University of Alberta

Extension of an ERP System Based on a Unified Feature Framework

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Engineering Management

Department of Mechanical Engineering

Spring 2014
Edmonton, Alberta

Abstract

Customer-oriented manufacturing demands that engineering design and production planning are fully integrated. This study proposes a generic feature association method and a detailed framework for the implementation of an advanced Enterprise Resource Planning (ERP) system that can unify product and process models in order to fulfill customer orders with small batch and high variation production nature. A conceptual solution is introduced for the information integration between design configuration features and manufacturing process features. To achieve this, three feature classes, customer feature, capacity feature and welding feature are suggested. Specific effort has been spent to model welding features which are currently not well studied. With the associative integration between product design and process feature domains, a preliminary order acceptance and scheduling prototype system has been implemented within an ERP order management system, and its semantic model is demonstrated within a unified and multi-facet feature framework.

Acknowledgement

My sincere gratitude goes to my supervisor, Professor Yongsheng Ma, for his advice and encouragement during my research.

I would also like to give special thanks to Professor Shuiyuan Tang for training on welding related knowledge and suggestions on my research.

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List of Symbols

[WF] Welding feature array

[D] Component geometries and parameters array

[W] Welding geometries and parameters array

[M] Material characteristic and properties array

(CM) Components' material

(MAM) Maximum service amperes required

(MAT) Maximum service voltage required

[MF] Machine capability feature array

[E] Machine working envelope size array

[P] Machine process parameters array

[T] Machine characteristics array

(MTX/MTY/MTZ) Maximum travel of direction X/Y/Z

(MT) Machine type

(PW) Power source

(ECY) Machine Efficiency

[MF] Machine capability feature array

[WB] Weldability array

(B_{ij}) Weldability for i machine with j welding technique

(WC) Waiting cost

(OC) Operational cost

(FC) Cost to manufacture a feature

(OVC) Overall cost of the whole welding processes

(SC) Setup cost

(UC) Occupancy cost

(LR) Labor cost rate

(CL) Current work load rate of the machine

(CU) Occupancy cost rate

(ECY_i) Efficiency of the machine to manufacture a feature

(Qty_i) Batch size

CRM - Customer relationship management

SCM - Supply chain management

ERP - Enterprise resource planning

OAS - Order acceptance and scheduling

HMLV - High mix and low-volume

MRP - Materials and resource planning

PLM - Product life-cycle management

PDM - Product data management

BTO - Build to order

BOM - Bill of materials

MIG - Material insert gas

Chapter 1 Introduction

1.1 Background

Oilsands or bituminous sands have become an increasingly important source of oil extraction and refinery in the past decade [1]. Unlike traditional sources of petroleum, oilsands are loose sand mixtures containing clay and water. There are large stores of oilsands located throughout Canada (approximately 173 billion barrels of oil capacity [2]). Developing oilsands introduces a profitable energy industry to Canada, especially in Alberta. During the recent decades, oilsands extraction and refinery have become the pillar industries in Alberta. It was reported that approximately 1.3 million barrels of oil were exported per day in 2011. In addition, in 2012, almost 30 per cent of US crude oil imports were exported from Canada [3]. According to data from Alberta Energy for 2011 [4], roughly 4.5 billion dollars were made in Alberta alone in royalties from oilsands projects. Large energy enterprises such as Shell, Syncrude and Suncor have been investigating and developing new oil fields. The economic prosperity stemming from oilsands extraction and the refinery industry introduces more related businesses in fields such as engineering, procurement and construction (EPC), and equipment manufacturing. Investment into the oilsands industry has been increasing as well, with 17.2 billion dollars invested in 2010 and 21.6 billion dollars in 2011. It is expected that by 2021, crude bitumen will produce 3.7 million barrels of oil per day. For more statistical information about the oilsands industry, please refer to the Alberta Energy report [4]. The development of new fields requires large amounts of equipment such as pipelines, pumps, and related installations, as well as calibrations and field services. Due to different geological properties and extraction methods of oilsands compared to traditional petroleum sources, specialized equipment needs to be designed and produced. There have been many more orders placed for oilsands-related equipment business, which provides great opportunities for local manufacturers.

However, many challenges currently exist for local manufactures in processing these orders. Firstly, various local manufacturers still run their businesses with a traditional job-shop-like business model with limited manufacturing flexibility and capability [5]. Order processing and scheduling is a manual process which is highly influenced by personnel's expertise. Secondly, as with those for oilsands equipment, many manufacturing orders are high-mix and low-volume (HMLV). Thus, re-engineering and re-configuration processes are constantly involved. Specific order feasibility and manufacturability have to be determined, but doing so is hard without the collaboration of sales, engineering and production. Efficient information sharing among different departments is critical, as it will influence the overall efficiency of the business. These technological demands are especially urgent to those manufacturers who adopt a collaborative manufacturing business model, which is a broader concept of concurrent engineering [6]. Collaborative manufacturing involves in-house manufacturing as well as a controlled supply chain among suppliers. Key information for each department, such as design intent, manufacturing feasibility and production due date, have to be shared among the different departments for decision-making purposes.

However, due to the increasing market need, more small batch but customized orders are placed and thus need to be processed in a limited time frame. In addition, machine capability and manufacturing processes need to be clearly modeled, evaluated and associated with the order processing procedure for acceptance decisions. Furthermore, raw materials to be ordered from vendors need to be prepared on time too, to ensure the order delivery date. Finally, in order to improve the efficiency of the business and remain competitive in the global market, manufacturers adopt global supply chain management and multi-site collaboration. This makes the business structure more complex and stakeholders in each department have to collaborate with each other as their tasks are now interconnected. Thus, manufacturers need to implement enterprise-level information systems such that both intra- and inter-company manufacturing activities can be improved with effective information sharing.

In the past two decades, the development and implementation of Enterprise Resource Planning (ERP) systems took a further step in realizing collaborative manufacturing. Basically, an ERP system is used to apply a computer-based information system combining accounting, inventory, shop floor control, and productions, while processing information based on a common data structure in implementing data sharing and inter-department communication. ERP systems are currently used as one of the cornerstones for manufacturing information management in many enterprises. However, most ERP systems were initially designed for accounting purposes [7]. Even among the few manufacturing-oriented ERP systems developed, the ability to integrate design and manufacturing capability information is very limited and needs new development effort. Moreover, some of the manufacturing processes, such as welding processes in the oilsands industry, are usually manual, which makes it hard to evaluate their feasibility. So far, such processes are not allocated automatically based on current equipment capacity. Such complicated factors present as obstacles in preventing ERPs from becoming efficient and effective information solutions for many companies. This study aims to improve the efficiency of an ERP system in the manufacturing industry, such as the oilsands-related equipment manufacturing, by integrating product and process feature domains, implementing an order-processing system with a unified feature sematic structure. In this study, all the information class definition models use a UML format. UML graphical symbols are followed whenever applicable in all figures.

In the following sub-sections, three related concepts, ERP, unified feature and welding processes are introduced respectively.

1.1.1 Unified feature and related concepts

The introduction and utilization of the term "Unified Feature" are aimed at enabling the integration of different engineering databases in the manufacturing industry [8]. Traditionally, features were developed to store characteristic engineering semantic patterns to allow engineering information to be transferred among different applications. The definition of feature varies according to engineering disciplines. For instance, in product modeling, it usually represents topological and geometry patterns of a part [9]. It can include parametric information for a specific shape [10], regions of an object for specific engineering activity [11], or even functionality of the design based on the shape information [12]. Feature technology has also been widely applied in the integration between CAx systems. For example, between CAD and CAM, product information can be transferred into manufacturing features for further manufacturing activities [13, 14].

However, even though most current product development software tools are feature-based, they are still limited to their feature data definitions. In 2006, Cheng et al. introduced the definition of "generic feature" [15]. It was defined as a basic feature entity template, or class, which aims at reflecting the reusability and capability of engineering semantic patterns for different engineering related applications [16], i.e. feature unification. The approach initiated has been considered a “higher-level” feature-based knowledge modeling in a recent review [17].

Based on the unified feature modeling theory [16], a feature can represent an information pattern associating different aspects of a product, such as geometry , materials, processes, and manufacturing features of components. Feature objects can be created supporting different design, manufacturing and assembly processes. Therefore, feature-based engineering informatics facilitates a comprehensive information technology solution for product lifecycles from design to production and to end-of-use such that more accurate and timely decisions can be made. For the manufacturing industry, based on the integration data, information patterns, and their comprehensive relations, shorter processing time of the order can be achieved with the cooperation between design engineers, plant planners and the machinists.

1.1.2 Enterprise Resource Planning

ERP is a business management system technology which supports controlling of enterprise resources [18]. It aims at integrating all isolated business systems and maintaining real-time resource accountability across an organization. This makes it possible for manufacturing planning and controlling to be more efficient and accurate [19].

The earliest stage of the ERP consists only of accounting, inventory and some amount of administration information [7]. Later on, other functionalities, such as order information and customer service, are integrated via the wide application of the internet [20]. Thanks to its capability of information integration between vendors and departments, such as manufacturing, customer service and human resources, ERP technology has become the leader with the largest implementation license base, most influence and fastest growing players in industry software applications [21].

Main ERP vendors include SAP, Oracle, Infor and Peoplesoft; many systems are developed for different businesses types [7]. As for manufacturing-oriented ERP software tools, examples include SAP, Oracle, Infor Syteline and Visual Manufacturing^{TM}. However, current available ERP systems are not good enough from both a functional and structural flexibility point of view; such situations lead to big risks in the implementation stage [22]. For a more detailed review about the history of ERP technology and current ERP capabilities, please refer to Chapter 3.

1.1.3 Welding process and welding equipment

Welding is a fabrication technique with wide applications in various fields such as pipeline fabrication [23]. Welding physically connects two separate components of the same or different materials. The welding process applies heat or pressure in order to form a permanent bond between the two pieces. The materials applicable to welding techniques are mostly metals and thermoplastics.

Based on the different mechanisms of joining separate components, welding can be divided into three types: soldering, frictional welding, and fusion welding. Soldering fills the gap between the two pieces of material by molten filler material falling into the gap. Soldering has wide applications in the electronic industry, where mild joint is necessary to protect individual components. Friction welding serves as an alternative, joining components without melting the materials themselves. Heat is generated through mechanical friction between a moving component and a stationary component. Fusion welding fills the gap between the two pieces to be joined by melting a filler material and part of the components themselves to form strong bonds upon cooling of the joint. The differences between soldering and fusion welding are that the soldering process only requires melting of the filler while fusion melts both the filler and part of the base pieces to form the joints.

Due to the simple process involved and relatively strong bonds created between the separate components, fusion welding is the most commonly used form of welding in industry. There are several kinds of fusion welding which have applications in different areas depending on their technique, bond properties and environment. Laser welding beams use lasers to join two or more work pieces. Concentrated heat is provided by the laser beam, allowing for narrow and deep welds to form at relatively higher rates. Hidden arc welding (also called submerged arc welding) can prevent the molten weld and the arc zone from atmospheric contamination by covering them with blankets of granular fusible flux comprised of silica, manganese oxide, calcium fluoride, and other compounds. The heat source in electron-beam welding is a beam of high-velocity electrons, which can be intense, sharp and accurate to form a deep and small weld zone. However, unexpected flaws can occur during the cooling process after welding, such as cracks due to the intensive heating during the welding process and sharp cooling afterwards.

As for arc welding, heat is generated by an electric arc between the base material and an electrode. Metal inert gas welding provides an improvement over traditional metal arc welding, as inert gas is purged during the welding process to prevent the other part of base material from being altered via melting or phase transformations. This study mainly focuses on the metal inert gas (MIG) process.

The MIG process can be applied to various materials, such as carbon steels, low alloy steels, stainless steels, aluminum alloys, and zinc-based copper alloys. During melting of the filler material (electrode), the base material is shielded by an inert external gas such as helium, CO_2 or other gas mixtures to maintain a good finish. During the welding process, the electrode is fed from a spool to the arc zone at a preset speed. The heat generated melts both the electrode and base material's edges so that the joint is formed by joining the molten electrode to the edges of the base materials.

Thanks to the development of modern manufacturing technology, some manufacturing processes, such as drilling and milling, can be implemented automatically with sufficient process and set-up characteristics information. Process information is usually expressed in feature patterns, and interactive with design features. But it is not a common practice for welding processes. Welding feature and welding capacity will be further discussed in Chapter 2.3.

1.2 Problem statement

Current ERP systems have been useful to manufacturing companies for information sharing among different departments; the impact is especially significant from the accounting and inventory perspectives. So far, the majority of those large enterprises around the world have been using ERP systems for daily inventory management and operation activities [21].

However, the structure of most current ERP systems is fundamentally based on data table transactions [24]. It facilitates information sharing and focuses more from the management point of view while neglecting the needs of engineering. Engineering information, which contains large amounts of product design and manufacturing patterns, is excluded from the ERP information models. However, engineering information is essential for the stakeholders from other departments in terms of decision making, especially in the processes of order management and scheduling. The incomplete information stored in current ERP systems causes several problems, such as capacity overload, overdue orders, and implementation issues for ERP, and further affects the entire efficiency of the business [22]. The following paragraphs discuss the drawbacks of the typical ERP system structures.

First of all, useful design information, related to new product function, customized specifications and the subsequent detailed design, is excluded from the ERP system. Therefore, when sales or other departments are making decisions, further communication with the design department is required, resulting in delays or even misunderstandings. These communication loops reduce the overall efficiency of the business. Then the risk of losing a potential customer increases when competitors can provide a faster response to a customer's request. Integration of the ERP system and engineering data can improve the ability of salespeople in recommending the best options to customers, and further determining the acceptance of an order with a delivery time commitment to the customer.

Another drawback of the current ERP system is that some detailed manufacturing information, such as machine capacity information and detailed manufacturing process standards, is seldom clearly addressed. As a result, handbooks and manuals have to be used by manufacturing companies for process parameter information. However, as the key process information is not consolidated into an integrated information system, it is challenging for new operators to follow the specified manufacturing standards correctly and efficiently. For example, the welding process specifications include various parameters, such as current and voltage ranges for different work pieces. Such process parameters are different from company to company. Process details are tedious with various technical terms. As key process knowledge is usually kept by operators, while the standard manuals also cannot specify the best process to fabricate a specific part, hence the training cost for a new or replacement of an operator is fairly high. In addition, because the operators have to consult process or design engineers with manufacturing details to determine the best process plan, production efficiency is further reduced. From the shop floor management point of view, it is also hard for a production engineer to do order planning, resource allocation and further scheduling. Such technological gaps cause non-value added information acquisition loops and prevent collaborative engineering from being implemented in the company.

Finally, it is difficult for current ERP systems to develop a process routine and scheduling without information about manufacturing capability and availability. Integrated information regarding capability and availability of all facilities is required in the production planning and scheduling process. Thus, the complete modeling of manufacturing processes as well as equipment capacities is critical and this information needs to be integrated with the ERP systems. Further, ERP systems cannot manage the difference between shop resource capabilities in order to determine the manufacturability of each order.

1.3 Objectives and scope of study

The main objective of this research is to provide a conceptual framework to enable information sharing between product and process domains at conceptual and detailed information levels. By integrating design and engineering information within the ERP system, this study intends to provide a conceptual solution to manufacturers operating a HMLV business model. This conceptual solution will provide the ability to consolidate their customer characteristics, resource capacity and manufacturing information, while interacting with their current ERP systems. A more technical objective is to store engineering information correctly and efficiently using well-defined data structures incorporating the detailed engineering information into ERP systems based on the "unified-feature" [8], so that engineering- and production-related information, such as product configuration, delivery date, and manufacturability can be passed on to sales people for them to make order acceptance and scheduling decisions.

1.4 Scope and methodology

Traditionally, engineering informatics is largely separated into two research and development domains, i.e., product domains and process domains. In this work, a feature-based conceptual framework is proposed with inter-domain feature definitions and management methods to facilitate the integration between the two domains. It aims to utilize features to enable the necessary business process automation and information sharing among sales, engineering and production departments. The bill of materials (BOM) system acts as the bridge between the product and process domains.

This research proposed a "customer feature" concept to link a customer-specific requirement with product configuration information. Specifications can be translated automatically into optional product configurations. This will improve the sales department's efficiency in helping the customer to select products without having to contact the engineering department. Thus, configuration design information is integrated into ERP and shared across different departments.

This study also proposes a feature definition for welding processes. A welding process is normally carried out manually and has not been well defined in industry. By defining the object type and applying data organization and classification of welding processes into welding features, welding capability can be managed for better scheduling using a system. This research uses the welding feature as a proof-of-principle case to demonstrate that design information can be shared by the production department, as welding is one of the most important processes in the oil and gas industry. The output of this effort will enable welding process inputs for process planning and scheduling systems. Similarly, the concepts developed in this study may also be applied to other manufacturing processes, such as cold machining. However, such expanded applications are not included in this research.

To prove the conceptual solution for product and process domain integration, two modules based on an ERP platform, the feature-based order acceptance and scheduling (OAS) module and the manufacturing capacity module are developed in a pilot effort. These modules are focused mainly on medium-sized oil-drilling manufacturers, and the effort provides insights in implementing and further expanding the ERP applications.

From the implementation point of view, Visio Studio 2010 is used as the development tool for the pilot module implementation to demonstrate the proposed concept. A business ERP package, Infor Express 10 (Visual), is customized, and data integrated. The Microsoft SQL Server serves as the package for data storage.

1.5 Organization of the thesis

The contents of this thesis are divided into seven chapters. This chapter provides the background of the study. The next chapter reviews previous research studies of collaborative engineering and relevant concepts such as ERP, OAS, process planning and scheduling, and welding processes. Following this, technologies related to the existing ERP business solutions are reviewed in Chapter 3.

Chapter 4 presents the proposed the feature-based engineering information framework with semantic models related to product and process domains. The customer feature is defined and an OAS module is designed theoretically to support the sales department selecting the right product incorporated with design information.

Chapter 5 further expands the proposed integration framework into detailed production levels. A manufacturing resource capacity model on welding equipment is investigated. Two new feature types, the capacity feature and related welding feature, are proposed. Their interactions with the ERP system are prototyped. Welding processes are classified and defined based on a unified method and maps with capacity information in the ERP system. The feature recognition part can be automated based on a CAD model with further effort.

Chapter 6 focuses on the implementation of the two modules introduced in Chapter 4 and Chapter 5. Pilot development and User Interfaces (UI) are explained in detail. An industrial case of drilling equipment, the "Tong," is studied and its procedures are walked through with the existing business ERP software, Infor ERP 10 (Visual Manufacturing). Finally, conclusions and future work recommendations are provided in Chapter 7.

Chapter 2 Literature review

This research aims at a conceptual solution which supports small batch and high variation production for integrating design information into the ERP order management system. Several research fields are studied, i.e., ERP, order acceptance and scheduling (OAS), manufacturing capacity, welding process and welding feature. This chapter reviews research efforts and studies relevant to the objective of this study.

2.1 Collaborative engineering based on ERP

The concept of enterprise resource planning (ERP) is essentially to manage a company's daily operating information flow, such as sales, accounting, product, and process, using a single database [25]. Historically, by expanding material resource planning (MRP) systems which control the materials/component flow and inventory, ERP has enabled centralized management of business operations. It can be said that an ERP system acts as the backbone of a company's operations, supporting information sharing among various departments. As rapid responses to customers' inquiries become more and more demanding, the need for efficient information management becomes imperative. Thus, the industry and academia are paying greater attention to ERP technology for global information integration based on scalable database technology, especially for accounting and inventory management.

Previous research has been conducted on the integration of ERP with other software packages such as supply chain management (SCM) [26], product meta model [27], and product data management (PDM) [28]. So far, however, most current commercial ERP tools are limited in integrating order acceptance with engineering design configurations and production capacity evaluation. Meanwhile, from the academic perspective, product information is the key component of product lifecycle management (PLM), which should be managed comprehensively and consistently [8, 29]. In practice, however, product engineering design models cannot be easily integrated with production process management models [29, 30]. It should be highlighted that currently there is no coherent and integrated software engineering model that propagates product configurations into an order fulfillment system generically and further supports the integration of process and product domains, even though some legacy systems are assumed to complete order fulfillment automatically, as reviewed by Zhang *et al.* [30]. A conceptual framework was proposed by Reichhait and Holweg to integrate process modules from the supply chain management (SCM) perspective [31], but the product configurations and manufacturing capacity were not fully considered.

This study takes SCM into consideration but mainly focuses on OAS responsiveness with the integration of product information. This study intends to expand the ERP information model in order to support flexible collaborative manufacturing activities across departments within a company, as well as the manufacturing collaboration across a supply chain, coordinated by a common ERP system.

In the past two decades, large enterprises have been applying ERP systems to achieve integrated data and functionality, thereby giving the enterprises a competitive advantage. However, for customer-oriented manufacturing, or build-to-order (BTO) manufacturing [30, 32], there exists a key technological challenge in creating a coherent and consistent platform where product orders collaborate with one another efficiently. So far in engineering practice, certain knowledge such as engineering intent and customer characteristics cannot be systematically consolidated and stored in a fully integrated system, like the ERP system. Some researchers have identified customer characteristics by using data mining models [33]. The disadvantage of these models is that they are mostly case sensitive and difficult to integrate with an ERP system.

It has been suggested that for customer-oriented or build-to-order (BTO) manufacturing, feature-based design and manufacturing can be used to integrate product development and process planning [8]. The unified feature modeling approach [29] is applicable not only in the product domain, which has already been reported with convincing results, but also in the process domain where information about customers, scheduling, machining capacity, process planning [34, 35], and the supply chain can be associated, stored, and shared [8]. There is currently an imperative need for an in-depth framework to consider the overall engineering and production cycles systematically. This study describes a further step in integrating the product and process domains based on a unified feature information model, aiming to integrate product and process features with a commercial ERP system.

2.2 Order acceptance and scheduling

Order acceptance and scheduling (OAS) is a common module in ERP systems used to manage orders and manufacturing activities [36], such that the overall performance of an organization can be managed. Thus, the input information of an OAS system should be comprised of live enterprise data [37] and a consistent data flow model [38-40]. The procedure of such a module becomes complicated and tedious for the ever-increasing BTO production scenarios. If production is delayed due to poor order scheduling, a company's reputation and customer relations could suffer seriously. There have been a variety of studies focusing on algorithms to implement OAS systems based on machine level information. For example, in terms of single-order scheduling, Hohn and Jacobs [41] enhanced the mapping of known order constraints while evaluating and comparing the influences of different order constraints using exact algorithms. Roundy *et al.* [42] developed a method based on capacity and workload for multi-machine scheduling. As for achieving business objectives, one research issue is the modeling of capacity constraint on order acceptance [43], which was considered a workload-based approach for busy job shops. Another research issue involves optimization in OAS decision-making, for which Moreira *et al.* [44] suggested that both sets of jobs, i.e., those entering the system and those being processed in the shops, should be considered simultaneously when dealing with workload and input control problems. A review of OAS taxonomy can be found in [36].

Running an OAS function is a complicated and dynamic process, as it needs to extract the exact product configurations and coordinate this with real-time shop-floor conditions. Wester *et al.* [38] analyzed three information sources in order-acceptance decision making in a customer-driven manufacturing environment: (1) detailed information about the current production schedule; (2) the sequential production schedule, and (3) global capacity load files. Their research showed that the machine capacity, availability, and order due dates highly influence the order acceptance mechanism. Piller *et al.* [39], on the other hand, studied the essential roles of product configurations, specifications and design details in an integrated mass customization system. A configure-to-order [40] platform was developed in other studies for mass customization such that product design, planning and supply chain management processes can be integrated. In the detailed application that Piller et al. [40] developed for injection-molded product families, mold prototype information can provide feedback for making order acceptance decisions. Therefore, integrating the current production information system with the product design system is essential in the OAS system of a customer-oriented and high variation manufacturer. Regarding OAS implementation in customer-oriented production, Zhang *et al.* [30]

proposed an integrated order fulfillment system at an operational level using predefined product and process family models. It was recognized that with a mass customization business model [30], a product configuration module has not been directly linked with the order fulfillment module. Furthermore, customers' conceptual requirements need to be stored in the order fulfillment system by mapping product configurations with real-time shop-floor capacity. Product configuration can be derived from a CAD module or PDM system [45]. A preliminary study [46] has been conducted by Qian *et al*., proposing customer profile modeling and further utilizing the profile and clustering similar product orders based on product configuration information while another study links orders with MRP updates processes [47] in order to increase production efficiency. Lin *et al.* [48] used an alternative BOM to link customer orders with the available materials and capacities in the supply chain environment for their "available-to-promise" order fulfillment processes.

