrusion (rib)	Milling ($Oper_6$)	+y, -z	M_2, M_3	C_7, C_8
F_7	A boss	Milling ($Oper_7$)	-a	M_2, M_3	C_7, C_8
F_8	A compound hole	Drilling ($Oper_8$) Reaming ($Oper_9$) Boring ($Oper_{10}$)	-a	M_1, M_2, M_3 M_1, M_2, M_3 M_3, M_4	C_2, C_3, C_4 C_9 C_{10}
F_9	A protrusion (rib)	Milling ($Oper_{11}$)	-y, -z	M_2, M_3	C_7, C_8
F_{10}	A compound hole	Drilling ($Oper_{12}$) Reaming ($Oper_{13}$) Boring ($Oper_{14}$)	-z	M_1, M_2, M_3 M_1, M_2, M_3 M_3, M_4	C_2, C_3, C_4 C_9 C_{10}
F_{11}	Nine holes arranged in a replicated feature	Drilling ($Oper_{15}$) Tapping ($Oper_{16}$)	-z	M_1, M_2, M_3 M_1, M_2, M_3	C_1 C_5
F_{12}	A pocket	Milling ($Oper_{17}$)	-x	M_2, M_3	C_7, C_8
F_{13}	A step	Milling ($Oper_{18}$)	-x, -z	M_2, M_3	C_6, C_7
F_{14}	A compound hole	Reaming ($Oper_{19}$) Boring ($Oper_{20}$)	+z	M_1, M_2, M_3 M_3, M_4	C_9 C_{10}

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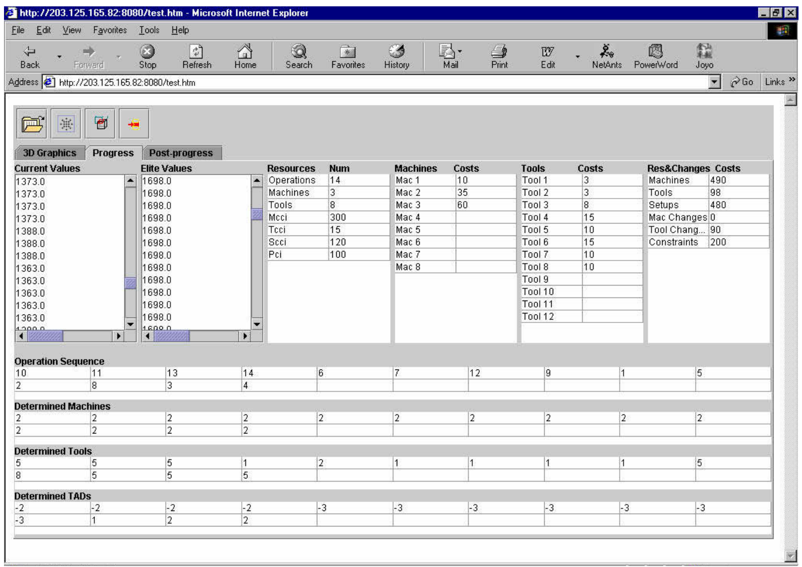

Fig. 7 The optimization results of the TS service for the design part.

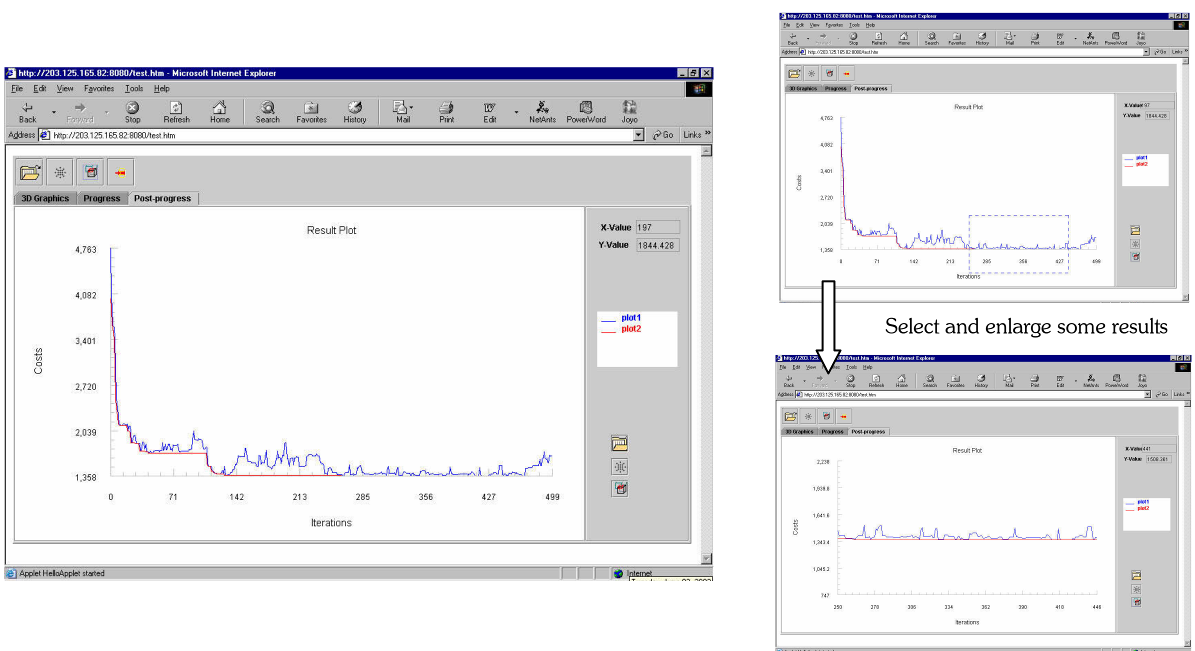

Fig. 8 A visualization window for the optimization results of the design part.