So far, to the candidate's knowledge, there has been no reported study focusing on the integration modeling among customer orders, their related product design configurations and manufacturing processes. The candidate believes that a systematic customer-driven feature information model is crucial for a generic solution for the proposed dynamic and integrated OAS system. The effective extraction, analysis and processing of customer-driven feature information provides a feasible near-real-time feedback system for the customer and shortens the response time between different departments by improving communication in job selection and order scheduling. In this study, based on the concept of the customer feature proposed [49], which has been implemented partially to link process and product domains, a new OAS module has been prototyped and integrated within an ERP system.

2.3 Welding feature and welding capacity

Welding process has been chosen as a case study for process feature welding and capacity evaluation. Comprehensive planning of the welding process modeling is imperative due to the vast application of field welding in many industrial sectors, but the systematic study is not sufficiently done because of the related complications in weldability, welding quality and process economics [50]. The traditional welding environment relies on operators to determine the welding parameters based on their experience and technical knowledge. One of the drawbacks of traditional welding planning is that the method and the resultant specifications vary between different operators. Further, if the specified operator leaves the company, additional costs for other personnel training might apply. In addition, manual input and determination of welding parameters is time-consuming. Finally, at the early order acceptance stage, the production manager cannot respond to sales in a timely and consistent manner regarding the order delivery dates. Thus, reducing the process planning time and maintaining a skilled staff become crucial in the manufacturing industry.

Determination of the welding process that is independent of skilled personnel and manual input has garnered much attention in academia. There are many important studies on this topic, in terms of the computing methodology or optimization of the welding joint. Several strategies have been implemented to improve the planning for the welding process. Kim *et al.* [51] used a controlled random search to determine the welding parameter by optimization based on the expected welding geometry. Another approach is to use linear and non-linear regression statistical methods to get the optimal process by using data from factorial design experiments [52]. Employing statistical methods, Sapakal and Telsang [53] used a variances analysis method while Tay and Butler [54] combined the experimental design and neural networks methods by collecting data from reference templates and processing them via a powerful neural network to retrieve a range of welding configurations.

In order to determine the various welding factors, design model information about the product domain needs to be fed and translated into manufacturing features, and the welding process parameters can then be determined based on an empirical data model [54]. Feature models, based on CAD models with basic geometry information, can be associated and used to determine the welding strategy factors [55]. However, only a handful of efforts have been reported for welding features, as the welding process is recognized as an additive feature, while most efforts currently focus on machining features (negative features) [56]. Maropoulos *et al.* proposed a process planning system for evaluating alternative design and processing options by identifying welding joint positions and selection of joining methods [57]. Wasim *et al.* were able to estimate the cost of welding processes using feature-based technology [58]. There are several studies on the control and analysis of the welding process based on geometric features [59-61]. However, few studies have investigated the definition and utilization of a welding process feature. A welding process feature should include information such as the cleaning and preheating of the base material, types of welding flux and wires, the welding position, groove type design, feed speed, and electrode direction, as well as the post-weld heat treatment. A successful welding procedure is usually conducted with careful determination of the correct consumable electrode wire (or welding rod), power source (welding current and voltage), shielding gas, travel speed, and contact angle of the wire and the preparation. In this study, the welding process feature addressing a specific well drilling equipment manufacturer is proposed and implemented for the pilot order management system designed in Chapter 6.

The term “manufacturing capacity” is often used in process planning and scheduling integration [62]. Process planning and scheduling are two of the most important activities in production [63]. Process planning develops the processes to manufacture a product, and transforms the engineering design model into detailed manufacturing features, and subsequently determines operation sequences and parameters. Production scheduling, on the other hand, manages when and where the specified operations should take place. Specified jobs are sent to process planning for manufacturing methods and then passed on to scheduling for allocation of shop resources.

For process planning, researchers have struggled to sustain the consistency between design intent and the manufacturing processes. Current research approaches can be abstracted into two classes: variant or generative approach [64]. The variant approach concentrates on the similarity of component features from the existing examples in order to develop a similar process plan, while the generative approach synthesizes the common rules and derives a new process plan. Machine capability information is incorporated into generic algorithms such as petri-net [65, 66] and knowledge-based systems [67]. As for scheduling manufacturing, capacity is usually used as the time constraint in the scheduling algorithm addressing the availability of work hours [68-70]. Newer research aims to address more of the integration of process planning and scheduling so that capacity information can be shared. For instance, Wang and Shen [71] integrate process planning and scheduling using agent-based techniques and implement the process planning system using real-time shop-floor status. However, manufacturing capacity should be an information pattern integrated with live production information (ERP) system which combines machine capability and availability matching with manufacturing requirements derived from customer orders. The matching results should be shared for downstream process planning and scheduling activities. So far there is no related research which provides a semantically comprehensive definition of a capacity feature that addresses both machine capability and availability with real-time manufacturing demands.

Chapter 3 Technological review and research methodology

Information sharing is one of the most important factors to implement collaborative engineering [72]. Before the invention of the ERP system, there were other solutions to manage manufacturing resources such as materials resource planning (MRP) [7]. The invention of the ERP improved information integration between different departments. Therefore, it provides convenient and efficient information sharing solutions in terms of inventory, accounting and operational management. However, it was discovered that information sharing between the current ERP systems and other information data, such as engineering data, is not sufficient for the current ERP system within the rapid growth of industry [49]. This causes problems in order management and manufacturing process planning. This chapter provides a historical review of ERP technology and some current ERP functions for information sharing between departments.

In recent years, customers have begun to approach an increasing number of suppliers to find the appropriate vendor with quicker response and early delivery dates. Therefore, shortening the lead time from order acceptance to product delivery is extremely important. Reliable and fast teamwork can reduce the order response and manufacturing times significantly; any advantage in turn-around time provides a competitive advantage over a company's rivals. As a result, companies are struggling to provide shorter lead-time by improving the collaborations between sales, engineering, manufacturing and inventory, which drew the attention of the information technology industry as well. ERP technology has then been developed to provide a common database for large enterprises to store, share and manage their data on a larger scale than individual departments.

3.1 Materials resource planning

Before the invention of the ERP, materials resource planning (MRP) technology provided an alternative solution for information sharing between product planning and inventory control [7]. Suppliers' scheduling, raw materials inventory updating, and manufacturing process planning were to be done by the MRP system. The lead time was shortened by more efficient materials management [73]. The main components of the MRP include the bills of materials (BOM), inventory module and preliminary scheduling functions [74].

MRP is driven by the dynamic recalculation of materials based on current or forecasted orders [75]. Unlike traditional inventory systems which could only process simple orders, MRP is capable of optimizing the raw materials/components supply chain in cases of multiple items with complex BOM [76]. Therefore, it is especially suitable for manufacturing companies whose inventory is expected to be dynamically determined by the external customer demands in order to reduce unnecessary inventory. However, the level of information sharing in MRP is limited to only within manufacturing-related departments about manufacturing operations and inventory status, with other engineering operations such as design and verifications excluded [7]. In addition, MRP cannot integrate the accounting and finance information of the enterprise.

3.2 History of ERP

To address information sharing between inventory, manufacturing and other production departments, ERP was developed [77], which expanded the functions of MRP. ERP is designed to effectively plan the overall manufacturing and production materials. It also connects trained personnel and manufacturing procedures more closely to ensure proper operation planning.

An ERP system is expected to manage a database system that covers more than material processing records: inventory control, and other daily operations, including sales and accountant databases, were integrated with the MRP system, which led to a comprehensive enterprise-wide and centralized information cluster. ERP enabled the management of more operations such as sales and accounting by a single system.

The first version of ERP was invented in the 1990s by the Gartner Group from Stanford University [7]. They developed their business software system successfully to transfer MRP to the ERP system. The most significant difference between the MRP system and the ERP system is that while MRP focuses mainly on internal resources such as manufacturing, the ERP system integrated the scheduling and planning of supplier resources based on external factors such as dynamic customer requirements and vendors [7].

In the mid-1990s, many efforts had been made to improve the ERP system and replace other traditional database control systems to reduce operating time [78]. ERP was expanded with additional functions (order management, financial management, warehousing, distribution production, quality control, asset management and human resources management [79]). With its recent development, ERP technology has also developed some advanced functions such as sales and marketing automation, electronic commerce, and supply chain management systems.

To further develop ERP technology, efforts have been made to improve it from main-frame based computing to the client/server era and now to the internet era [80]. Unlike the mainframe computing system, in a client/server environment, the server is used for storage of data, maintenance of its integrity and consistency, and processing the requests from the desktops of clients. Therefore, ERP is divided between the server and the client for the task of data processing and applications. After the 2000s, ERP vendors were able to move forward from a traditional client/server system to a browser/Web server infrastructure to deliver e-business capabilities [81, 82], which also became a trend for other software suppliers. One part of the infrastructure is a powerful server which hosts the databases based on relational database technology and business logic predefined as server procedures. The relational database system enables the vendor to build in the necessary flexibility with respect to business logic and data infrastructure to facilitate parallel business practice implementations. In general, these technologies can allow vendors to build the system to install, customize and extend in shorter timeframes [80]. Such technological advancement allowed ERP to grow from a software tool managing enterprise operations to a valuable infrastructure with efficient collaboration functions with other business partners.

The candidate believes that a modern ERP system should be highly capable of managing a global supply chain, with potential customer profile management and HMLV order fulfillment and delivery. Competitive ERP software must address the need for information flow between departments and update this information in real-time to serve the entire enterprise, its customers, and vendors. Otherwise, there are risks of disconnection and being excluded from future competitions [83].

It is worth mentioning here that because of ERP's significance in information sharing leading to improved performance and lower costs, ERP systems are widely used by governments and non-profit organizations. For more detailed reviews about the evolution of ERP systems, refer to Chen [84] ,Chung *et al.* [85] and Jacobs *et al.* [7].

3.3 Current ERP solutions

Many different ERP systems have been developed since the 1990s, with different architecture designs and data platforms for the integration and unification of business activities. ERP vendors which have significant portions in the market, such as Infor, EPICOR, Microsoft and SAP, offer multiple software packages to satisfy their customers' needs [86]. As various ERP packages exist, selection of the suitable package for the business becomes extremely important for both large, complex organizations and small companies with lower revenue. The majority of the statistics from this section come from the survey of CA Magazine [87]. In this section, four major ERP packages designed for manufacturing companies are reviewed from the order and manufacturing perspectives. The advantages and disadvantages are discussed.

Some ERP vendors have good compatibility with commercial operation system while other vendors prefer their own architecture. Microsoft Dynamics, EPICOR and Infor Syteline use the .NET framework which has improved compatibility with Microsoft products, such as Outlook™ and Word™. SAP and Infor Visual, on the other hand, use their SOA architecture with their own integrated reporting and development tools [88]. From the database perspective, all of these ERP systems are compatible with the Microsoft SQL server data engine. However, SAP's ERP system is compatible with multi-data engines, such as DB2 and Oracle. EPICOR, on the other hand, supports other databases such as progress databases. One of the drawbacks of Microsoft Dynamics (MS DYM) is that it only supports the MS SQL engine, which serves as an obstacle in their ability to serve the needs of large enterprises. From the client support point of view, VISUAL and SAP Business One (SAP B1) do not have integration into Web-based UI. This is one of the major drawbacks for implementing these systems in Web-oriented manufacturing companies.

From the financial and distribution point of view, since these are the fundamental functions of ERP systems, major ERP vendors had been developing these modules for years. Thus, functions related to financial and distributions are all well developed.

With regards to customer service, current solutions are not sufficient for handling customer requests. SAP and MS DYM have separate customer relationship management (CRM) modules integrated with the ERP platforms respectively. Further, EPICOR, Microsoft Dynamics, and SAP have integrated mobile solutions within their ERP solutions. This helps sales specialists to release sales orders with a smart phone without a computer. However, so far design information is not incorporated into the ERP system and shared. Therefore, an order specification module with multiple design configurations based on the existing design options has not been implemented in these solutions.

Since these packages are targeted to the manufacturing industry, they all possess excellent MRP and manufacturing data tracking functionalities. Manufacturing factors such as work order data collection and downtime tracking can be achieved with these packages. However, current solutions do not have the ability to match machine capability with manufacturing features. Even though these software tools can automatically load BOM into the ERP database [89], integrating design configuration information into the ERP still has a long way to go and the application has not been included in business solutions.

Chapter 4 Feature-based information framework

4.1 Customer oriented manufacturing

There are two business models for manufacturers: the traditional forecast-based approach and the customer-oriented approach which has been developed in recent years. Widely used by large retailers such as Wal-Mart, the forecast-based approach allocates production resources for fabricating a predetermined amount of products based on sales personnel's expertise or statistics/ forecasting models. The advantage of this approach is that it provides a snapshot of current and projected orders and their impact on annual sales. However, in terms of the manufacturing companies with high mix and low volume (HMLW) business modes, the performance of the forecast-based approach is not appropriate for business operations. Orders vary from customer to customer, especially for those who require specific customizations (specific technological functions, technical factors, and customized product strength under different conditions). Some customizations such as changing motors and increasing torque output may demand design changes or even re-designing of the entire product. In addition, related engineering activities such as simulation and analysis are also required along with modifications to the design. With modern flexible manufacturing technology, it is widely recognized that traditional forecast-based business structure is generally shifting into a customer-oriented business model in the manufacturing industry.

Unlike the forecast-based approach, the customer-oriented manufacturing business method is much more complicated with more demands for accurate management systems, such as inventory control systems, global general ledgers, and better labor and parts tracking. Due to the order-driven nature of manufacturing, the lead time of each product needs to be established accurately and simulated based on the current in-house manufacturing capacity, loading capability of the supply chain and reasonable assembly time. For small and medium sized manufacturers, production planning information is usually managed by experienced experts. However, for manufacturers which are expanding with HMLV production orders, managing enterprise resource planning (ERP) information manually becomes a great challenge. Moreover, engineering information for the determination of downstream manufacturing processes must be shared throughout the business to improve the efficiency of the entire company. These requirements warrant the development of a new generation of the manufacturing information management system.

Due to increasing market competition, it is extremely beneficial for manufacturers to design their products based on customer characteristics. Since different customers have specific and detailed product requirements, manufacturers need to strive to provide a wide variety of customization options for their products and services, thereby maintaining a competitive advantage. As the traditional forecast–based manufacturing approach is being replaced by customer-oriented manufacturing, effective and efficient processing of such customized orders becomes increasingly important. Dealing with such specific orders demands integrated engineering and planning/scheduling systems.

A typical customized order consists of multiple customization features and configuration requirements. Specific requirements, such as fixation, safety options, and materials could even vary between two orders from the same customer for the same product. Moreover, some customers may specify a manufacturing process, such as the gear manufacturing method. Thus, order acceptance and production job allocation become the bottleneck for companies, especially for those which adopt a collaborative manufacturing business model. For any customer-specified product inquiry, the sales department needs to consult the engineering department for design feasibility and the production department for delivery dates. Any delayed response to a customer will be detrimental to customer satisfaction, which may then result in the opportunity loss of a potential order. To reduce the product order confirmation response time, the ordered products and processes have to be carefully evaluated, and hence, the related information needs to be well integrated. Such integrated information systems will be helpful in developing a customized solution and further determining the feasible production schedule. Ideally, in the process, the preliminary specifications are generated and the implied engineering intent can be evaluated and further decomposed into engineering activities; quickly a customized solution can be developed. Next, the customized engineering design needs to be transferred to production planning engineers for schedule prediction. Finally, the resulting product and process information can be used for order acceptance decision making so as to apply the entire business strategies with a sound basis. Therefore, enhancing the ability to respond quickly to a customer according to the current design and process information is essential for business even though this function is an engineering challenge. Further, once the order is confirmed, the committed schedule must be followed up by production activities and monitored continuously.

4.2 Unified product engineering and production framework

Several approaches can be utilized to improve the efficiency of customer-oriented manufacturing processes. The most popular approach is to further develop application modules based on ERP systems. However, the lack of complete product information in ERP systems, as well as data isolation among software packages, makes it difficult to develop a coherent manufacturing solution. A typical ERP system records and tracks operational process-related data (set-up time, run-time, and number of machines) while a typical design information system focus on product structure and its detailed features and parameters. For most companies, the captured customer information from customer relation management (CRM) tools and coordination details related to collaborative manufacturing are still elementary. Such ERP modules are currently not intelligent enough to identify the customers' unique engineering requirements. In industry, the evaluation of such a big picture is usually managed by a face-to-face meeting among experienced managers, salesmen, and engineers. However, in practice, sales and engineering departments have different vocabulary, concepts, and concerns. These communication challenges can often lead to the limitation of customization and potential internal conflicts- (or unnecessary compromises), which can sacrifice business opportunities or delay the production cycle.

In order to reduce the response time and manage the production tasks in a responsive and collaborative environment with different contractors, the candidate has developed a system framework for knowledge representation and interdisciplinary collaboration among multiple stakeholders (see Figure 4-1). Feature definitions are extended to support collaborative engineering by encapsulating customer profiles, requirements, and engineering intent within a unified feature system [8]. Feature-based data-sharing is investigated with a case study.

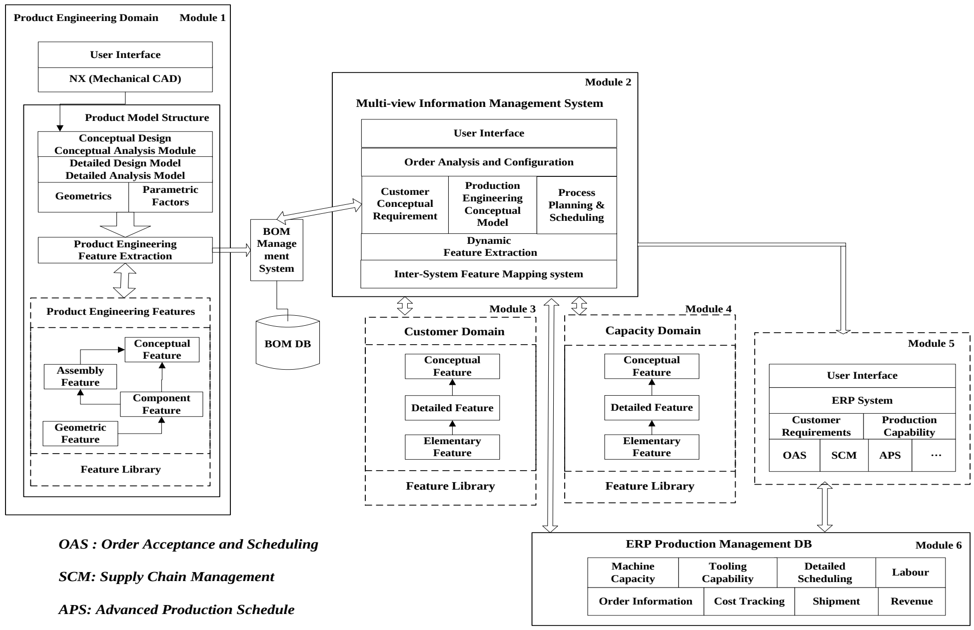


Figure 4-1 Multi-View Feature-oriented Product and Process Engineering System Framework

A typical engineering information system can be divided into product and process domains. In Figure 4-1, Module 1 is the product engineering module in which conceptual and detailed design models can be developed using a parametric and feature-based approach based on a typical CAD system, such as NX^{TM}. Features can be at the product level, assembly level, or component level. Design engineering principles, reference data, and other constraints are embedded in features and can be managed with some application tools. They are contained within both design assemblies and individual parts. To build up the feature system in the product domain, feature applications can initiate feature objects from templates in the built-in feature library. These feature objects subsequently extract data from product domain entities, such as geometries and attributes. For example, manufacturing features are identified or recognized based on the expected manufacturing method and the corresponding feature library templates.

To enable customer-driven manufacturing, manufacturing processes have to be selected based on the manufacturing feature on the related product. To achieve this, process domains need to involve product information modules. Although the manufacturing processes are intended to produce the designed products, the processes are driven by manufacturing features instead of design features. Such manufacturing features are associated with the design intent but adopted for those selected manufacturing methods and the process implementation [90].

The product feature data is fed into an inter-system feature mapping module, which is a multi-view information management system (Module 2). This module maps customer conceptual specifications into conceptual design features, and then into process capacity requirements in the process planning and scheduling sub-module.

Customer conceptual requirements are expressed using customer domain features as defined and managed in Module 3. For each customer order, the sales department needs to confirm how soon the production can be completed. This is not a trivial question in the context of collaborative manufacturing because it will be dependent upon the production capacities of the member partners (Module 4). Hence, the sales department needs to consult the planning and scheduling departments for capacity information. Once the order is accepted, the new production tasks will consume some capacity of the collaboration chain, and these tasks will be incorporated into the new schedule.

From the product domain features to the manufacturing process features, a mapping mechanism needs to be built to support a feature-based production engineering conceptual model. The resulting manufacturing conceptual features are then used by the process planning and scheduling models for cross-checking with the available manufacturing capacity of the collaborative manufacturing chain. Subsequent jobs are then transferred into an ERP system (Module 5), and the production management database (Module 6) will be updated. The libraries provide customer and capacity feature definition templates. These templates are dynamically matched and selected from the library lists, and further instantiated in the intended feature model using semantic reasoning. The predefined associative process features are generated based on customer domain features, and also the system feeds the related process domain information, such as process costs and time, back to the inter-system feature mapping system, forming a closed loop to provide a solution fulfilling the customer's requirements. The multi-view information system can also provide the salesperson with an analysis model. This model, based on customer features as well as the feedback information generated from the integrated ERP, will contain sufficient decision-making attributes about the related feasibility, penalty, revenue, and cost. Thus, integrating the product and process domains can potentially automate the transfer of engineering knowledge between the design/manufacturing engineers and the sales department.

4.3 Unified process domain feature definitions

The connection between the parallel product and process domains can be possibly developed through a sub-system within the BOM module. The BOM module usually associates the set of parts uniquely identified for a product. This module provides sufficient traceability of the overall material flow so that any item related to the final product can be directly tracked back to a specific part drawing, its raw material, the operator, and manufacturing processes involved. Different product assembly configurations, which were defined based on product development strategies, are managed by the BOM module systematically. Such individual assembly processes are then implemented accordingly through the process domain. Manufacturing features are referred to via pointers by an extended BOM management system which not only identifies and organizes products, sub-assembly parts, and out-sourced items, but also organizes design and manufacturing features.

More detailed information for the unified feature system is shown in Figure 4-2. In the process domain, customer orders and requirements are first captured by interacting with a feature-oriented specification module. The result of this module is the specified product configurations that the customer requires. The configurations are expressed in terms of the company's detailed product design features. The feasibility of satisfying a customer's requirements needs to be evaluated via an engineering evaluation process. In addition, the specified configuration is decomposed into outsourced components and in-house parts to be manufactured. Those "to-be outsourced" components involve supply chain management actions, while those made in-house involve production planning and scheduling actions. Then, the manufacturing activities expressed as production processes are further developed and decomposed into machining and assembly processes, which are defined by machining and further related to machines, tools, and workers.

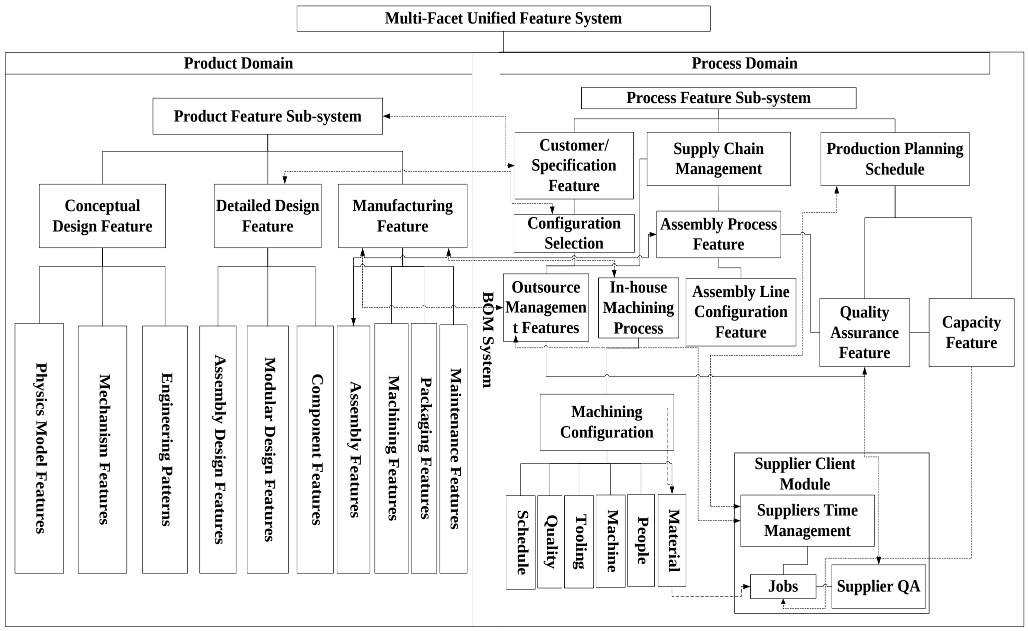


Figure 4-2 Unified Feature-based Domain Definitions

Historically, feature definitions in the product domain are well established. In the process domain, however, except for machining features, other features are rarely identified. No previous research has provided a clear conceptual framework about different process features. The candidate believes that the process domain can be effectively modeled and intelligently computerized with a feature system in order to deal with the variation of products and related business activities. In this angle, as shown in Figure 4-2, the process domain is represented as a part of the multi-facet unified feature system. The product domain consists of "horizontally" associated feature types: conceptual design features, detailed design features, and manufacturing features. Each of these horizontal-feature categories consists of several vertically classified feature types such as assembly features, mechanism features, component features, and geometrical features. Like the product domain, the process domain also allows for the abstraction of application features into a few vertical categories, such as customer features, supply-chain management features, and production scheduling features.

Process features are associated with product features in many ways. For example, customer features are closely related to (or collaborate with) product features for specifications in customer orders, but are expressed according to marketing attributes and terminology. The specified configuration selections which form a set of integrated product specifications should be evaluated and recorded with a mapping table between customer requirement features and their corresponding detailed design features. Solid lines in Figure 4-2 represent the derivative relationships between the features, and the dashed lines represent reference mapping between the product domain and process domain based on the BOM system. Note that the system framework proposed in Figure 4-1 has two new feature domains, customer and capacity, which have not been clearly defined in previous studies.

A typical customer feature consists of customer-related, characteristic properties associating sales, engineering and production information. For example, sales information can be recorded as a customer's order history and preferred selections. Based on the prepared customer features, qualified information and procedures that support relevant decision making can be represented, instantiated, modified, stored, and regenerated in a ERP system to facilitate an order's efficient interpretation and processing. Note that some customer profile modeling functions can be seen in CRM (customer relationship management) systems, which help to improve customer acquisition, retention, loyalty, and profitability [91]. However, CRM systems focus mainly on customer characterization without incorporating detailed product features, so they contain insufficient information about mapping between customer requirements and engineering designs. Thus, engineering intent cannot be effectively translated to salespeople to help them decide what products a customer needs. Moreover, CRM systems also do not contain production information such as available resources and occupancy levels. Therefore to address the current information gap between customer requirements, engineering feasibility, production costs, and schedules, it is important to integrate different aspects of knowledge.

4.4 Customer feature

A detailed definition of the customer feature is shown in Figure 4-in the UML format [92]. A customer's basic information, such as name, address, and credit level, is in the top position of the feature structure. The customer feature uses supporting lower level features, which are categorized into three types: customer financial feature, customer scheduling feature and customer order feature. A customer's financial feature is used to store a customer's financial transaction history, which generates a credit rating at order times and shows payment history. This information is then characterized into attributes. These attributes are fed to the multi-view feature mapping module for decision making analyses as well as auditing purposes. Crucial information required to evaluate any customer, such as the mutually agreed-upon terms and conditions, is also stored in this feature. The customer scheduling feature is designed to manage characteristics such as manufacturing schedule, tardiness, resource occupation, and other logistics regarding production and delivery for the individual customer. Note that each item in the feature definition can be defined as a class object which could possess further decomposed attributes and methods. For example, a schedule should be a well-defined class object. Further, tardiness is also a class object which can be broken down to the actual time delayed, tardiness tolerance by the customer, and other relevant information. The tardiness tolerance of each customer can be used to minimize production delay costs in case of a crammed situation. The customer scheduling feature also connects to the customer relation feature and influences the information regarding customer satisfaction.

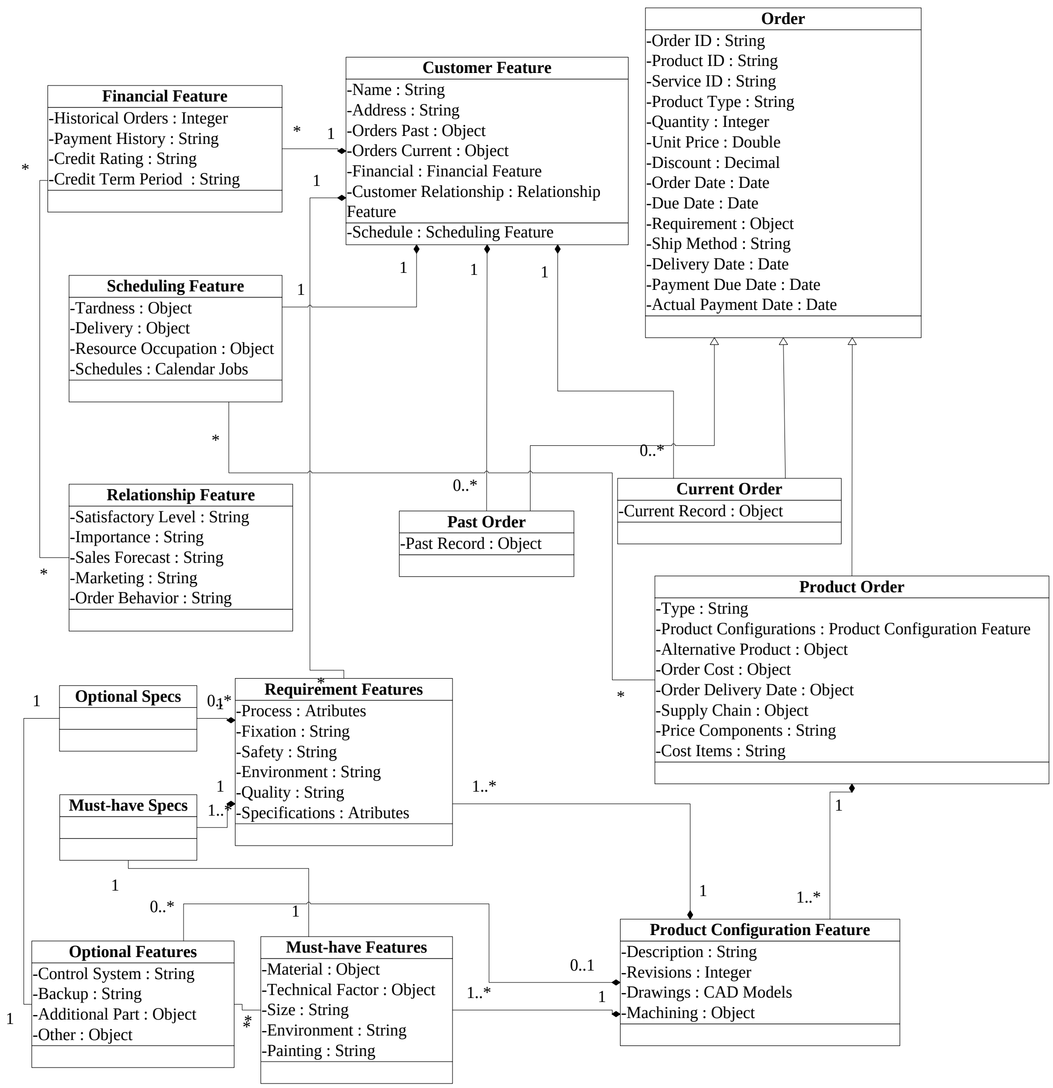


Figure 4-3 Customer Feature UML Definitions

Customer order features are divided into past and current customer orders. Both orders follow the same template, i.e., "Order," which is pre-defined and embedded into the ERP system. The product configuration feature is part of the product order feature where necessary product configuration feature information, such as the "must-have" and "optional" product features, is extracted and stored into the order object.

Customer product orders contain information about customer requirements and design configurations. Traditionally, they were mapped manually in the manufacturing industry. The product configuration feature in the top layer consists of the product model revision and geometric dimensions, among other descriptions. Customer requirement features are also associated with the product configuration feature. Their contents can be generated as default selections based on existing configurations, or specified as new configurations by the customer and constructed using semantic modeling. The requirement feature contains mandatory and optional specifications which can also be mapped into "must-have" and "optional" features. "Must-have" features are the basic features of any configuration that are necessary for the product to deliver the expected functionality. The optional features support additional functions that are needed only when there are specific requirements, such as environmental configurations and additional safety configurations. Product configuration changes will automatically update the product order’s related costs and adjust the order due date, which is associated with the ERP system’s scheduling models. Furthermore, the "optional" and "must-have" features are linked with customer order behavior attributes in the CR feature, and are used to update the customer’s order history. The customer’s historical orders related to the targeted product will be loaded, as will be the past selections of configuration features. Other customer preferences about the product will also trigger suggestions based on the same customer’s previous orders.

Detailed customer feature applications are shown in Figure 4-4. The customer feature interacts with the CRM system on satisfactory rating and payment aspects. Another function of the customer feature is that it can help search for related product configurations based on customer requirements. This feature is activated when the customer accesses the OAS system, and is presented with available choices. Order status, delivery checking information, and fault reports are stored in the order tracking system. The tracking system works with the ERP scheduling module and interacts with the customer feature to ensure that the customer order timelines and satisfactory ratings are maximized at minimum cost. The feature structure also includes a maintenance schedule, which is not often considered up front when ordering, but is essential for customer satisfaction and customer loyalty. Maintenance can occupy shop resources and interfere with the assembly schedule, thereby complicating production scheduling. If maintenance is well managed — that is, if it is appropriately scheduled and maintains the right configurations for the customer's specific requirements —production will be more efficient and revenues will increase.

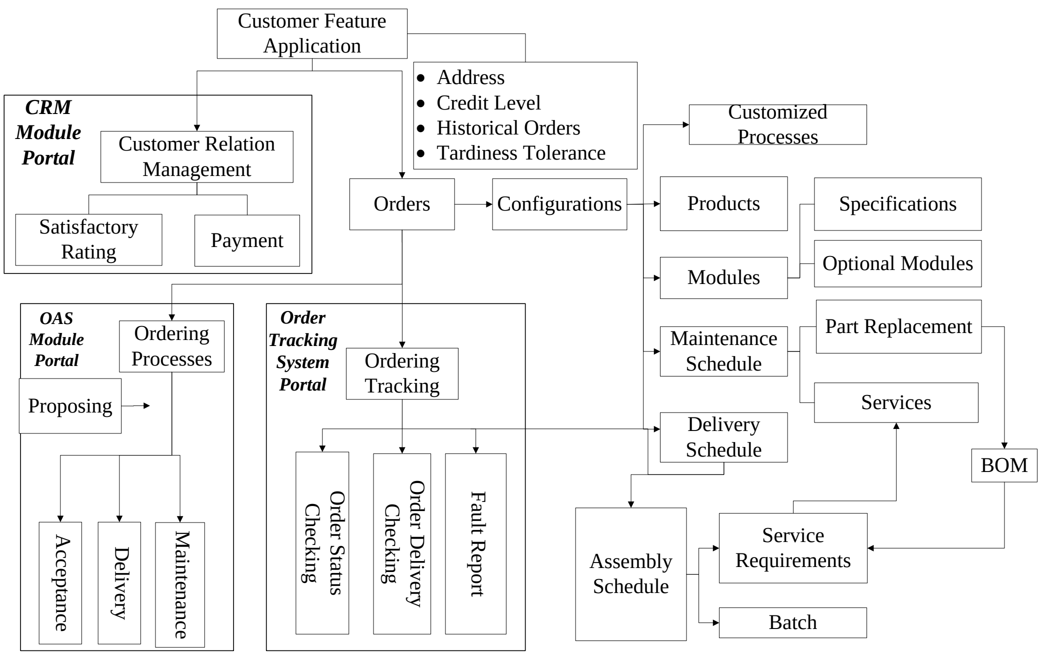


Figure 4-4 Customer Feature Application Definitions

Chapter 5 Order Acceptance System, capacity features and related modeling

5.1. Introduction to OAS

As mentioned in Chapter 3, there has been past research on the OAS in order to better manage HMLV orders and help with decision making, so that customer-oriented manufacturing processes can be more efficient. Data isolation among software packages creates significant barriers for the OAS to become a coherent manufacturing solution. Although current IT technologies, such as ERP systems, are aimed at information sharing across an organization based on a common data structure, most companies use the CRM module of the ERP to capture customer- and order-related information. However, these tools cannot identify the manufacturing step of customer engineering requirements, nor can they evaluate the impacts on the current workload, including manufacturing capacity [37], which is another critical factor in the determination of order acceptance and scheduling.

In the traditional practice, the process planner usually determines manufacturing processes and sequences. In contrast, modern process planning software derives “best” processes from a knowledge base, regardless of the shop-floor conditions and machines’ capabilities. The determined process plans will be localized/implemented by the production manager to formulate a production plan. As a result, shop floor resources are not balanced with alternative manufacturing plans owing to the lack of knowledge about the ongoing manufacturing load and the available machine capabilities, and hence it is difficult to achieve good global production planning. The same case applies to the sales department when determining order acceptance, as it is hard for sales managers to predict delivery dates. Thus, the OAS needs to be fully integrated with the company’s design and manufacturing information systems to enhance order contents' accuracy and module efficiency.

As mentioned in Chapter 4, product information, such as detailed design features and parameters, is not fully integrated and relayed to downstream manufacturing activities, such as job assignment and production scheduling. Ideally, associated information related to customer orders, production scheduling, product design and related engineering activities can be shared among the enterprise stakeholders and fed back to design engineers for product re-engineering and customization based on the system framework proposed for interdisciplinary collaboration purposes among departments [49]. Similarly, related information in the process engineering domain, such as customer profiles, conceptual requirements, and manufacturing process features, can also be integrated into a unified feature system [8] through the generic feature definition extension. In this chapter, a further study focusing on the "capacity domain" as mentioned in Figure 4-1, including a new feature definition, and the related application model, is addressed. The new feature type addresses the manufacturing capacity, named as capacity features, and is discussed with detailed constituents.

A typical collaborative manufacturing framework can be divided into the product domain and process domain [49]. A conceptual framework of a customer-driven collaborative manufacturing system is shown in Figure 5-1. Software modules managing product configurations, design, and product data management (PDM) belong to the product domain, while those taking care of scheduling and BOM and other functions, like process planning and production scheduling information systems, belong to the process domain. In the product domain, product engineering information, in the form of conceptual and detailed design models are developed in CAD systems for both design assemblies and individual parts.

Customer specifications will first be tracked by sales experts or an e-commerce system. These requirements must be translated into detailed product configurations based on engineering semantics, and then matched with the PDM system for available products. In certain cases, a more specific engineering process needs to be involved after a customized order is placed. All the details about products and processes will be fed into the OAS for order acceptance. Accepted orders will be translated into work orders with manufacturing features and BOM information. The work orders are stored in the process planning system [3, 16] and ERP databases. The system for process-planning and production scheduling is a common information system (PSIS), where orders are broken down into manufacturing processes and allocated to shop-floor resources for production purposes.

To better coordinate the OAS with ERP and further enable customer-driven manufacturing efficiently, product feature information required for order confirmation and needs to be relayed to the process domain, i.e., fulfilling the order. Moreover, other procedures in process domains, such as selecting manufacturing methods and the process implementation, require consulting product feature information. Finally, the product domain also needs feedback from the process domain for design maintenance, product modifications, and new product development. Thus, features in the process domain need to be associated with the design features in the product domain.

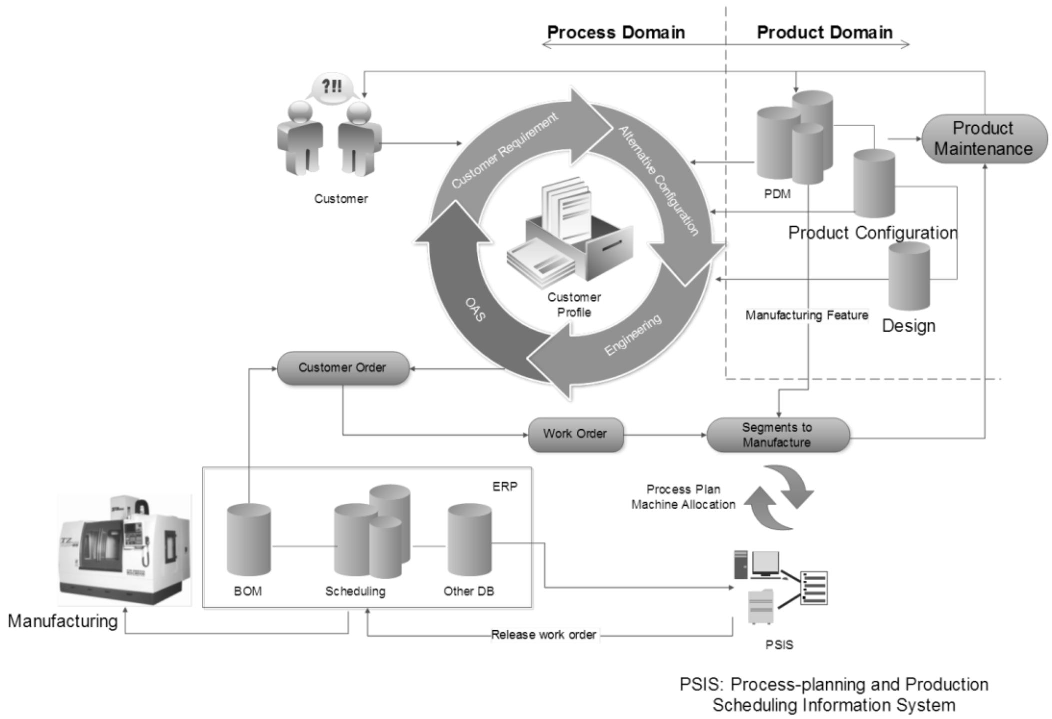


Figure 5-1 The Concept of Customer-driven Collaborative Manufacturing System Framework

To achieve the goal of customer-driven manufacturing, feature technology can play a pivotal role in system integration. Feature, as an informatics class in engineering, is defined as an "information carrier," to manage engineering principles, design entities, reference data, and engineering constraints. Feature definitions in the product domain have been well established [93]. There has been good practice where product features are translated into manufacturing features and then passed down to the process domain. However, in the process domain, the feature system is not well defined and the information systems use elementary data structures only. The candidate believes that there needs to be a feature mapping system that links the design domain to the manufacturing domain [9, 10]. Other process domain features can also be modeled and integrated with each other intelligently and effectively throughout the product lifecycle. For example, customer requirements can be associated with alternative product configurations for product model selection. Furthermore, delivery data can be better predicted with other related process information, such as resource capacity available, scheduling flexibility, and supplying partners' capability from a supply chain angle.

As shown in Figure 4-2, product domain feature entities can be classified into several associative feature types, forming a feature system. Similarly, the process domain can also be represented with a feature hierarchy. So far, associating process features with product features is not well-achieved. The BOM system in ERP identifies not only a list of parts to be used for assembly but also different configurations where the assembly modules with different design engineering considerations. These configurations are essential to satisfy customers during product selection, and the final product confined must be related process engineering activities. The candidate proposes that the BOM system can be extended supporting the integration of product and process domains. Unfortunately, however, unlike the product domain, many of the process domain features and modules are not yet well defined.

Feature objects can easily extract design entities from product models, and then transfer these properties to the process domain. Hence, process features can use product entities and link them with product features in many ways. In this chapter, a new category of features, the capacity feature, is modeled. Real-time shop floor resources' capabilities are encapsulated in capacity feature objects and closely related to product configurations for the accepted customer order. Further, the capacity feature is also associated with the customer feature and some ERP modules, such as MRP, scheduling, and production planning. The systematic modular associations are proposed in Figure 5-3.

5.2 Capacity Features

Figure 5-2 shows the proposed capacity feature application structure designed to functionalize the framework in the context of collaborative production in a supply chain. A resource's capacity is defined in the form of an object, whose properties are the parametric attributes describing the resource capability to fulfill an input process feature. The abstracted class is named a "capability feature" as a data type. Capacity features are to be used for collaborative production planning and scheduling by providing the manufacturing partners' resources and availability in a timely manner. A breakdown of the capacity feature constituents is shown in Figure 5-2.

A machine capacity feature is the fundamental attribute that shows how well a process feature can be dealt with, e.g., setup power, fulfillment space, quality, and time. For example, for a CNC center to machine a part with a set of machining features, its capability feature can include information such as machine layout type, cutting axes, tool magazine, pallets and controller. Such information combines with other supporting facility information such as storage, material handling, and environmental conditions, and collectively forms the entire capacity data structure. The machine configuration features can be loaded from a separate data file or embedded into the ERP system as the outer built-in resources information.

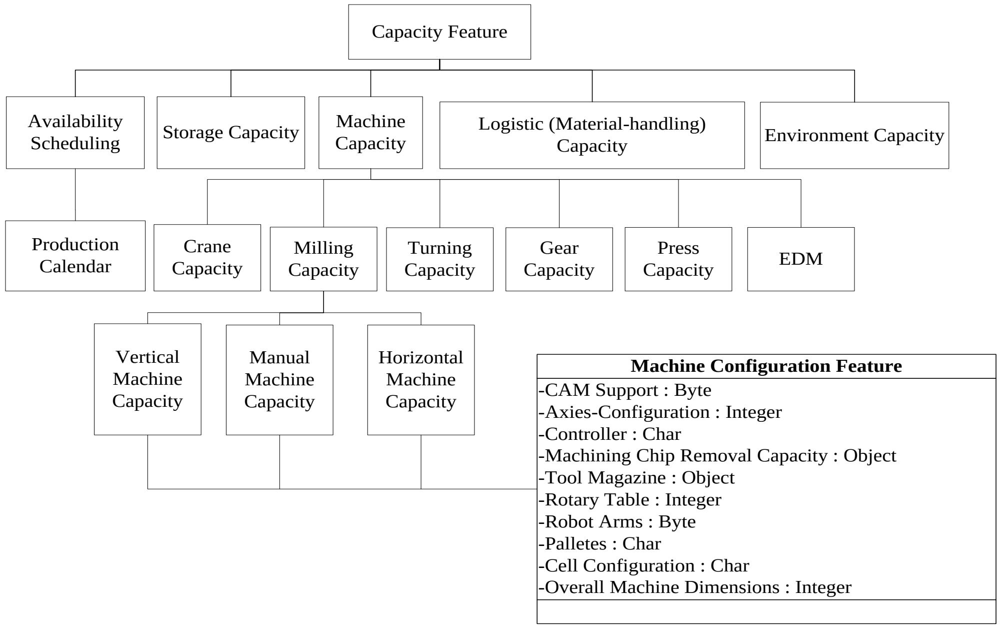


Figure 5-2 Capacity Feature Application Definitions

5.3 OAS under the Unified Feature Framework

As shown in Figure 5-3, the overall application framework consists of three main parts: the ERP, the OAS, and a unified feature module. Some important ERP modules involved with the OAS are MRP, production planning, scheduling, and other management modules for customer inquiries, orders, quotations, operations and shop resources. The customer inquiry module in the ERP acquires customer requirements and triggers an inquiry cycle via the information services module in the OAS. The information service module translates customer requirements into a consistent data structure, i.e., a requirement feature, and associates the requirement feature with a customer feature created for that customer via the customer profile module. The customer feature also manages the historical configurations and preferences via a unified feature module, and passes this information to the OAS module and passes in-depth, customer-specific product information into the customer inquiry module. Subject to the customer’s interactive evaluations and selection, the ERP order management module handles the creation and management of the orders, and the confirmed order information is permanently recorded in the ERP for further processing; customer-related feature information is updated via the related profile management module in OAS. The customer feature-related information is consistently managed by the unified feature module and its earmarked data will be stored in the product database eventually. Note that the arrows in Figure 5-3 indicate the directions of the information flow.

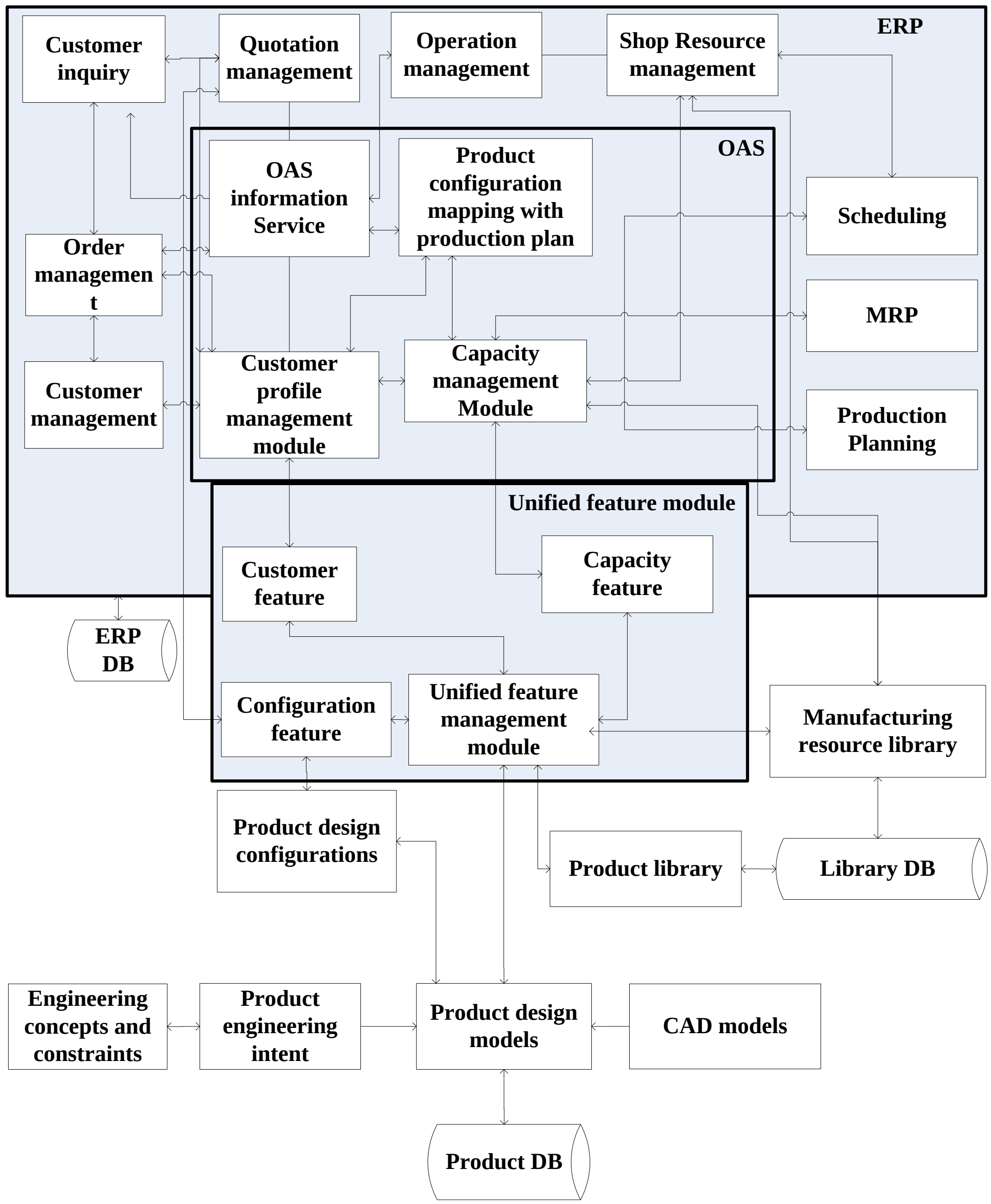


Figure 5-3 Capacity Feature Applications in the Context of OAS with ERP

Product configurations related to the specific customer have to be mapped with the corresponding production plans to ensure feasibility, avoid scheduling conflicts, and take into account other related manufacturing processes. In fact, this module requires the translation from product design features into manufacturing features. The OAS mapping module interacts with the capacity management module, customer profile module and information services module, so that real-time resource capacity and occupancy information can be used for configuration selection and order acceptance.

Again, refer to Figure 5-3, the capacity management module links manufacturing capacity feature information with the stored manufacturing resources library in a unified feature module. Pre-existing machine parameters from the ERP shop resources management module are fed into the OAS capacity module for analysis and evaluation. All this information will be evaluated in detail by the capacity feature, providing matched results of the process features and resources available. Hence, feasibility of production for the specific customer can be concluded. Once confirmed, the capacity management module will interact with the ERP functioning modules, such as the MRP, production planning, and scheduling, to confirm the order if the customer chooses to do so. Thus, the OAS is integrated with ERP based on the unified feature module, which also links from the product domain and the process domain using the customer feature.

For the readers' benefit, the concept of the unified feature modeling system can be found in [8]. It was designed to be a multi-view feature-based engineering information management system. In this thesis, it is proposed that the customer feature maps conceptual requirements with conceptual design features. These design features collectively define the customer's required product configuration. As discussed above, such customer-specific configurations are mapped with process capacity requirements and determine shop resource allocation as well as overall production scheduling. Thus, customers and salespeople can directly observe product feasibility and manufacturing capacity feedback through the functioning interfaces of the unified feature module. When an order is accepted, manufacturing jobs will be allocated and further incorporated into a new production schedule. Engineering concepts and design constraints that have been collectively managed in the product engineering intent module are checked and the validation information is further returned back to the functional module managing product design models which are usually developed using software re-development tools such as NX OPEN++™. Feature information is stored in a product database at their corresponding levels: product, sub-assemblies, and components. CAD models provide essential geometric input for the product design models, where parametric and geometric information are embedded. All the entities in the product design model are referred consistently with the unified feature management module for data consistency management and sharing purposes.

5.4 Manufacturing capacity features analysis

Manufacturing capacity refers to a comprehensive pack of information representing the performance of an enterprise regarding its capabilities, including production capacity, new product design ability, innovation in manufacturing processes, application of new technology, resource allocation, quality assurance, cost control, delivery management, and after-sales service at a certain time point. Manufacturing capacity is the primary source of sustainable competitive advantages in the manufacturing industry. Production capacity is one of the important indicators of manufacturing capacity, referring to quantity of products to be delivered in a planned period of time. Traditionally, production capacity is described at a plant level in terms of the number of products that can be produced in a given amount of time. The capacity of a machine is described by its maximum part size to be accommodated and its machining processes to be carried out with detailed attributes. However, there is huge gap in scheduling a product order with the available manufacturing capability even though the workshops are not fully occupied. Thus, matching the unused machine capability with complex process constraints such as supported machining features, dimensions, and accuracy in order to meet customer order requirements is a challenging process. The matching mechanism must have a clear "supply and demand" relationship in 100% detail. That means much finer descriptions on new order production requirement are necessary while the compatible answers to the required functions from the low level machine capacity are expected. In such a way, a feasible matching of manufacturing capacity and order requirement can be found, and further optimized when multiple options are available.

With the dynamic matching requirement in modern collaborative manufacturing, a generic mechanism to support the "match-making" requirements is highly important. The candidate believes that the structural representations of "demand" and "supply" must be comprehensive, compatible in information interaction, and consistent for management in the long production life cycle. The terms referred, or the generic elements used to describe the specific "demand" should be the same as those describing the element of "supply." In this study, the "part process feature" is the generic representation of the supply. A part process feature measures a manufacturer's overall ability to produce the final product and related parts based on in-house manufacturing and supply chain management, as well as machining capability based on shop floor resources. The capacity feature is a pattern to be used in collaborative production planning and scheduling by providing the manufacturing partners' resources and availability in a timely manner.

A detailed UML diagram representing the plant level capacity as well as machine level capacity is proposed in Figure 5-4. Usually, manufacturing of a product can be separated based on two aspects: parts and assembly. Similarly, plant level capacity can be divided into two sub layers: assembly capacity and part processing capacity. The assembly capacity feature represents the assembly ability assuming all the available parts are prepared, which contains attributes such as the constraint list, reference entity, and parameter list, while part processing supplies the parts in a timely manner [94]. The part processing class is a separate class which manages the sources of each part, as it is usually balanced among the three methods, through in-house manufacturing, withdrawal from standard parts inventory, or through outside vendors by outsourcing. Thus, the part capacity class contains three sub level classes: the inventory capacity feature, machine capability feature and SCM capability feature; each stands for parts supplied from in-house manufacturing, inventory control or KANBAN, and outsourcing. Each of these three features will serve as an information pattern and interact with other manufacturing systems, such as the SCM system and the KANBAN/ inventory control system. The SCM capacity feature also connects to the assembly capacity feature to adjust the assembly schedule based on the lead time of outsourcing parts.

The machine capacity feature has four attributes: machine ID, dimension limits, machine schedule, and manufacturing features. The part dimension attribute manages the dimension limits of each part for further mapping with machine working envelopes. This class can link to design software such as NX. The manufacturing feature attribute interacts with the manufacturing feature database and implements the mapping between machine factors, which is stored in the machine class and manufacturing requirements in manufacturing features. The scheduling feature sub class is designed to manage the availability of machines. It interacts with the ERP system to extract sufficient scheduling information.

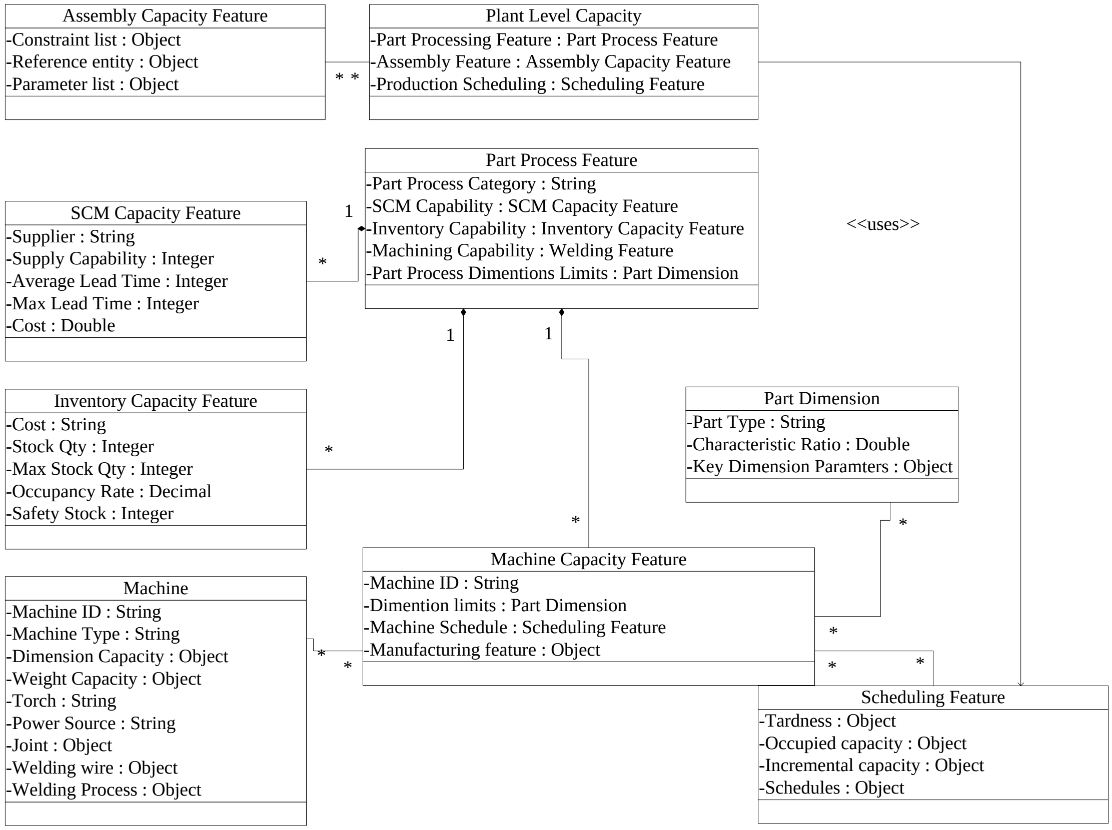


Figure 5-4 The UML Diagram of the Part Process Feature and its Sub-features

5.5 Welding feature modeling

5.5.1 Welding feature definition

The welding process is specified by the base material, structures to be welded, and process-specific requirements. Generally, the welding process is affected by the following factors, cleaning results and preheating temperature, welding flux and wires, groove type design, process parameters, and post-weld heat treatment. The welding method is determined by the base material and its specification. Generally, there are several methods suitable for the base material. The designer selects, based on his/her knowledge and experience, the ideal method and relevant electrode, welding flux and wires, welding electrical parameters and nozzle to implement the welding process. Welding parameters include welding current, voltage, and welding speed. Post-weld heat treatment can eliminate stress resulting from the process.

To represent the welding process using computer software, a detailed structure of the welding feature is defined in UML format and shown in Figure 5-5. Related terms are shown in Figure 5-6. The welding feature is the main class with each object associated to one welding operation with four attribute features: the quality feature, welding process feature, design feature and equipment feature. Following the framework proposed as shown in Figure 4-1, the design feature is expressed using the sub class welding product feature, while the process feature is expressed by the welding process feature. The welding product feature manages information generated during design processes. Thus, engineering intent, which is generated in the product domain, can be stored in the welding feature and used in downstream processing activities. The welding product feature class can be defined using four member features, of which joint, seam and groove are the three main classes representing the parametric factors for the design of the weld. Geometric information is expressed in CAD modules, and the material attributes control the material of the parts to be welded. It will influence the welding strength and related seam features. The groove feature mainly includes the angle of the groove, type of groove, groove depth, and root radius. Joint features include connection type, welding pool size, starting point, welding direction, joint gap and other related attributes. The seam feature only contains height and seam length attributes, because groove, joint, and seam use the same welding geometry. Welding geometry actually combines joint and groove, and the joint feature determines the size and shape of the seam. The seam feature is also used by process sub features to determine welding parameters, such as the welding method, shielding gas and, most importantly, welding equipment. The welding process feature and process sub feature stores most of the factors that will be used during the welding processes, namely location, welding method, seam requirement, welding parameter, preheating and cleaning.

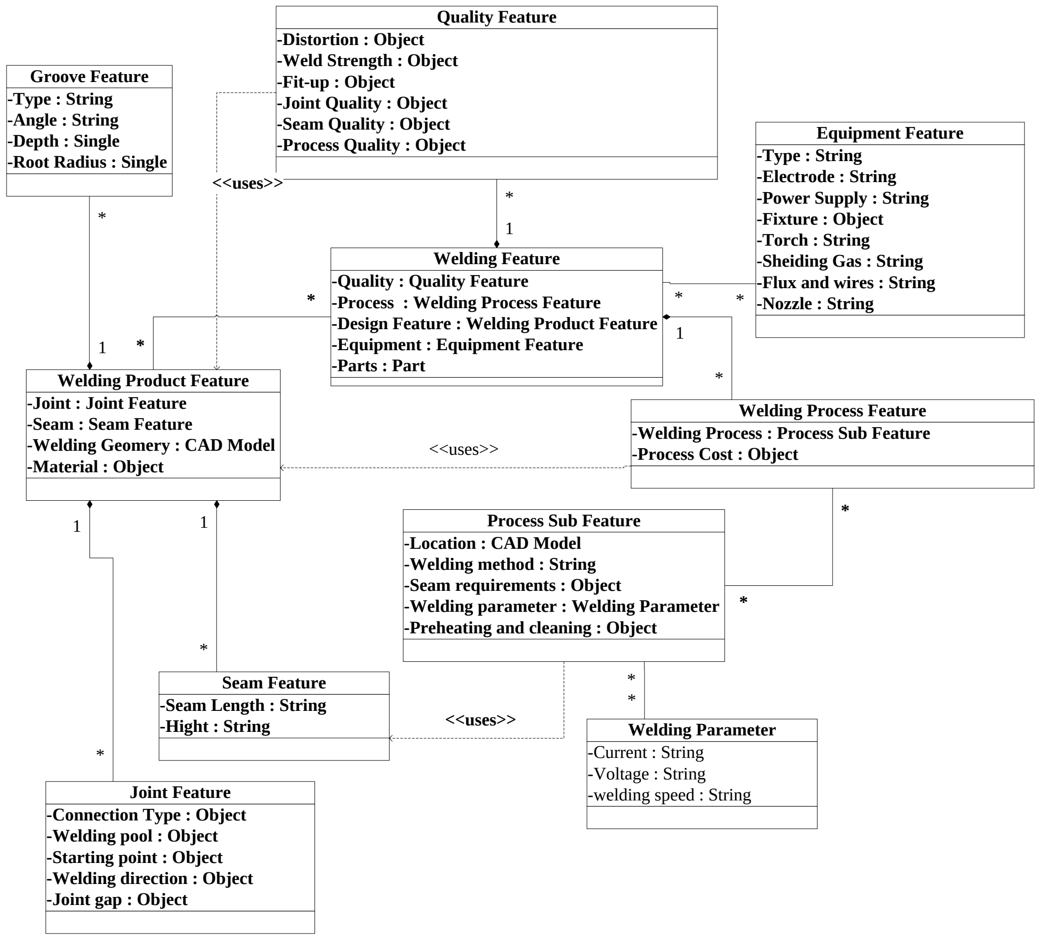


Figure 5-5 The UML Diagram of the Welding Feature and its Sub-features

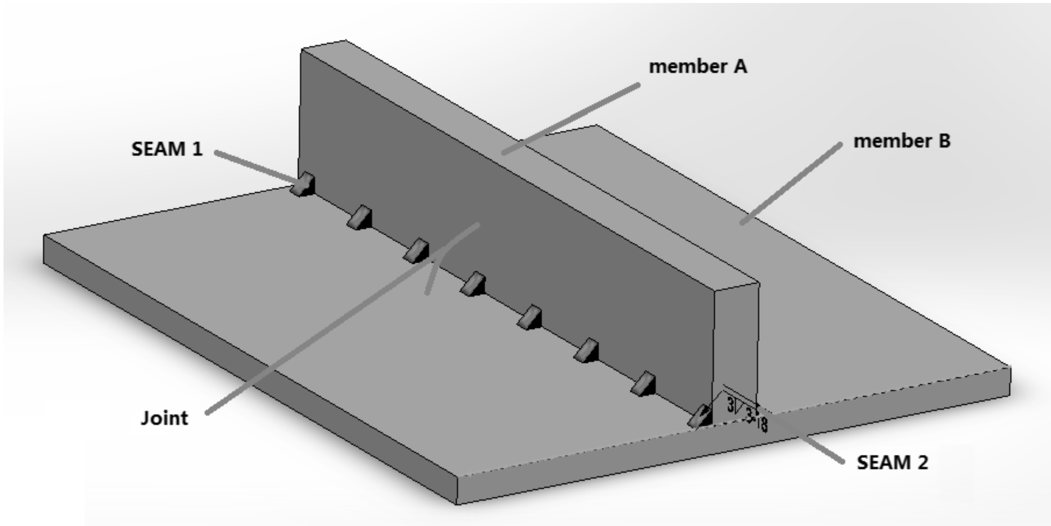


Figure 5-6 Diagram Expressing Welding Terms

5.5.2 Data Input of Welding Feature

In a welding operation, product data is usually organized with a hierarchical graph structure, such as a system BOM, which can be used to associate a set of member parts. Detailed welding joints are classified into seams. Each is related to a sub process feature. This hierarchical graph provides a connection among feature elements, such as the graphs for conceptual design elements and detailed design elements respectively. Traditional studies of manufacturing features mostly focus on machining processes, and have rarely examined welding processes and related features. This is because welding is usually a manual and flexible process, and is usually considered as one of the "assembly steps" from the design point of view. In this study, a welding module is considered a permanently assembled module with member parts. One specified weld usually consists of a number of design and manufacturing features, which can be classified into welding joint features. The information will then be used by design and manufacturing engineers for equipment selection and further process planning purposes.

As shown in Figure 5-7, a detailed classification of welding elements is made based on welding symbol standards of the American Welding Society (AWS A2.4-93). A suitable welding process with available welding equipment can be decided based on the joint of the two parts, with different grooves, and related seams. A weld consists of three main elements: groove, seam and joint. Each of the elements has several sub elements which will combine with each other to determine the type of a weld. With related parametric and geometric factors, the selected welding classification can represent information from both design and manufacturing aspects. Design information is usually used by design engineers by determining the location and geometry of the weld, as well as calculating the strength. The manufacturing aspect is used by production engineers for further process planning and quality control. For example, a T-type plate welding seam usually has the following types: symmetrical, cross, and all-along. These factors can be revealed by the distance between these two triangles. From the design side, the geometry can follow certain standard libraries with related design cost and lead time. Figure 5-7 shows a series of welding design classifications which provide information on precise geometries and their related constraints.

Each welding feature element in a single enterprise should follow the same coding strategy for standardization purposes. In this study, the candidate defines it as a three-section, 12-character code. The first three characters represent which joint, seam, and groove will be used, while the following number represents the sub type in this class. The following characters and numbers represent the type of and which machine to be used. The last character represents the design code. In this example, the element code is "TSD-001GM01," a T-joint (T), double-sided (D) seam with no grove (S). The seam is symmetrical and uses the GMAW welding machine 01. For different companies with different equipment, the coding may vary, which will match the equipment information in the ERP system.

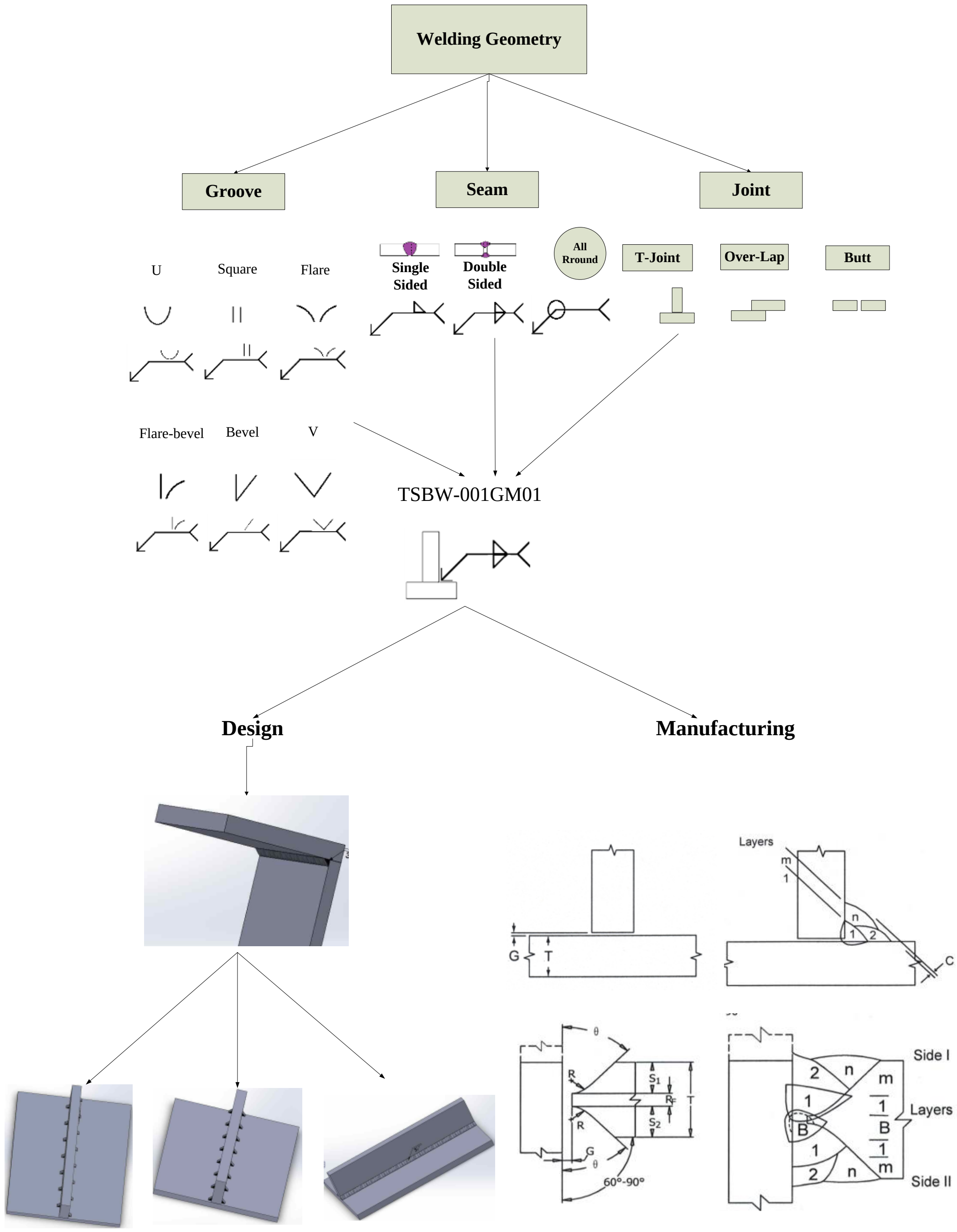


Figure 5-7 Classification of Welding Feature

5.5.3 Mapping model

After welding elements have been defined and classified based on the welding features, product data can be related as referenced attributes and entities; and constraints are kept in the form of the welding feature and ready to be used by the ERP system to map with shop resources based on the capacity feature proposed in Section 5.3. For welding equipment, there are several types and choices, and each of them has pros and cons, as shown in Table 1. For instance, MIG welding is a low cost process but it cannot handle some materials such as stainless steel, and the distortion is usually very high. Hidden arc welding has a high finishing standard and the welding speed is fast, but it will only work for plain seams. Moreover, the working envelope size needs to be checked so that the room is big enough to accommodate the part with specified fixtures and the welding rod as well as the holder. Moreover, the number of setups should be reduced to minimize the overall cost.

Table 5.1 Comparison of Different Welding Techniques

Method	Good finish	Distortion	Quality	Weld Speed	Material
MIG	Fair	High	Fair	Fair	No Stainless Steel
TIG	Fair	High	Good	Low	Most
Laser-beam	High	Low	Good	Good	Thin
Hidden arc	Fair	High	Fair	Good	Flat
Electron-beam	High	Low	Good	Fair	Without High vapor pressure

With the involvement of various constraints, the mapping mechanism between the welding feature and capacity feature becomes a non-linear and complex problem. Moreover, due to the flexible nature of the welding process, manufacturers sometimes sacrifice quality characteristics, such as high-quality finishes, in order to meet certain deadlines or to reduce costs. Taking the above-mentioned factors into consideration, mapping should be designed as a strategic process with different constraints. Storing the feature attributes in arrays makes mapping possible when modern computer technology is involved [95]. Certain software tools, such as Matlab™ and Mathmatica™, can be used for investigating the realization, and further optimization of the mapping mechanism between features. In this study, the candidate provides pilot efforts in the modeling of the two features, and related comparisons between the machine capacity feature and welding feature with a sample industrial case, based on arrays and comparing algorithms as a proof-of-principle for the feature mapping. Full mapping and interacting between the two proposed features are not included and require further effort.

- *Welding features description*

Each welding feature can be expressed in the form of

$$\mathrm{WF} = [\mathrm{D}, \mathrm{W}, \mathrm{M}] \tag{1}$$

Where,

$$\mathrm{D} = [\mathrm{lenth}, \mathrm{width}, \mathrm{height}] \text{ (in units of [mm])} \tag{2}$$

$$\mathrm{W} = [\mathrm{F}, \mathrm{y_x}, \mathrm{Step}] \text{ (}y_x\text{ in units of [mm])} \tag{3}$$

$$\mathrm{M} = [\mathrm{CM}, \mathrm{MAM}, \mathrm{MVT}] \text{ (MAM, MVT in units of amperes and volts)} \tag{4}$$

Array [D] represents the geometries and parameters of the components to be welded, namely width, height, and length of the components. Array [W] represents the joint, namely the type of the feature (F), such as seam, groove, bead or joint type, their related geometry and parameter factors y_x and the manufacturing sequences. The definition of y_x varies depending on the elements to be included. Array [M] defines the material properties such as components' material (CM), maximum amperes (MAM) and maximum volts (MVT).

As the entire welding process usually consists of one or more welding features, the whole array can be expressed as follows, where m different welding features exist.

$$[\mathrm{WF}]_{m*1} = \begin{bmatrix} \mathrm{WF}_1 \\ \vdots \\ \mathrm{WF}_m \end{bmatrix} \tag{5}$$

- *Capacity feature description*

For a specific welding machine, the capacity feature can be expressed using the following array:

$$\mathrm{MF} = [\mathrm{E}, \mathrm{P}, \mathrm{T}] \tag{6}$$

$$\mathrm{E} = [\mathrm{MTX}, \mathrm{MTY}, \mathrm{MTZ}] \text{ in units of [mm]} \tag{7}$$

$$\mathrm{P} = [\mathrm{S}, \mathrm{I}, \mathrm{V}] \text{ in units of [mm/s], [A] and [V] respectively} \tag{8}$$

$$\mathrm{T} = [\mathrm{MT}, \mathrm{PW}, \mathrm{ECY}] \tag{9}$$

A machine capacity feature array consists of [E], work envelope dimension, [P], process parameter, and [T], machine characteristics. The working envelope dimension array is comprised of the maximum amount of travel in each direction (MTX, MTY, MTZ). The process parameter includes the welding speed (S), maximum service current (I) and voltage (V). The machine type (MT), power (PW) and efficiency (ECY) are the components of machine characteristics.

Therefore, the capacity of a size of m different welding machines can be expressed as

$$[\mathrm{MF}]_{m*1} = \begin{bmatrix} \mathrm{MF}_1 \\ \vdots \\ \mathrm{MF}_m \end{bmatrix} \quad (10)$$

- *Mapping between capacity and welding feature*

In this research, two kinds of factors are considered during the process of mapping the capacity feature with the welding feature: constraint factors and strategic factors. Constraint factors are comprised of the raw material weldabilities, working envelope sizes and power sources. They are used to determine whether or not the machine can carry out the designed welding process. That is, the machine is not feasible for the welding feature unless all of the constraints are successfully satisfied. After the machines' feasibilities are determined, strategic factors are used to select the most suitable welding machine out of those feasible ones based on the operational strategies applied. The strategic factors of each machine are machine waiting time, setup time, welding efficiency and its characteristics compared to the other machines.

- *Constraint factors*

According to [96], the weldability of different materials used by different welding techniques can be determined based on common practice and then expressed into an array [WB] = [B_{ij}], where B_{ij} represents i machine with j welding technic. The value of B_{ij} determines whether the technics is highly recommended (B_{ij} = 2), regularly used (B_{ij} = 1), or not applicable (B_{ij} = 0). To weld the part successfully, the dimension of a working envelope size must be larger than the dimension of the part to be welded to accommodate the part and set up the machine properly. Similarly, the maximum power of a machine must be greater than the power needed during the welding process.

- *Strategic factors*

To compare and select the feasible machines, a strategic model is built according to the main operational strategy of the business. In common practice, the manufacturer selects the most suitable machine by optimizing the cost and the delivery time. As an example, when cost is the only goal to minimize, the candidate mainly considers four types of cost: operational cost (OC), waiting cost (WC), setup cost (SC) and occupancy cost (UC), which will be further explained in later paragraphs.

The first step to compare the feasible machine is to determine the efficiency factor of machine by calculating the number of layers needed to be welded to join the parts which related to the operational cost. During the process to form a welding bead, the welding machine heats up the flux to a temperature higher than its melting point and, subsequently, melts a sufficient amount of material, which falls into the joint and forms a bead by bonding to the molten base material. To calculate the volume of the bead, it is simplified as a combination of three geometrics, BV1, BV2 and BV3, as shown in Figure 5-8. BV2 is a cone cylinder body, while BV3 and BV1 are sphere segments. Thus, the volume of the bead can be calculated by (11).

$$V = \frac{h2}{3}\left(R^2 + r^2 + Rr\right) + \pi h3\frac{(3r^2+h3^2)}{6} + \pi h1\frac{(3R^2+h1^2)}{6} \qquad (11)$$

The amount of energy needed to form the bead contains two different types of energy: warming the welding flux and melting the flux and base material, respectively. The two types of energy are calculated using the formula below, where C, H_f and ρ are the special heat capacity, heat of fusion and density of the welding flux, respectively. ΔT is the difference between the room temperature and the melting temperature of the material.

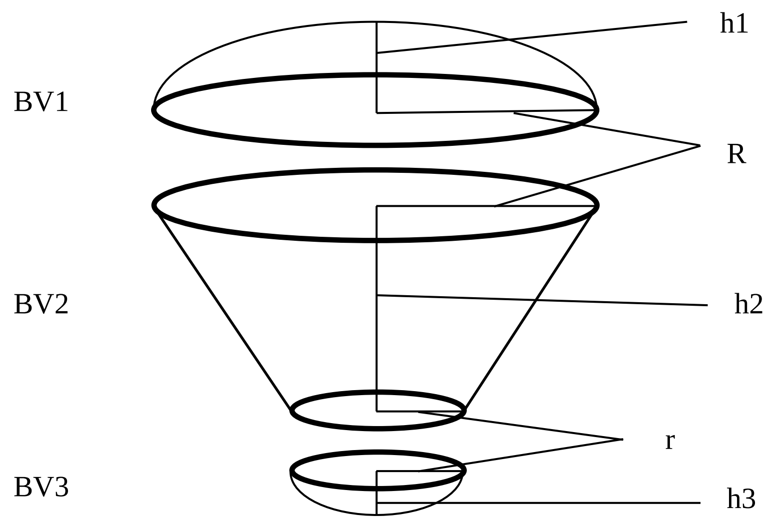


Figure 5-8 Welding Bead Simplified Model

$$E_{need} = C \cdot m \cdot \Delta T + m \cdot H_f = \rho V(H_f + C \cdot \Delta T) \qquad (12)$$

As a welding machine usually supplies a specified range of power, the minimum and maximum size of the bead to be created in a certain unit of time can be expressed as follows where M stands for the molar mass:

$$E_{supply} = P \cdot \Delta t = (U \cdot I) \cdot \Delta t = \rho V(H_f + C \cdot \Delta T) \qquad (13)$$

$$V_{max/min} = \frac{M(U_{max/min} \cdot I_{max/min})}{(H_f + C \cdot \Delta T)\rho} \Delta t \qquad (14)$$

Therefore, the selection of the welding machine from the bead point of view can be expressed in (15) (16), where δ is the welding layers overlap factor.

$$\text{If} \begin{cases} V < V_{min} & \text{the machine can't be used} \\ V_{min} < V < V_{max} & \text{Weld single layer} \\ V > V_{max} & \text{Weld multiple layers} \end{cases} \tag{15}$$

$$\text{Number of Layers} = \frac{V}{V_{max}} \times \delta \tag{16}$$

$$\text{Efficiency Factor} = \frac{1}{\text{Number of Layer}} \tag{17}$$

After the number of layers that need to be welded is calculated, together with the historical/calculated time spent to form a welding bead and the cost rate, the related cost factors can be calculated to select the most suitable machine.

If a machine is occupied when there is an immediate job request, a waiting cost should be applied since interrupting the current job will result in an additional setup. To simplify the illustrative model, in this thesis it is assumed that the job cannot be interrupted once started. Thus the WC can be calculated using the formula below, where t_p is the time spent to form a welding bead of the current job of the machine and Qty_p is the size of the batch for the current work load of the machine. In addition, WR is the hourly waiting cost rate and N_{beadp} is the number of welding beads needed for the job on the machine, respectively.

$$WC = CW_p \cdot Qty_p = WR \cdot t_p \cdot Qty_p \cdot \frac{1}{ECY_p} \cdot N_{beadp} \tag{18}$$

Similarly, the operational cost of the current job can be calculated, where t_c is the time spent to form a single layer of the current welding feature and LR is the labor hourly cost rate, respectively.

$$OC = CO_c \cdot Qty_c = LR \cdot t_c \cdot Qty_c \cdot \frac{1}{ECY_c} \cdot N_{beadc} \quad (19)$$

Common setup procedures can be shared if the job is going to be run in batches. As a result, the setup cost can be expressed as the average setup cost for each feature. N_{setup} represents the total number of setups of the whole welding process since the setup for each welding feature may not be the same. t_{setup} stands for the setup time for a welding feature..

$$SC = N_{setup} \cdot LR \cdot t_{setup} \cdot Qty_c \quad (20)$$

Apart from the OC, WC, and SC, the last important factor for machine selection is the UC. Each machine has unique characteristics, which can be derived from the machine characteristic class in the capacity feature. If a job can only be achieved using a specific machine, there is an additional cost of the machine while the other parts are waiting for its availability. Therefore, the UC is calculated according to the time spent on the manufacturing resource, as well as current work load of the machine. In the formula below (21), CL stands for the current work load of the machine; CU is the hourly uniqueness cost rate; and UF is the uniqueness indicator.

$$UC = (t_c \cdot \frac{1}{ECY_c} \cdot N_{bead} + t_{Setup}) \cdot Qty_c \cdot CL \cdot CU \cdot UF \quad (21)$$

In this study, weighted factors are assigned to the aforementioned costs; they are used to determine the suitability of a machine to manufacture a feature. The weights of cost factors can be expressed using an array [DX] = $[a_1\ a_2\ a_3\ a_4]$. The weight values represent the relative importance measures among the cost factors, which should be derived from the business' operational strategies, and should be consistent for the default setting of the jobs. However, for certain urgent or unique jobs, the values of [DX] can be artificially adjusted, which won't be discussed in this research. Therefore, the cost function can be expressed using the following formula:

$$\mathrm{FC} = [a_1\ a_2\ a_3\ a_4] \times [\mathrm{WC\ OC\ SC\ UC}]^{\mathrm{T}} \tag{22}$$

$$\mathrm{FC} = a_1\mathrm{WC} + a_2\mathrm{OC} + a_3\mathrm{SC} + a_4\mathrm{UC} \tag{23}$$

The overall cost of the whole welding process is written as [OVC]. Thus, the most suitable machines can be determined using the following equation:

$$[\mathrm{OVC}] = \textstyle\sum_{\mathrm{i}}[\mathrm{FC}]_{\mathrm{i}} \tag{24}$$

- *Sample Case*

A sample case is built based on a real industrial case. Two plates need to be welded together with two side bars in the middle, as shown in Figure 5-8. Usually, the whole welding process can be separated into four steps: welding the top plate with the side bar (left), welding the bottom plate with the side bar (left), welding the top plate with the side bar (right) and welding the bottom plate with the side bar (right). The white lines in Figure 5-8 show the locations to be welded.

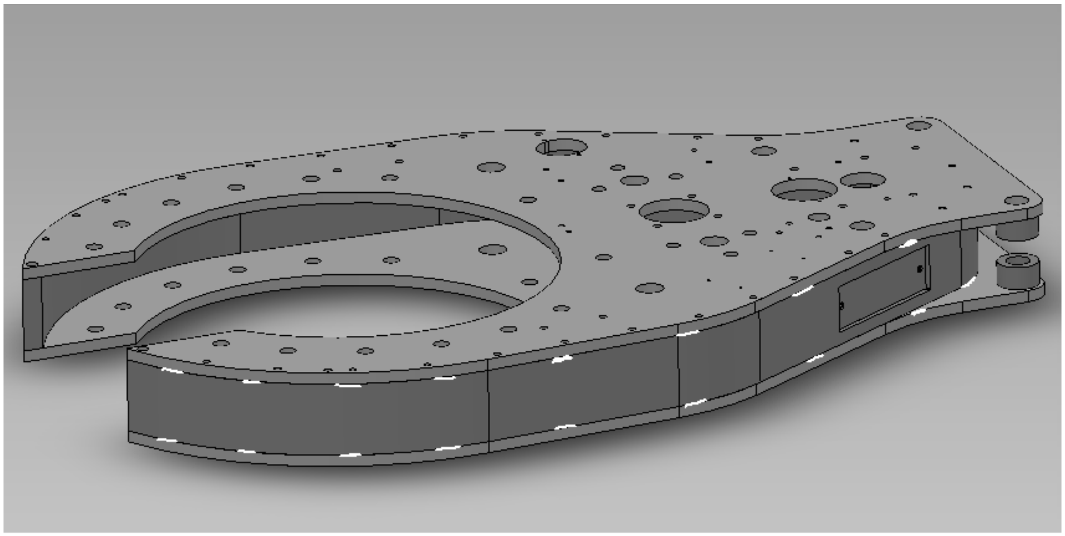


Figure 5-9 Sample Part with Welding Locations

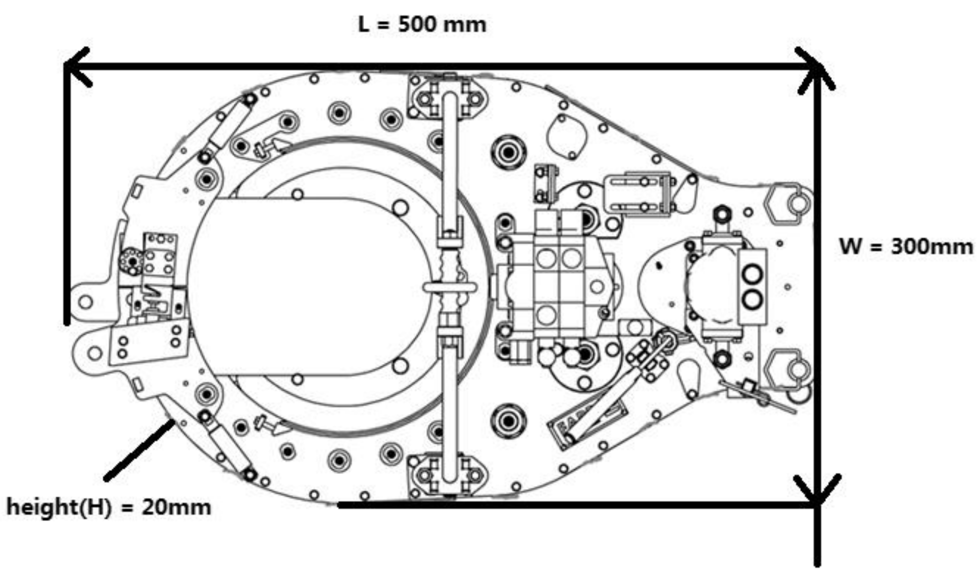


Figure 5-10 2D Drawing of Tong Body with Diameters

According to the drawing of a tong body (Figure 5-9) the dimensions of the components to be welded can be expressed as follows,

$$D = [500,300,20] \quad (25)$$

As mentioned in the model definition, when defining welding parametric arrays [W], the y_x factors differ from the type of the welding feature [F]. Therefore, based on the definition in 5.5.1, the welding feature matrix [WF] can be defined in the following four types: joint, groove, seam and bead (welding parameters). The parameters for a T-joint type feature are expressed in Figure 5-10. As shown in Figure 5-8 and Figure 5.9, the four welding steps are exactly the same. Thus, the feature can be expressed using the following array:

$$WF = [\text{Joint-T},G,T,F,L1,L2,L3,A,\text{Step}] \quad (26)$$

In this case,

$$WF_{j(1\text{-}4)} = [\text{Joint-T}, 1, 20, 2,50,100,0,45,1\text{-}4] \quad (27)$$

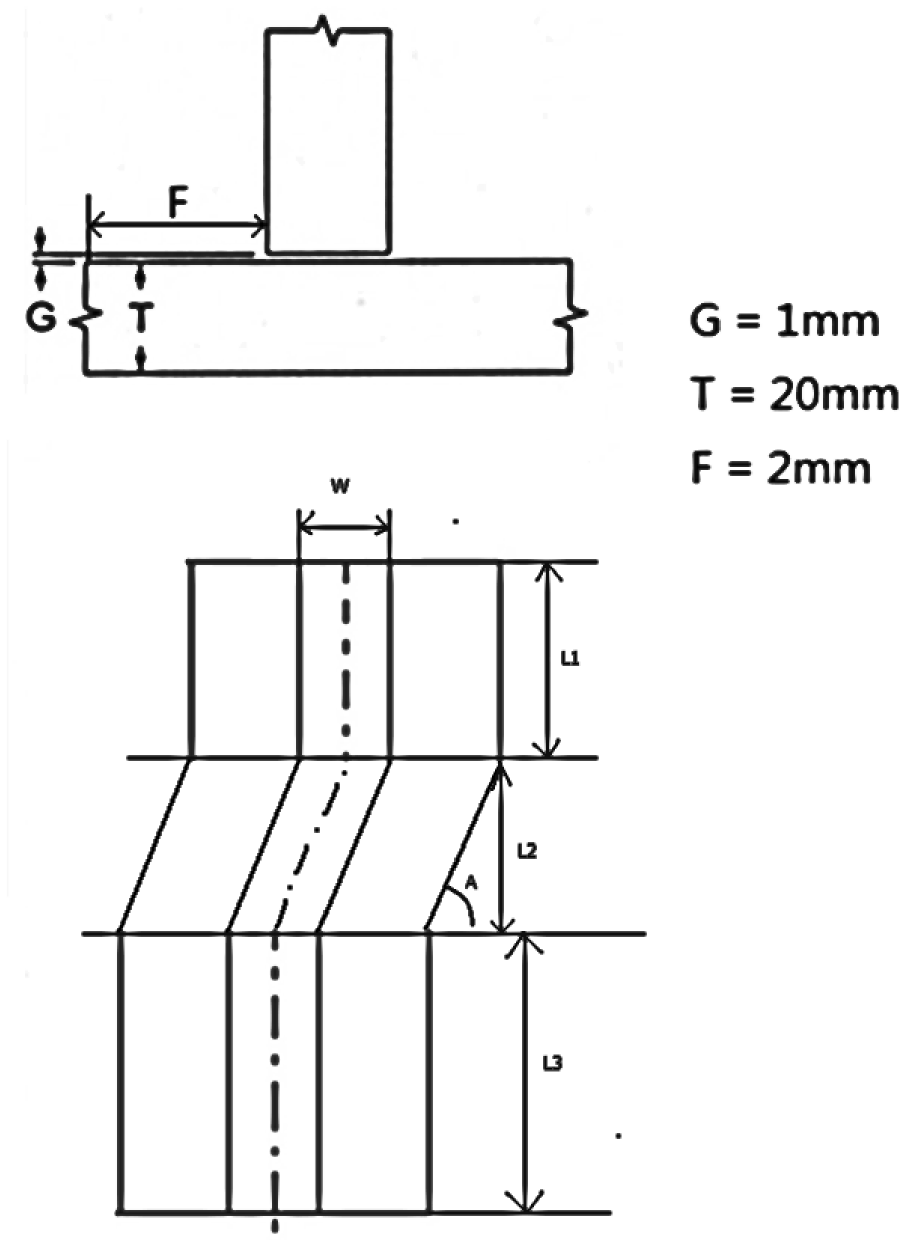


Figure 5-11 Welding Feature Joint Sub Feature Parameters

Similarly, bead features are defined in Figure 5-11. P stands for the penetration of the welding bead. M stands for the layers that need to be welded. In this example, the array can be expressed using following array:

$$WF = [B\text{-}T, BW, BH, BT, BR1, BR2, BB, P1, P2, Step] \quad (28)$$

In this case,

$$WF_{B(1\text{-}4)} = [B\text{-}T, 6, 5, 2, 6, 2, 1, 0.5, 0.5, 1\text{-}4] \quad (29)$$

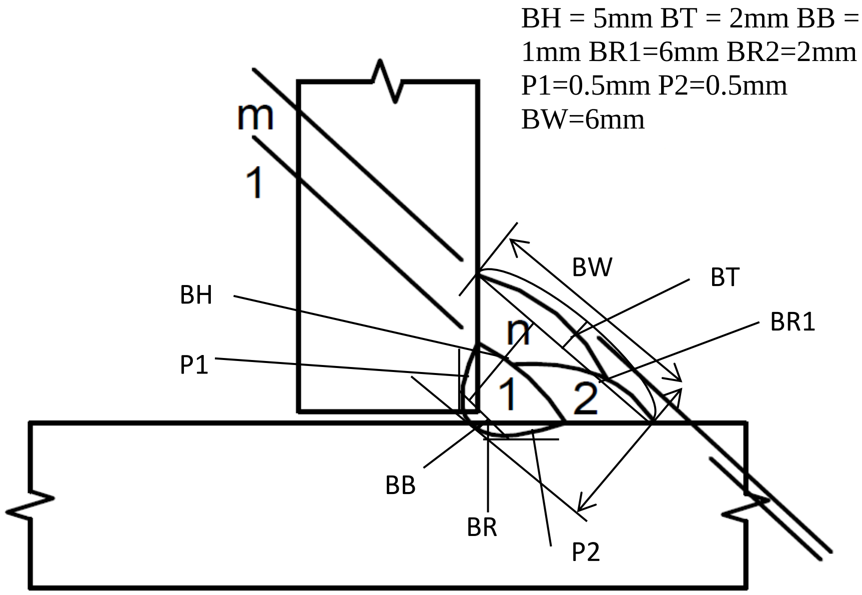


Figure 5-12 Welding Feature Bead Sub Feature Parameters

The seam feature can be defined according to Figure 5-12. IS stands for the initial start length. S stands for the length of the weld, while d stands for the space between the seams. Thus, the seam feature can be expressed as follows:

$$WF = [S\text{-}T, IS, s, d, Step] \quad (30)$$

In this case,

$$WF_{s(1\text{-}4)} = [S\text{-}T, 32, 15, 75, 1\text{-}4] \quad (31)$$

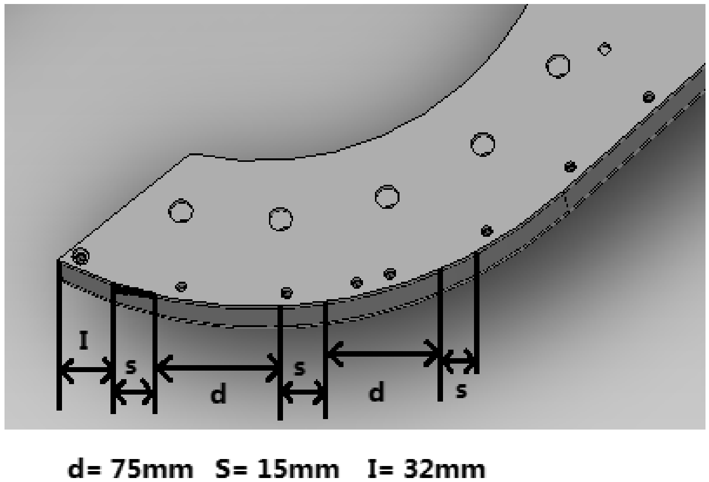


Figure 5-13 Welding Feature Seam Sub Feature Parameters

As for the groove, the definition is based on Figure 5-13. A groove is defined using the depth of the groove (B), type of the groove, width of the groove (C) and angle of the groove (A). Thus the array for the groove feature is:

$$WF = [S\text{-}T, Type, A, B, C, Step] \quad (32)$$

In this case (left figure),

$$WF_{g(1\text{-}4)} = [S\text{-}T, SQR, 0, 0, 0, 1\text{-}4] \quad (33)$$

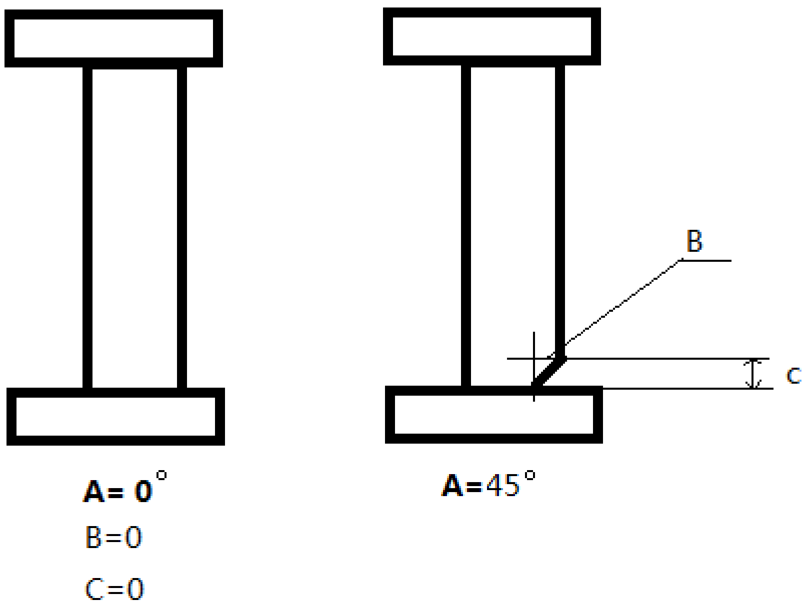


Figure 5-14 Welding Feature Groove Sub Feature Parameters

Therefore, the entire welding feature [WF] is defined and ready to be matched with the machine capacity feature. Welding parameters information is referenced from the company's welding manual [97], because both the plates and side bars are made of carbon and low-alloy steel construction (CSA W59) [97]. The [M] arrays can be expressed as follows:

$$M = [W59,360,30] \tag{34}$$

As for welding resources, there are five welding machines on the shop floor: one hidden arc (PDG-309), one electron-beam (LASTRON-100-200-W), and three MIG machines (two K2496-2 and one K2471-2. Detail specifications are referenced in [98-101]).

Based on the methods expressed above, firstly, the weldability array [WB] needs to be built, which is showed in Table 5.2. Because the components to be welded are not flat plates

(Figure 5-8), the hidden arc machine cannot be used. Electron-beam welding is commonly used, while MIG is highly suggested. The weldability matrix can be referenced in [96].

Table 5.2 Welding Suitability for Carbon and Low-alloy Steel

Machine/Material	W59
Hidden Arc (E1)	0
Electron-Beam (E2)	1
MIG 1 (E3)	2
MIG 2 (E4)	2
MIG 3 (E5)	2

Next, the maximum dimensions of the working envelope [E] need to be determined, in order to make sure the envelope is bigger than the work pieces' dimensions [D]. For electron-beam welding, the maximum travelling distance is usually given in the product manual. However, as for hidden arc welding and MIG welding, as there aren't fixed working spaces, the work envelope dimensions are determined by the size of the fixture and the working spaces of the cell. As MIG 5 has rotary table fixtures, the components dimensions are limited by the rotary table size. In this study, the wire feed rate is considered as the main factor for welding speed. The machine capabilities are summarized in Table 5.3.

Table 5.3 Summarized Machine Capability Table

	Working Envelope	Wire feed Rate mm/s	Current Control Range (A)	Voltage Range (V)	Power Source
Machine1	unlimited	0-17000	40-315	27	PDG-420
Machine2	200*150*100	0-250	0-0.3A	40-100k	
Machine3	unlimited	41.6-338.3	60-500A	12-42	CV400
Machine4	unlimited	21.7-211.7	30-140A	0-20	140c
Machine5	600 * 600 * 600	41.6-338.3	60-500A	12-42	CV400

According to [102], the welding flux to be used is made of mostly Mn (66.66%) and Si (33.33%). Thus, the average specific heat capacity, heat of fusion and molar mass can be calculated using the formulas below:

$$C = \frac{2C_{Mn}\rho_{Mn} + C_{Si}\rho_{Si}}{2\rho_{Mn} + \rho_{Si}} \quad H_f = \frac{2H_{fMn}\rho_{Mn} + H_f\rho_{Si}}{2\rho_{Mn} + \rho_{Si}} \; M = \frac{2\rho_{Mn} + \rho_{Si}}{\frac{2\rho_{Mn}}{M_{Mn}} + \frac{\rho_{Si}}{M_{Si}}} \tag{35}$$

Table 5.4 Components of Welding Flux (L-50) and Related Factors

	(%)	Density (ρ)(g/cm^3)	Heat of fusion (H_f)(KJ/mol)	Special heat capacity (C) (J/(mol K))
Si	33.33%	2.329	50.21	19.789
Mn	66.66%	7.21	12.91	26.32

Thus, H_f = 18.1 KJ/mol , C = 25.4 J/(mol K), ρ = 5.583g/cm^3, M = 48.5 g/mol

According to the parameters in Figure 5-11, the volume of the bead to be created can be determined as

$$V = 210.7\ mm^3 = 0.2107\ cm^3$$

Thus, the V_{min} and V_{max} of each machine can be calculated as follows:

Machine 1 $V_{min} = 0.26\ cm^3$ $V_{max} = 2.06\ cm^3$

Machine 2 $V_{min} = 0\ cm^3$ $V_{max} = 7.26\ cm^3$

Machine 3 $V_{min} = 0.17\ cm^3$ $V_{max} = 5.08\ cm^3$

Machine 4 $V_{min} = 0\ cm^3$ $V_{max} = 0.67\ cm^3$

Machine 5 $V_{min} = 0.17\ cm^3$ $V_{max} = 5.08\ cm^3$

Therefore, from the bead point of view, these machines can all make the bead in a single layer.

Therefore, the [E] and [P] arrays can be expressed below:

$$E1 = [unlimited]\ P1 = [15000,315,27]\ T1 = [HARC, PDG420,1]$$

$$E2 = [200,150,100]\ P2 = [250,0.3,100000]\ T2 = [EB, NA, 1]$$

$$E3 = [unlimited]\ \ P3 = [338.3,400,38]\ T3 = [MIG, CV400,1]$$

$$E4 = [unlimited]\ \ P4 = [211.7,300,32]\ T4 = [MIG, 140c, 1]$$

$$E5 = [600,600,600]\ \ P5 = [338.3,500,42]\ T5 = [MIG, CV400,1]$$

Compared to the [D] matrix, the electron beam welding is not applicable as the working envelope is not big enough.

As for the power source, based on the calculation of the efficiency factor, all the machines are powerful enough. Therefore, according to the constraint factors, machine 4, machine 5 and machine 3 are feasible.

According to capacity feature, machine 5 is equipped with a rotary table; it can reduce the number of setups from two to one by rotating the part and welding the other side. Machine 4 has greater accuracy which is feasible for welding with high finishing requirements. Cost rates, machine work load and time spent on one welding bead are loaded from the ERP databases.

$$WR = \$15/hour \quad LR= \$25/hour \quad CU= \$50/hour$$

Assuming currently a welding job with a batch of 2 (Qty_c) needs to be allocated with a manufacturing resource. Eight places need to be welded ($N_{beadc}= 8$). All three feasible machines are currently working on jobs with the following information:

Machine 3

$$t_c= 5 \text{ minutes} \quad t_p= 5 \text{ minute} \quad Qty_p= 2 \quad \frac{1}{ECY_p} = 1$$

$$N_{beadp}= 10 \quad UF = 0 \quad CL = 0.6 \quad t_{setup} = 30 \text{ minutes}$$

Machine 4

$$t_c= 6 \text{ minutes} \quad t_p= 3 \text{ minutes} \quad Qty_p= 1 \quad \frac{1}{ECY_p} = 1$$

$$N_{beadp}= 5 \quad UF = 1 \quad CL = 0.8 \quad t_{setup} = 20 \text{ minutes}$$

Machine 5

t_c= 5 minutes t_p= 5 minutes Qty_p= 1 $\frac{1}{ECY_p} = 1$

N_{beadp}= 10   UF = 0   CL = 0.5 t_{setup} = 50 minutes

Therefore, the related cost factors can be calculated:

WC_3= 25 OC_3= 33.3 SC_3= 12.5 UC_3= 0

WC_4= 3.75 OC_4= 40 SC_4= 12.5 UC_4= 104

WC_5= 12.5 OC_5= 33.3 SC_5= 10.42 UC_5= 0

Based on the current operational strategy, all the costs are treated as equal, so a_i = 1. So the cost for manufacturing a feature can be calculated:

FC_3 = 70.83 FC_4 = 160.25 FC_5 = 56.25

In this example, as the four manufacturing steps are the same, the overall cost can be determined as:

FC_3 = 70.83*4 = 283.32 FC_4 = 160.25*4 = 641 FC_5 = 56.25*4 = 225

Therefore, machine 5 is the best option to allocate the job.

Chapter 6 Case study and prototype demonstration

6.1 Customer order module

Based on the framework proposed in Figure 4-1, a feature-based OAS module has been developed on top of an existing ERP software package. As shown in Figure 6-1, the module contains five layers: data, core feature management, supporting functional modules, run-time application module and user interfaces (UIs). All elementary databases, such as the ERP database and product database, are supposed to be conceptually contained in the bottom data layer. Feature information is identified, extracted and stored in the core feature management layer, where the necessary elementary data are associated and mapped into different feature attributes. This layer also controls the data flow between databases and functional modules. As a result, data can not only be referred to by features and other applications, but can also directly flow to modules via updating mechanisms if there is any change, as triggers can be used to monitor the activities of selected data flows. Above the core feature management layer is the application module layer, where all the functions, such as scheduling, inventory control, order tracking, cash roll back, and tracking are enabled and embedded into the ERP system. On top of the functional modules are the dynamic buffering data structures used to support software functions. The top layer is the user application layer, or interaction layer, where the modules are managed and combined into different user interfaces (UI). With the five-layer framework, collaborative manufacturing can be implemented with interdisciplinary information associated across different application modules. Since the entire application shares a common feature system structure, feature-based fine-grain process information can be easily updated with engineering design or customer requirement changes, and can be further transferred into the production ERP system.

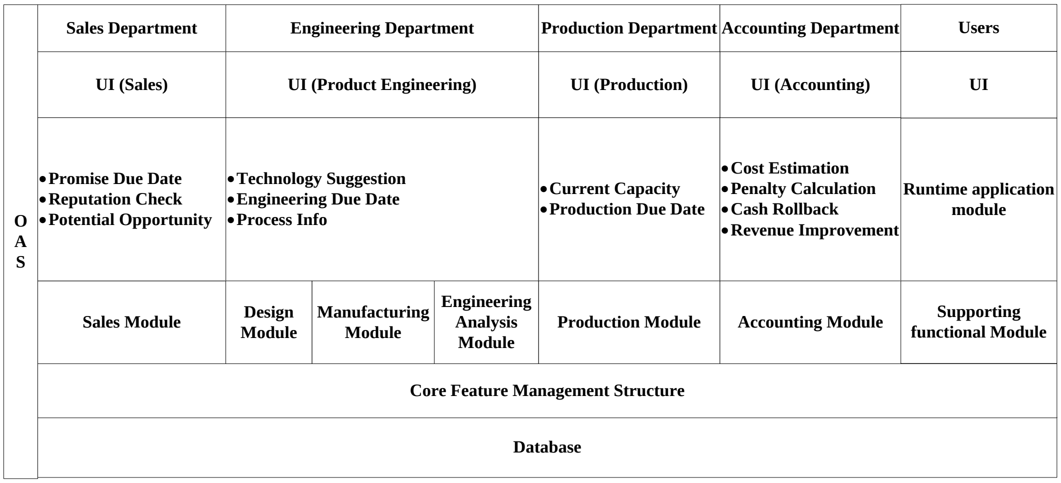


Figure 6-1 Feature-oriented OAS Module Framework

Figure 6-2 shows a detailed flowchart of the system response procedures. When the sales department receives a customer inquiry, sales staff needs to fill in a form on the sales UI about product requirements from the customer point of view. For instance, when a customer is ordering a product, performance factors are usually specified, such as torque required instead of the motor that produces the torque. Such information is specific to the customer and is documented and memorized by sales managers. Integrating the customer feature into the ERP system makes it possible to organize more detailed and formalized requirement information systematically for reuse and sharing. When a customer approaches the sales department, sales personnel will check the customer's profile and load any existing order history. The system will make some suggestions to the sales person about the possible products with configurations that were previously generated from the customer's perspective. This function will shorten the business cycle and improve the sales department's efficiency. If a customer is ordering a new product which cannot be quickly finalized, the salesperson will use a configuration sub-module under the sales module as shown in Figure 6-1 and fill out all the critical specifications as well as optional choices in the sales information system. Such product request information is then transferred to the engineering department to configure a product solution. The Design module in the engineering view will translate the specifications into recommended products and configurations based on all available data on product models and configurations compared to customer specifications. The optional specifications are well translated by selecting the required accessories; the order can then be generated and submitted to the OAS Module. If the optional specifications cannot be translated reasonably, the OAS semantic module will generate a request email to engineers to interpret these specifications for the feasibility check. The results will be stored in the semantic database and the order updated with the matching products and configurations. As for accessory selection, the system will determine the current module by prioritizing popular selections based on the current module and the order history. Whenever the customer makes a specific selection, the customer feature will be concurrently updated.

After checking engineering feasibility and schedule costs, the salesperson can confirm the order. The next step is for the OAS module to process all the confirmed orders. The ERP system’s scheduling module will be activated and simulate the conditions of the plant resource capacity occupancy. The ERP system will also evaluate the customers' financial factors stored in the customer feature to calculate cash roll back and other accounting-related terms. With all the rules defined by upper management and implemented in the ERP system, the OAS Module will help the salesperson to decide whether or not the order is acceptable. Once the decision is made, the customer relationship updates the customer feature, such as the satisfaction rate. Subsequently, the order potential is updated and the related data transferred to the CRM system. Further, the manufacturing orders are issued and the production planning and scheduling actions are to be followed.

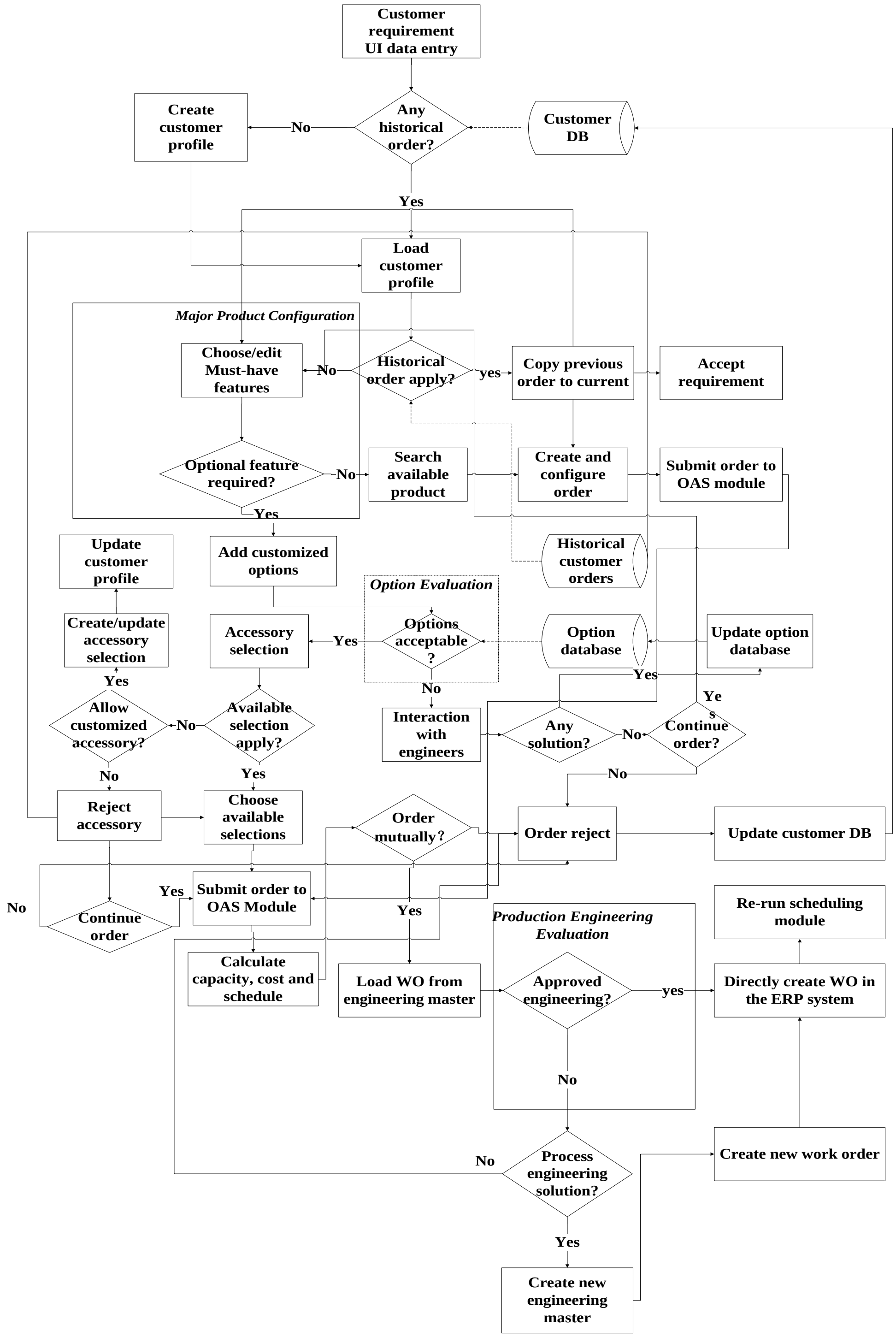


Figure 6-2 Feature-oriented OAS Module Flowchart

6.2 Capacity and welding feature Module

Another major issue in the OAS is the determination of due dates as well as matching them with the real-time shop floor resource, which is related to the shop resource capacity. Based on the framework proposed in Figure 6-1, an expanded module in the form of the capacity and welding feature module was developed. This module can be used by the sales department to determine the welding feasibility and manufacturability based on current shop resources' status and capabilities. Meanwhile, it can also support the production department in improving process planning and scheduling from a welding perspective. By providing good input to process planning regarding machine capacity, the production department can better allocate order segments based on current shop floor status. A detailed work flow is expressed in Figure 6-3. The ERP functionalities are in the big rectangle area. Other information, such as machine capability and process plans, are stored in feature libraries and interactive with the ERP system for further business activities such as scheduling and quality assurance.

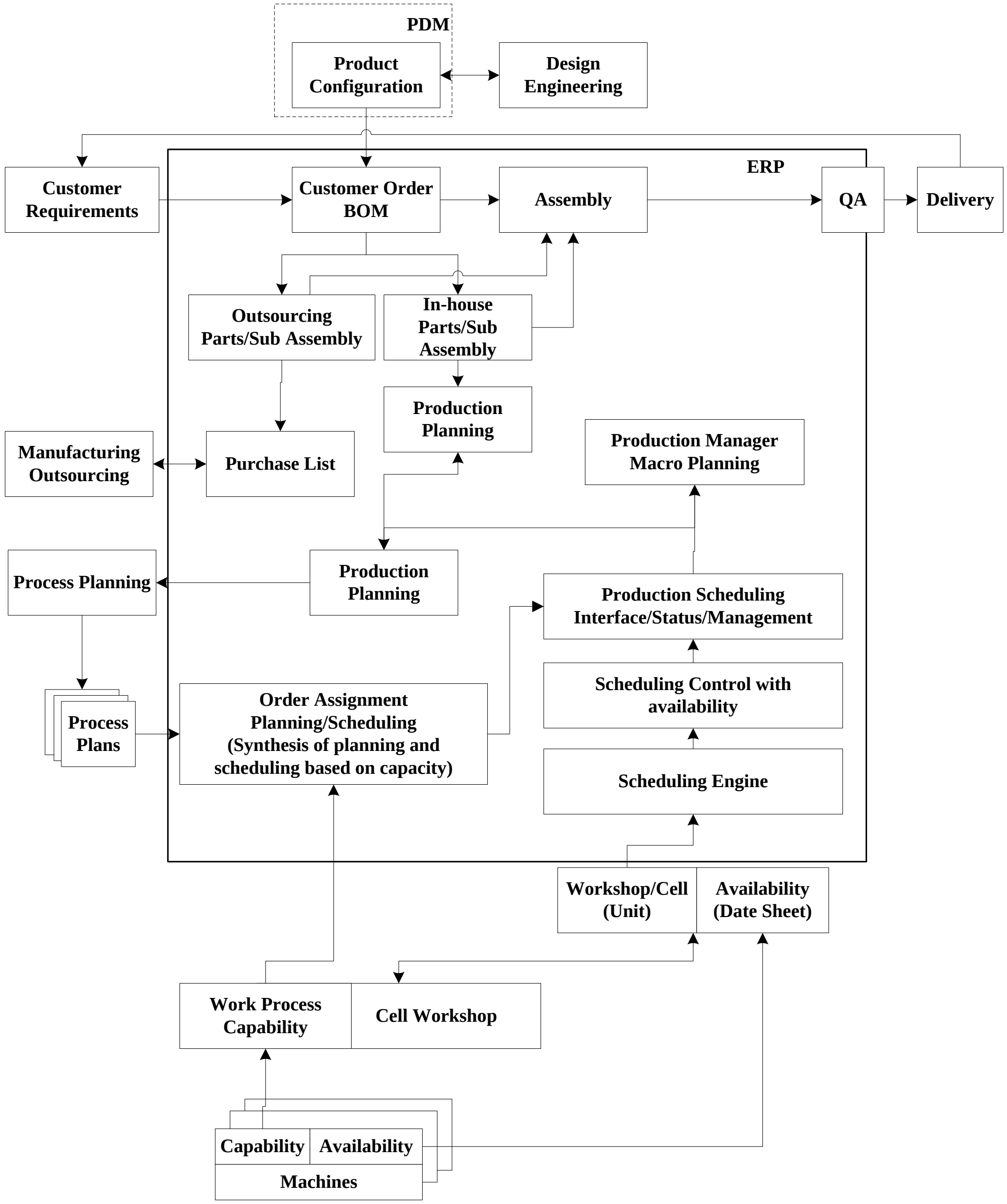


Figure 6-3 Information Flow for Downstream Activities after Order Acceptance

Thus, a detailed flowchart of the capacity and welding feature module is shown in Figure 6-4. A feasible customer order, which is one of the outputs of the customer module, is represented as the input for the overall module. After no additional engineering is needed, a BOM will be loaded from the ERP database with manufacturing process information. As this study focuses on the welding processes, the welding feature definition of each process will be checked. If a welding feature already exists, related requirements will be loaded and passed on to the capacity-requirement matching function. The system will match the feature requirements and machine capacity stored in the capacity library. For welding processes in this industry, four types of requirements will be considered: fixture, distortion, good finishing and material. If one of these requirements cannot be satisfied, the system automatically loads the next equipment. Qualified machines will be checked for availability according to the schedule function of the ERP system, and will recommend optimum scheduling options to the production engineers.

If a welding feature is not defined, there are two ways for the module to obtain the definition. As CAD software can create files using XML and txt formats, related feature information can be converted into these formats. The welding feature module allows inputs using these two formats. However, how to convert CAD files into txt and XML will not be addressed in this study. Another method is to manually define welding features. After defining the joint, groove, seam, and related sub types, the type of welding feature will be determined. Note that the automatic loading approach is not developed and requires further efforts.

After the welding feature is specified, the user needs to define all other parametric factors such as requirements for distortion, finish, and material. This information is combined with the welding class information and becomes the welding feature. The definition will be stored in the feature DB in the ERP system. With the feature information and machine selected, the module will generate a “manufacturing code” mentioned in Chapter 5, and then load the welding standards of the business at hand. The standard report will be used for operators to determine the detailed welding parameters, such as currency and angle.

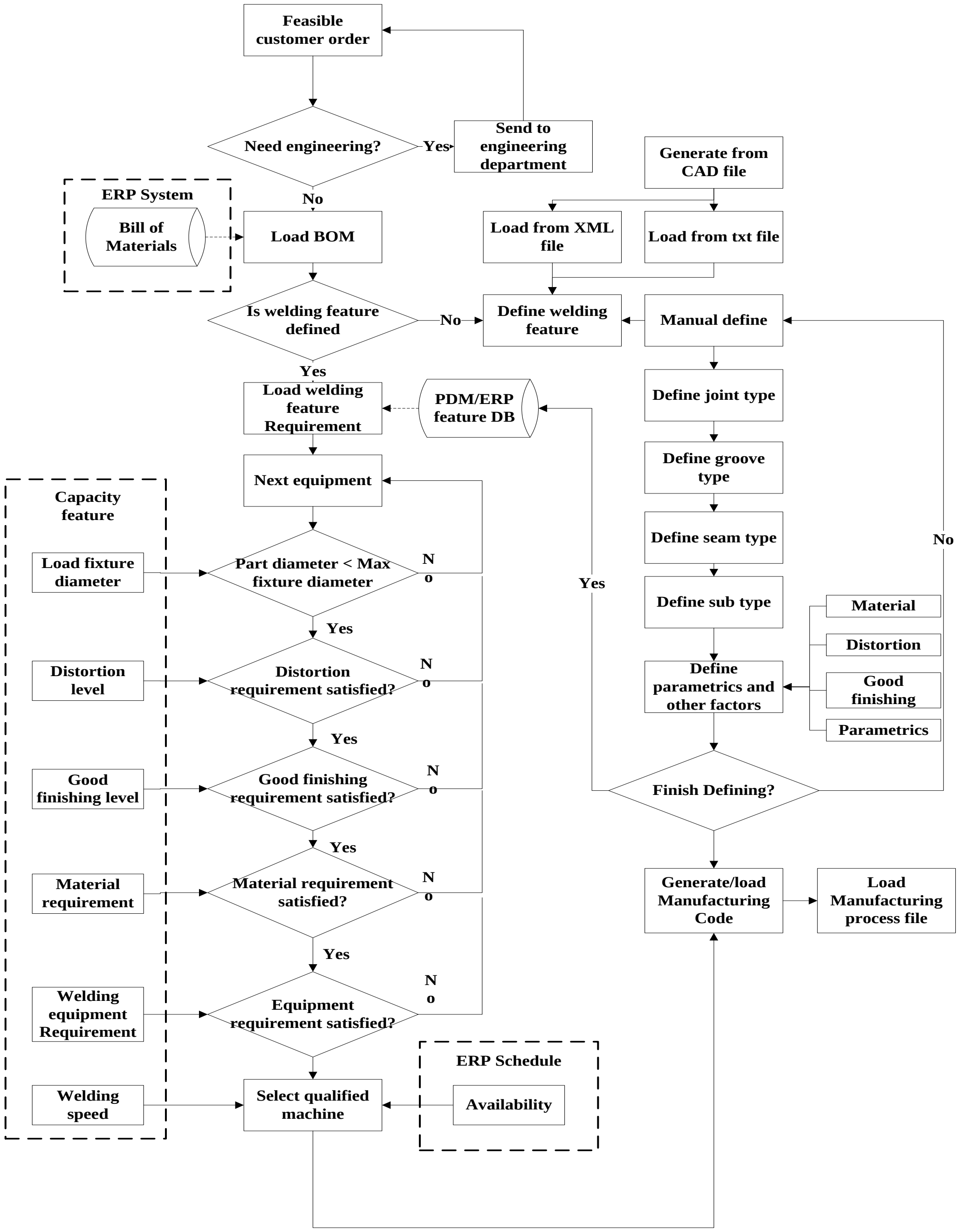


Figure 6-4 Machine Capacity and Welding Feature Mapping Module Flowchart

6.3 Customer feature module demonstration

In this study, the candidate uses a real-life case of an oil well drilling tong and its accessory selection process to demonstrate the advantage of our proposed feature integrated OAS module*. This module is developed with Visual Studio 2010™ (Microsoft) and integrated into a commercial ERP system package, Visual Manufacturing ™ 6.5.3 (Infor, New York). To determine the product configuration of a tong order, the size of the target drilling pipe and the torque applied onto it are the crucial specifications due to their influence in the design configurations, which include the size of the tong, the gear combination factors, and the selection of the supporting hydraulic motor. There are other factors such as the size of rotary gears, accessory jaws and dies. The control system of the tong automatically detects and controls the torque and stress applied on the pipeline. All of the information on the above factors is incorporated in the prototype module, and will be discussed in the next two paragraphs. Feature information such as product configurations and manufacturing features is integrated with the ERP system using user-defined tables, and managed by the OAS module. The pop-up properties of the customer feature and order information of the ERP system are associated as shown in Figure 6-5. The top left panel shows the customer feature data items. The "2MTEKI INC" has three current orders, and an "excellent" credit rating. In the lower right window, an opened order feature shows the "KK-0500-*," representing the customer's historical order product type category, which signifies that the drilling pipe size in 5"(12.7 cm). Other items include the estimated manufacturing cost, delivery date, and supply chain options. The stored procedures associated with the customer feature UIs, such as historical orders, tardiness tolerances, and satisfactory ratings, are developed on top of the MS SQL database for updating ERP tables,.

**All copyrights of figures related to the product tong belong to the McCoy Corporation, including but not limited to Figure 6-7, Figure 6-8, Figure 6-13, Figure 6-22,*

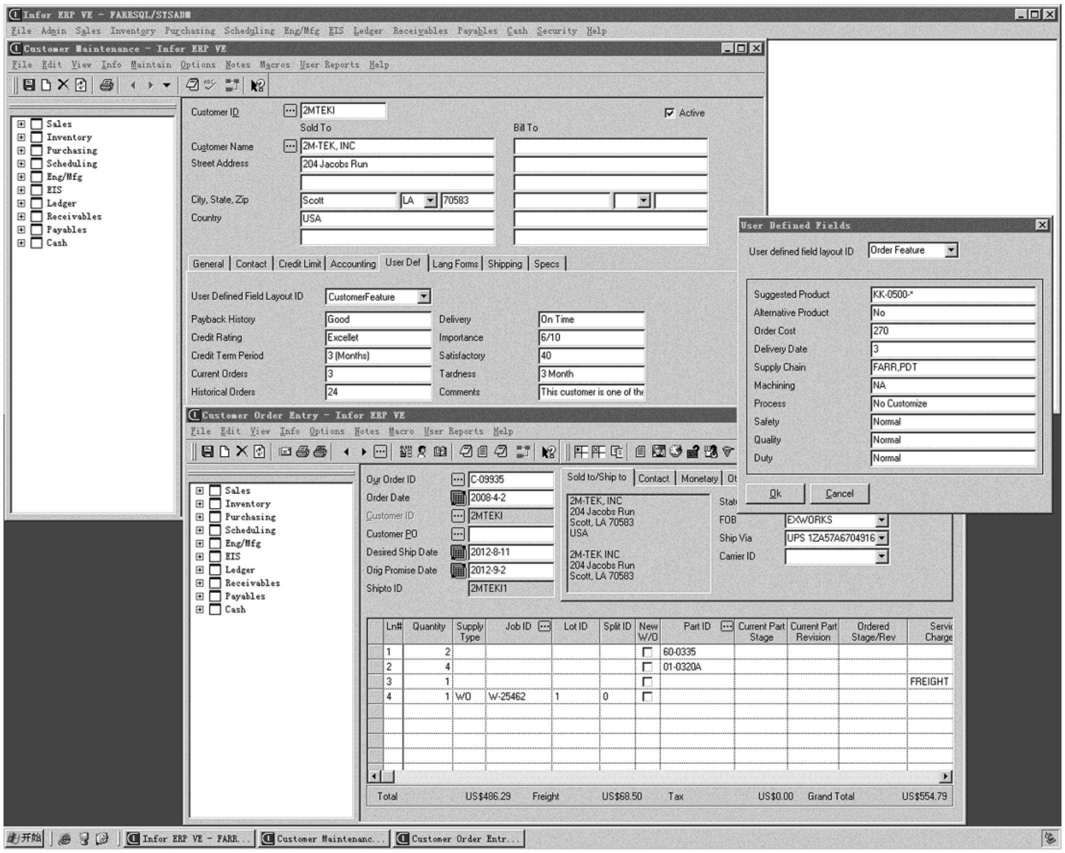


Figure 6-5 Customer UI in ERP System Integrated with Feature Data

The designed OAS module is comprised of three main UIs: the customer information UI, configuration UI, and order report UI. Figure 6-6 shows more extensive customer information, which includes current and historical orders. In Figure 6-6, current orders #1 and #2 are quick re-orders, represented as "60-0335" and "01-0320A." This customer information UI is intended for sales people to review the customer’s related information, such as historical orders, financial status, and satisfactory rate, which are either manually evaluated by sales personnel or calculated by the ERP system. By using historical order templates, sales personnel can process a quick re-order directly by searching the related information in the ERP system. Such quick orders will be processed by the OAS module and passed on to ERP systems for scheduling purposes. Hence, the order processing can be accelerated and the data completeness of the order is improved. Eventually, the efficiency of the entire sales department is increased. In addition, this "Customer Feature" implementation can reduce the learning cycle for new sales members by sharing specific and relevant customer information for different orders.

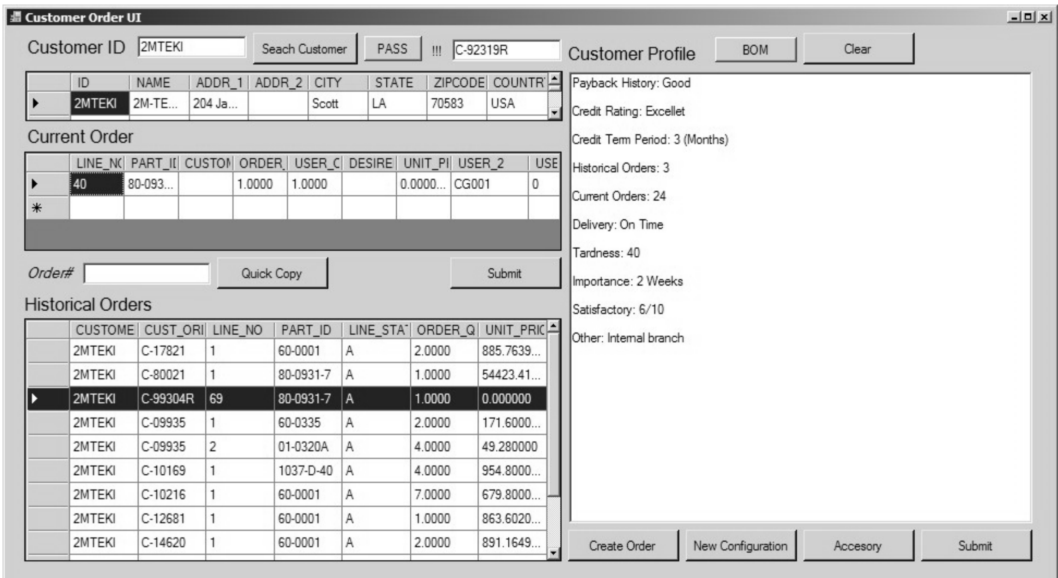


Figure 6-6 OAS Module Customer Information UI

In the case of new product orders, as in order #3 shown, the product is selected based on the customer's requirement which is shown in Figure 6-7 (customer product selection(Figure (a)), and accessory selection (Figure 6-7 OAS Module Configure Selection UI (b))). For tong type selection, the "must-have" attributes are listed and illustrated instantly on the right side with a labeled image. Based on the "must-have" feature, product engineering intent and parametric design knowledge can be extracted and documented via the OAS module, and transferred to the PDM and ERP systems for further processing. The 3D product model is shown in Figure 6-8. The three-key driving assembly feature parameters are shown. They are specified in Figure 6-7 (a) in the top section. For example, consider the gear combination design. The applied torque and size of the target pipe and motor are the critical specifications. To transfer them into design configurations, key feature parameters, in this case the width of the tong assembly (P1 in Figure 6-8), center distance of the last gearing stage (P2), center distance between the drive gear and the rotary gear (P3), are calculated from the specified drilling pipe size. In industry, these meta-design data are stored as attributes associated with the BOMs of the entire tong assembly. In the prototype OAS module, basic specifications, such as fixation, pipe size range, torque, and motor are taken as the input and the suitable key parameters are recommended based on historical configuration data and engineering rules built in to the product selection functions. The suggested messages are shown in the suggestion field of Figure 6-7(a). Sales personnel can obtain design parameters by selecting the “get suggestion” button to better address the needs of a customer.

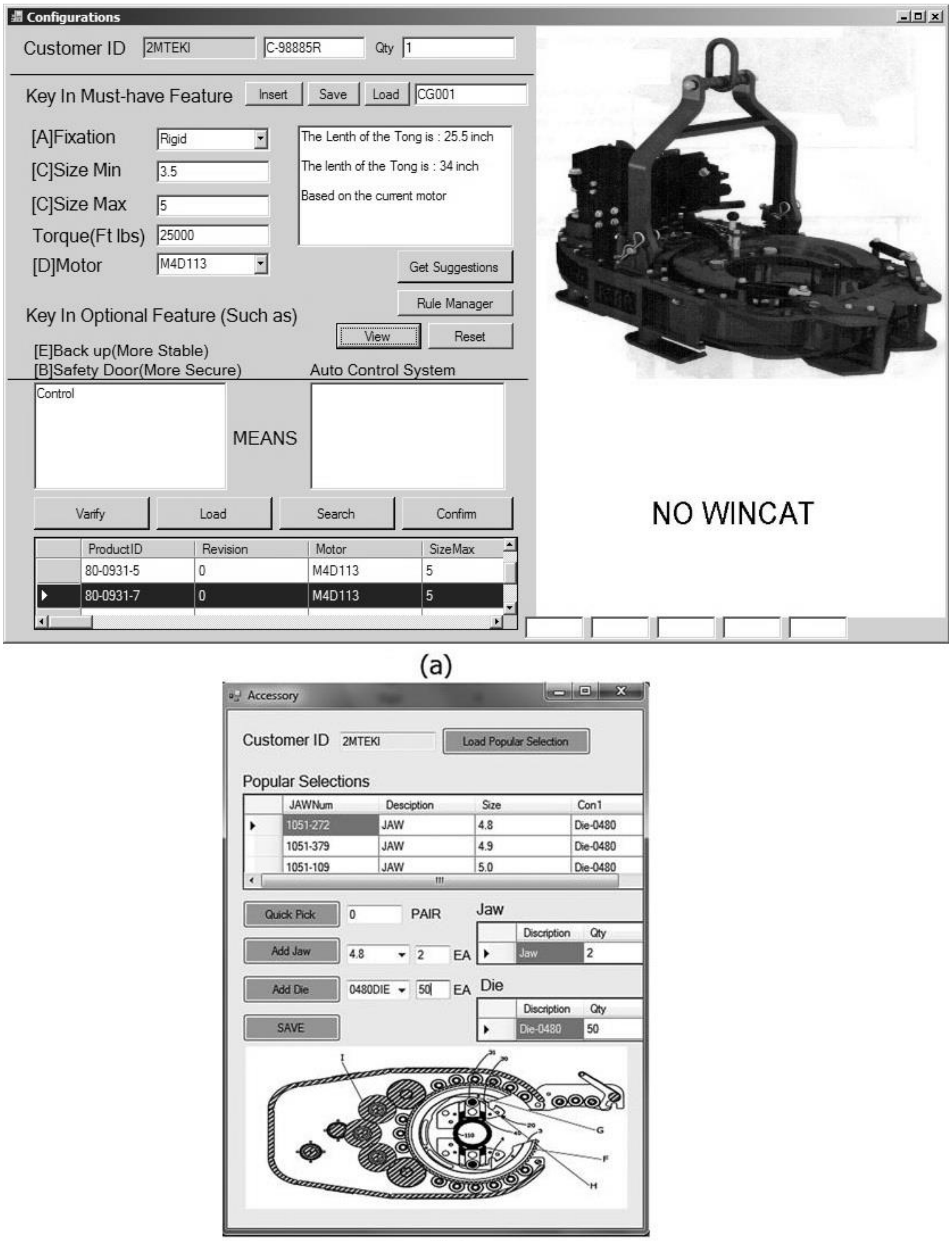
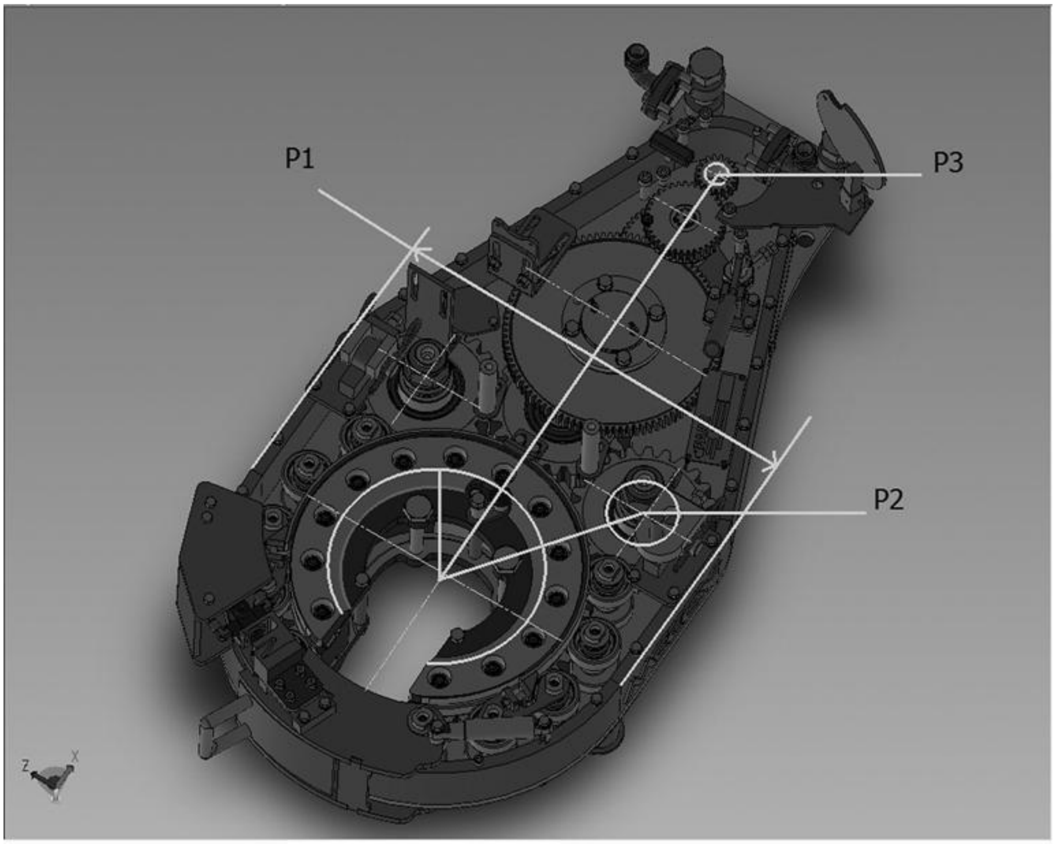


Figure 6-7 OAS Module Configure Selection UI

Optional feature descriptions are shown in Figure 6-7(a) in the lower half. It can be appreciated that such optional specs are always case-sensitive and require semantic translation into technical engineering terms. For instance, the term "auto-control system" for the customer means "Wincat" for the manufacturer, which is a specific product name. Similarly, "more stable" requirements by the customer means "back-up" assembly option, while "more secure" means the selection of a "safety door" module. Therefore, a simple semantic mapping module is developed. To do so, the engineers input the relations of the possible terms and their corresponding technical interpretations, storing them in the rule database in the ERP. The OAS module maps customer requirements collected by the sales person. Next, based on the technical terms generated, a search function is developed to find specific matching products based on the categorizations of the terms and product attributes. The selection attributes tree is shown in Figure 6-9. A typical page for drilling tongs product selection specifications used by the sales department is shown in Figure 6-10. Similarly, accessories are selected as shown in Figure 6-7(b). Once the products to be ordered are confirmed, the order processing module will process the order. A feasibility check of this order selection will be conducted by sending emails to the engineering department. If the order is not feasible, the OAS module will return the order to the sales department for further negotiation with the customer.



Pipe	5 Inch Pipe	9 Inch Pipe	13 Inch Pipe
Parameter 1 (cm)	64.008	71.1327	83.964
Parameter 2(cm)	32.598	40.624	42.791
Parameter 3(cm)	75.859	87.231	134.526
Torque (N*m)	25353	29827	47453

P1 Width of the tong assembly

P2 Center distance of the last gearing stage

P3 The center distance between the drive gear and the rotary gear

Figure 6-8 Gear Solidworks Module with Main Design Parameters

After the product selection process, a dynamic report is generated by the OAS module, which is shown in Figure 6-10. It shows the list of all parts, which could be either "purchased (PUR)" or "fabricated (FAB)", as well as their required quantity, lead time in production schedule, and machining time. Using this feature-based OAS, salespeople will be able to share knowledge with production engineers and therefore improve decision-making on order selections.

The above case tests and proves the idea that the product domain and process domain can be integrated using an associative "customer feature" and thus enhance the overall service quality and efficiency of customer service. This system is also useful in capturing customer-related knowledge and procedures, which is demanded by competition in the marketplace, especially for training new sales engineers. Information related to engineering design and production can also be generated automatically and dynamically for more efficient collaborative design and manufacturing. The main concern for further research is how to efficiently incorporate semantic input from the design and production departments for information processing. If the engineers failed to provide sufficient engineering knowledge to the module, the module cannot identify the right configurations based on the customer specifications provided.

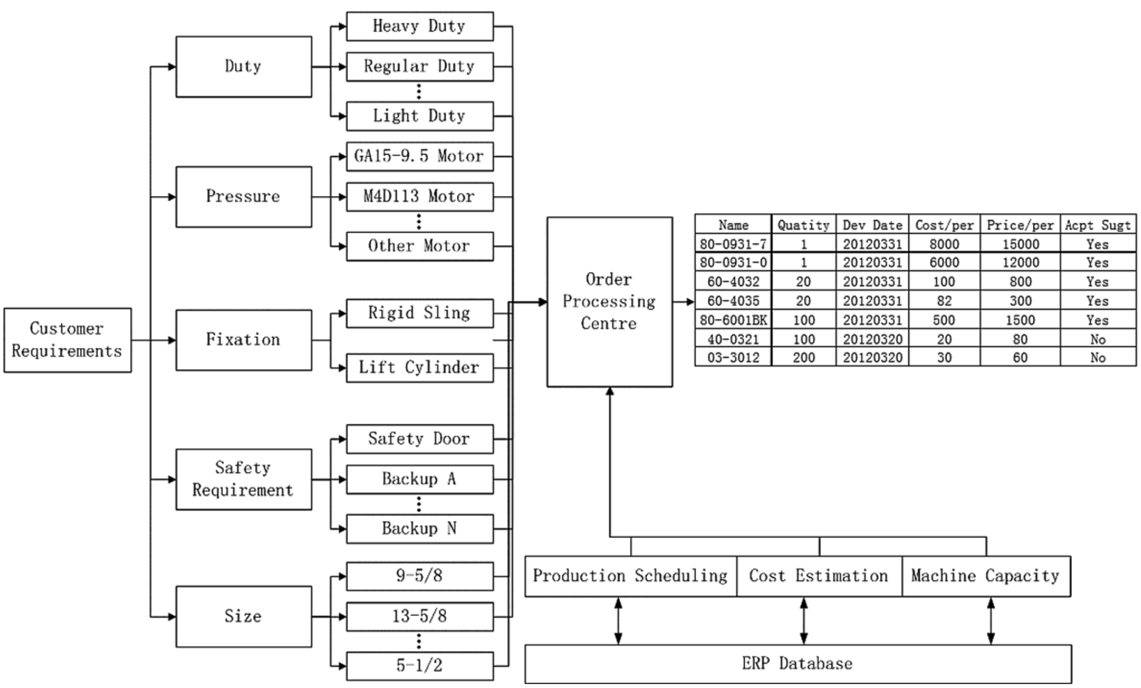
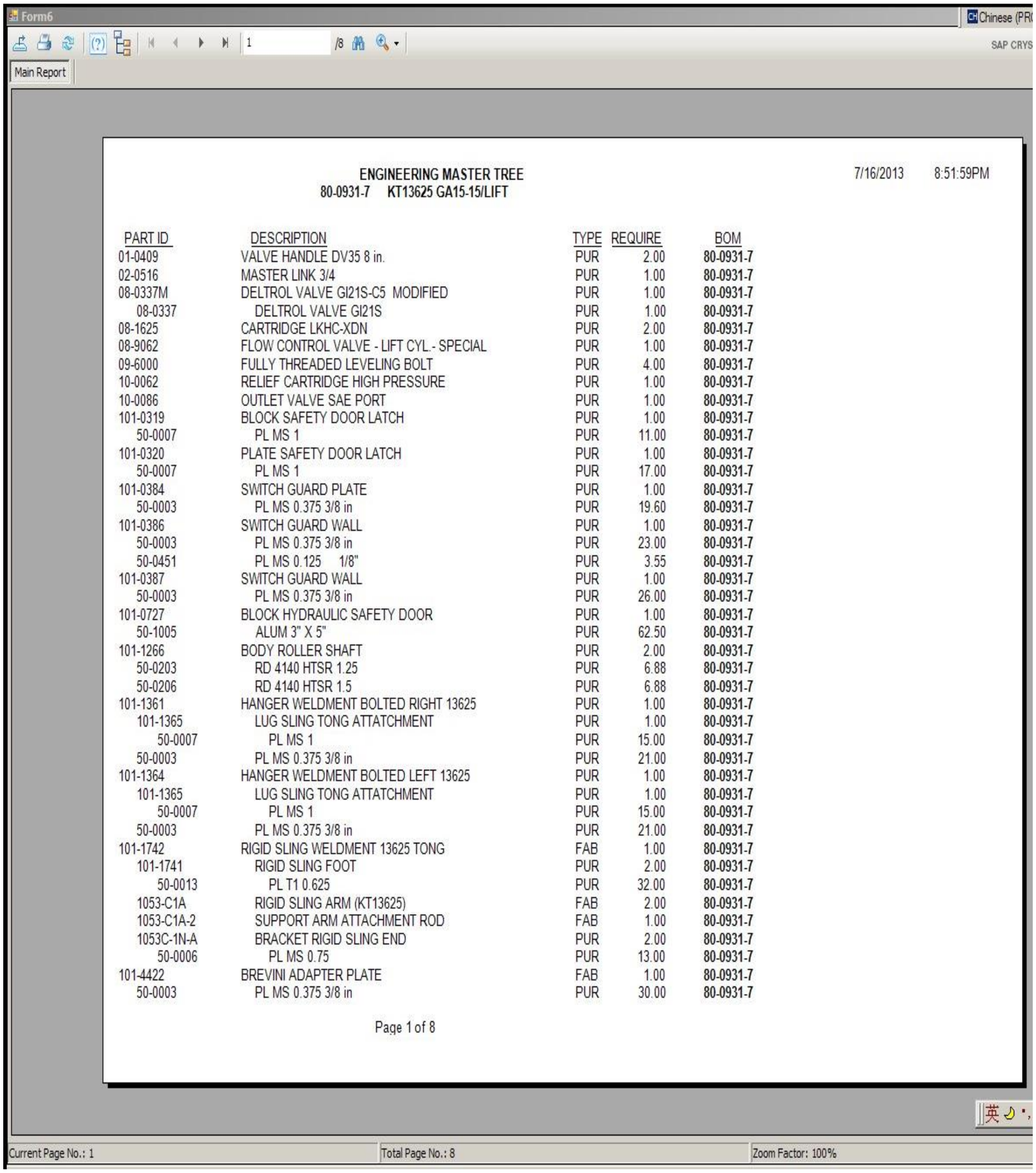


Figure 6-9 The Selection Attributes Tree



ENGINEERING MASTER TREE
80-0931-7 KT13625 GA15-15/LIFT

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PART ID	DESCRIPTION	TYPE	REQUIRE	BOM
01-0409	VALVE HANDLE DV35 8 in.	PUR	2.00	80-0931-7
02-0516	MASTER LINK 3/4	PUR	1.00	80-0931-7
08-0337M	DELTROL VALVE GI21S-C5 MODIFIED	PUR	1.00	80-0931-7
08-0337	DELTROL VALVE GI21S	PUR	1.00	80-0931-7
08-1625	CARTRIDGE LKHC-XDN	PUR	2.00	80-0931-7
08-9062	FLOW CONTROL VALVE - LIFT CYL.- SPECIAL	PUR	1.00	80-0931-7
09-6000	FULLY THREADED LEVELING BOLT	PUR	4.00	80-0931-7
10-0062	RELIEF CARTRIDGE HIGH PRESSURE	PUR	1.00	80-0931-7
10-0086	OUTLET VALVE SAE PORT	PUR	1.00	80-0931-7
101-0319	BLOCK SAFETY DOOR LATCH	PUR	1.00	80-0931-7
50-0007	PL MS 1	PUR	11.00	80-0931-7
101-0320	PLATE SAFETY DOOR LATCH	PUR	1.00	80-0931-7
50-0007	PL MS 1	PUR	17.00	80-0931-7
101-0384	SWITCH GUARD PLATE	PUR	1.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	19.60	80-0931-7
101-0386	SWITCH GUARD WALL	PUR	1.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	23.00	80-0931-7
50-0451	PL MS 0.125 1/8"	PUR	3.55	80-0931-7
101-0387	SWITCH GUARD WALL	PUR	1.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	26.00	80-0931-7
101-0727	BLOCK HYDRAULIC SAFETY DOOR	PUR	1.00	80-0931-7
50-1005	ALUM 3" X 5"	PUR	62.50	80-0931-7
101-1266	BODY ROLLER SHAFT	PUR	2.00	80-0931-7
50-0203	RD 4140 HTSR 1.25	PUR	6.88	80-0931-7
50-0206	RD 4140 HTSR 1.5	PUR	6.88	80-0931-7
101-1361	HANGER WELDMENT BOLTED RIGHT 13625	PUR	1.00	80-0931-7
101-1365	LUG SLING TONG ATTATCHMENT	PUR	1.00	80-0931-7
50-0007	PL MS 1	PUR	15.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	21.00	80-0931-7
101-1364	HANGER WELDMENT BOLTED LEFT 13625	PUR	1.00	80-0931-7
101-1365	LUG SLING TONG ATTATCHMENT	PUR	1.00	80-0931-7
50-0007	PL MS 1	PUR	15.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	21.00	80-0931-7
101-1742	RIGID SLING WELDMENT 13625 TONG	FAB	1.00	80-0931-7
101-1741	RIGID SLING FOOT	PUR	2.00	80-0931-7
50-0013	PL T1 0.625	PUR	32.00	80-0931-7
1053-C1A	RIGID SLING ARM (KT13625)	FAB	2.00	80-0931-7
1053-C1A-2	SUPPORT ARM ATTACHMENT ROD	FAB	1.00	80-0931-7
1053C-1N-A	BRACKET RIGID SLING END	PUR	2.00	80-0931-7
50-0006	PL MS 0.75	PUR	13.00	80-0931-7
101-4422	BREVINI ADAPTER PLATE	FAB	1.00	80-0931-7
50-0003	PL MS 0.375 3/8 in	PUR	30.00	80-0931-7

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Figure 6-10 OAS Module Order Report UI

DESCRIPTION	PART NUMBER	TORQUE	SPECIFICATIONS	WEIGHT
KT5500: GA15-13/LIFT	80-0420-13	18700 ft-lbs	Rigid Sling Rineer GA15-13 Motor Motor & Lift Valve Safety Door	1140lbs
KT5500: GA15-13/LIFT/CBU	80-0422	18700 ft-lbs	80-0420-3 = CONFIGURED TONG Rigid Sling Rineer GA15-13 Motor Motor, Lift,& Backup Valve Safety Door 85-0404 = 5500 CLINCHER BACKUP COMP	2050lbs
KT5500: GA15-13/LIFT/CBU	80-0420-16	18700 ft-lbs	80-0420-3 = CONFIGURED TONG Rigid Sling Rineer Ga15-13 Motor Motor, Lift,& Backup Valve Safety Door 85-0408 = 5500 CLINCHER BACKUP COMP LOW PROFILE BACKUP	2050lbs
KT5500: GA15-13/LIFT/FBU	80-0421-1	18700 ft-lbs	80-0420-3 = CONFIGURED TONG Rigid Sling Rineer GA15-13 Motor Motor, Lift,& Backup Valve Safety Door 85-0400 = 5500 FARR BACKUP	1700lbs
KT5500: GA15-13/LIFT/FBU/CC	80-0421-2	18700 ft-lbs	80-0420-9 = CONFIGURED TONG Rigid Sling Rineer GA15-13 Motor Motor, Lift,& Backup Valve Safety Door Closed Centre System 85-0400 = 5500 FARR BACKUP	2050lbs
KT5500: GA15-13/LIFT/CBU	80-0421-3	18700 ft-lbs	80-0420-3 = CONFIGURED TONG Rigid Sling Rineer GA15-13 Motor Motor, Lift,& Backup Valve Safety Door 85-0506 = 5500 CLINCHER BACKUP TENS	2050lbs
KT5500: GA15-13/6.5 2SPD/LIFT/FBU/ WINCATT	80-0421-4	18700 ft-lbs	80-0420-14 = CONFIGURED TONG Rigid Sling Rineer GA15-13/6.5 Two Speed Motor Motor, Lift,& Backup Valve Wincatt Dump Valve Safety Door 85-0400 = 5500 FARR BACKUP	1750lbs
KT5500: GA15-13/6.5 2SPD/LIFT/FBU	80-0421-5	18700 ft-lbs	80-0420-15 = CONFIGURED TONG Rigid Sling Rineer GA15-13/6.5 Two Speed Motor Motor, Lift,& Backup Valve Safety Door 85-0400 = 5500 FARR BACKUP	1750lbs

Figure 6-11 Product Configuration Sheet for Sales Department

6.4 Capacity feature module demonstration

A real industry-based case is presented in this section, implementing the integration of the capacity feature, welding feature and ERP system using the same tools as in Section 6.3. The base of the tong (Figure 6-8) is used as a showcase for the capacity module.

Based on the information passed on from the customer module, shown in Figure 6-12, the manufacturing dashboard module is able to load order information and break it into sub-assembly parts. In this case, an "80-0931-7" tong can be divided into a tong body, rotary gear, cage plates, and gear assemblies. Customer feature related information can also be loaded from the manufacturing dashboard. In this example, the satisfaction rate and late tolerance information are loaded from the customer feature. The dashboard is also linked with the 3D CAD model for manufacturing engineers to view the drawing, as shown in Figure 6-13.

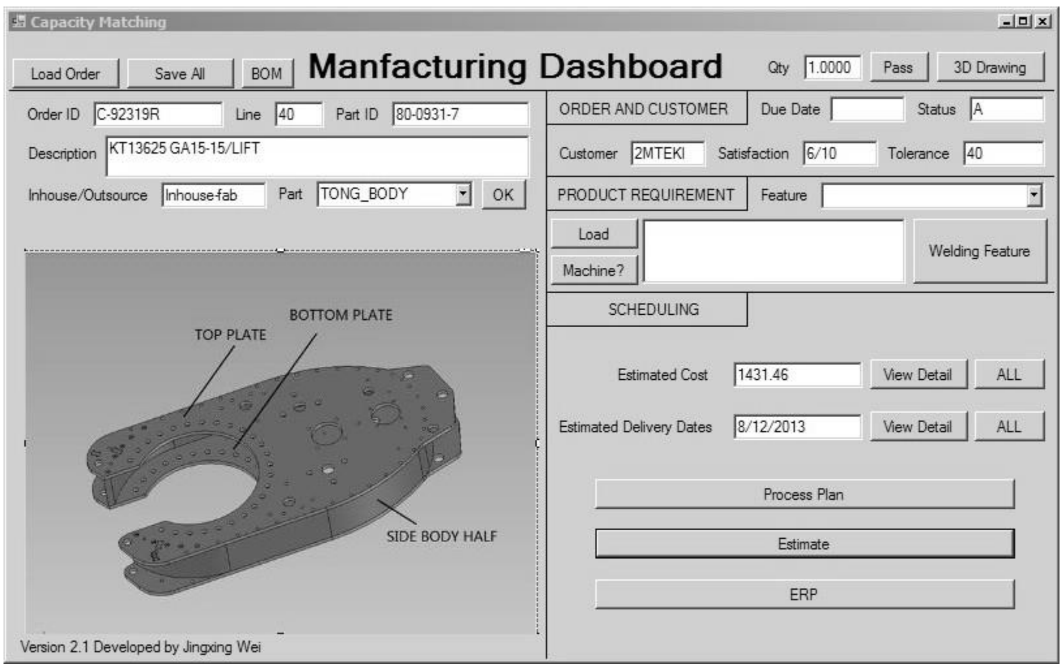


Figure 6-12 Manufacturing Dashboard

The 3D module of the tong body is shown in Figure 6-12. It considers four parts: the top plate, bottom plate and two side body halves. The top and bottom plates also have some holes in them which require drilling and milling. The two side body halves are welded to the two plates. A detailed process will be reviewed in Figure 6-14. There are three welding steps needed to make a tong body. However, in this case, the candidate mainly focuses on the welding among side body halves and the side body (Process 50). The side body half is welded to the plates with some equally distributed seams with a fixed step. Based on the 3D model, process 50 can be classified as a T-shape joint with double side welding with no groove.

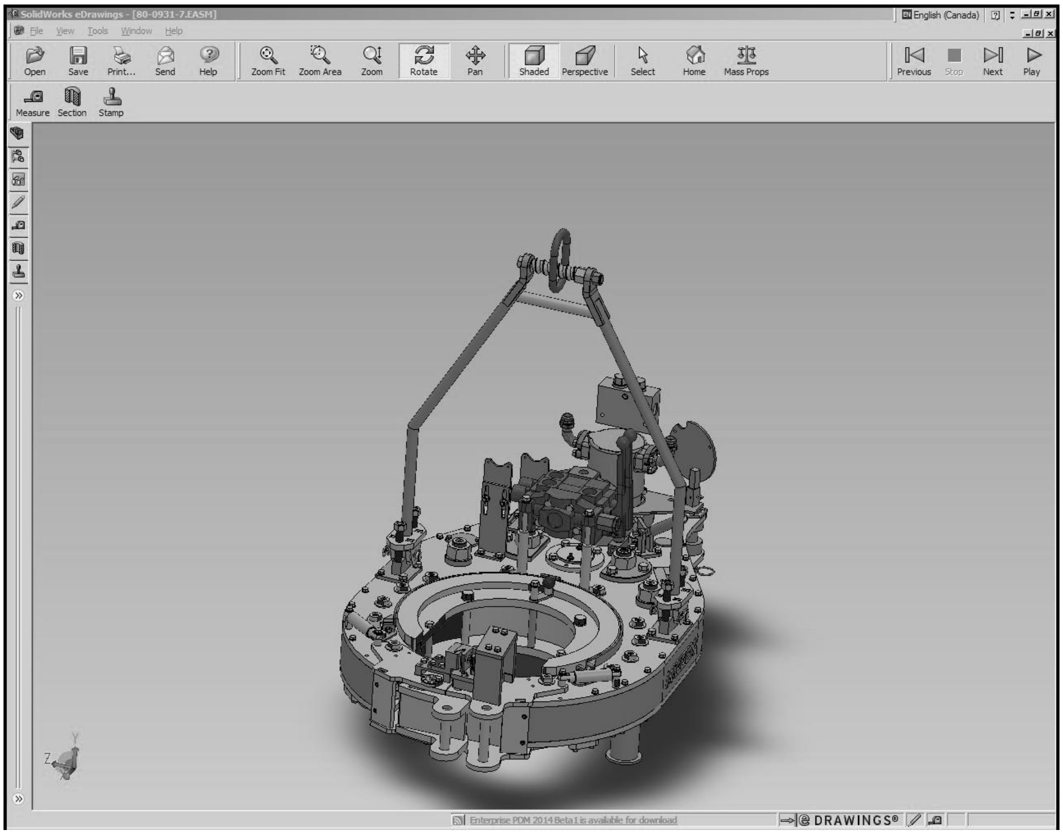


Figure 6-13 3D CAD Model of Tong

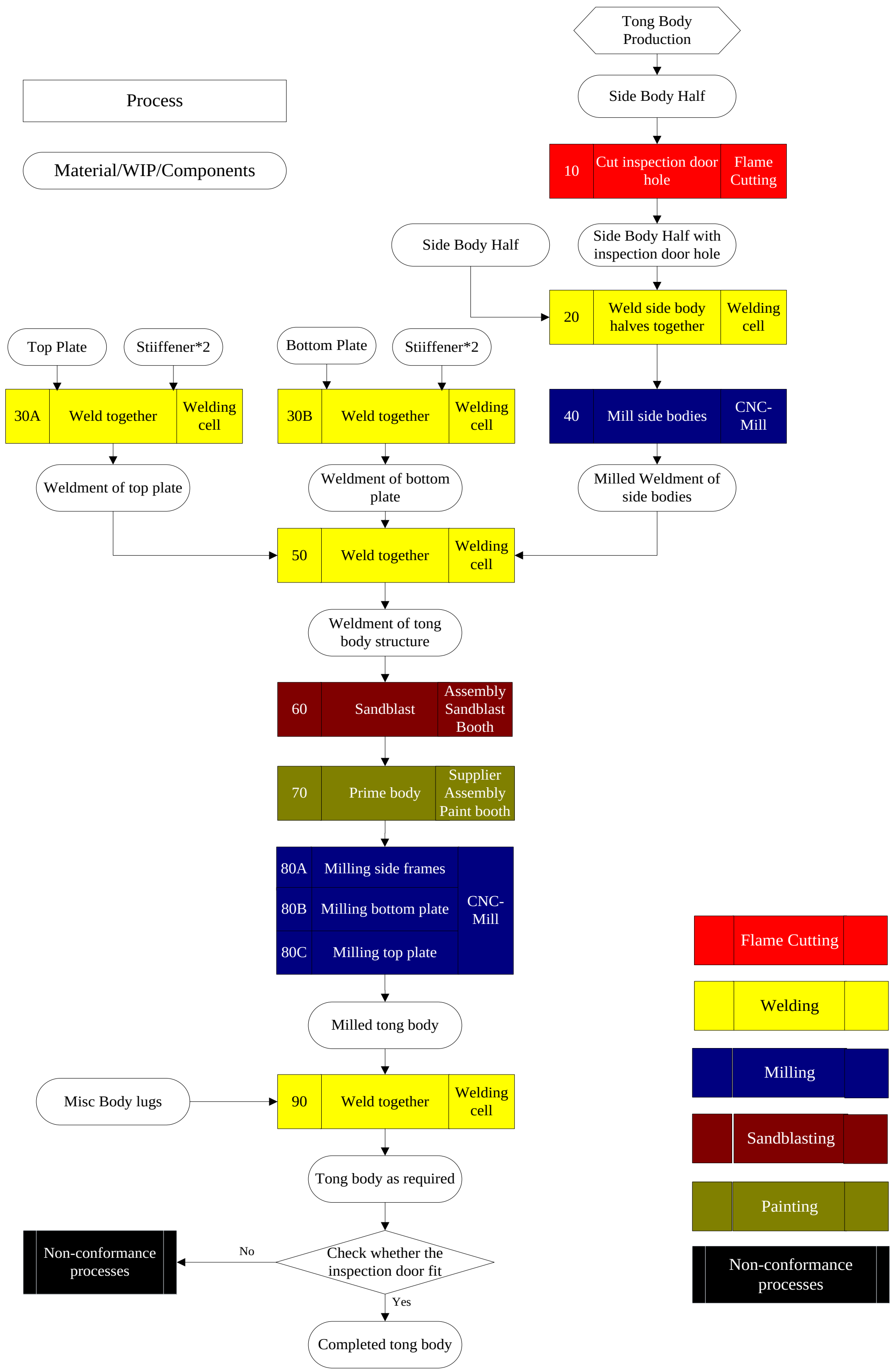


Figure 6-14 Tong Body Whole Manufacturing Processes

The designed welding feature and capacity module has four sub modules: the welding feature, matching module, machine module, and report module. The report module is similar to the order report module in Figure 6-3, which dynamically extracts information from the ERP and module database while showing reports in the report viewer. Figure 6-15 shows the UI for the welding feature. Each welding feature has a unique feature ID shared across the module. In this example, "WF-004" is the feature ID. The module can both create new features and load stored features. Introductory information on types of joints, grooves and seams is shown in the picture boxes at the bottom. As shown in Figure 6-2, a feature can be classified using four parameters: joint, groove, seam, and related sub parameter. After selecting the type of joint, groove and seam, the module will search its database and check if the welding joint is unique. If there are sub types, the records will be retrieved for users to select. For example, a butt joint with a square groove and double sided seam has two sub types. Based on the locations of the welding spots, it can be divided into "symmetric" and "cross" (not symmetric). After a welding joint is determined, a conceptual picture will be shown. In this case, the user selected the T-joint with the SQUARE groove and single side seam.

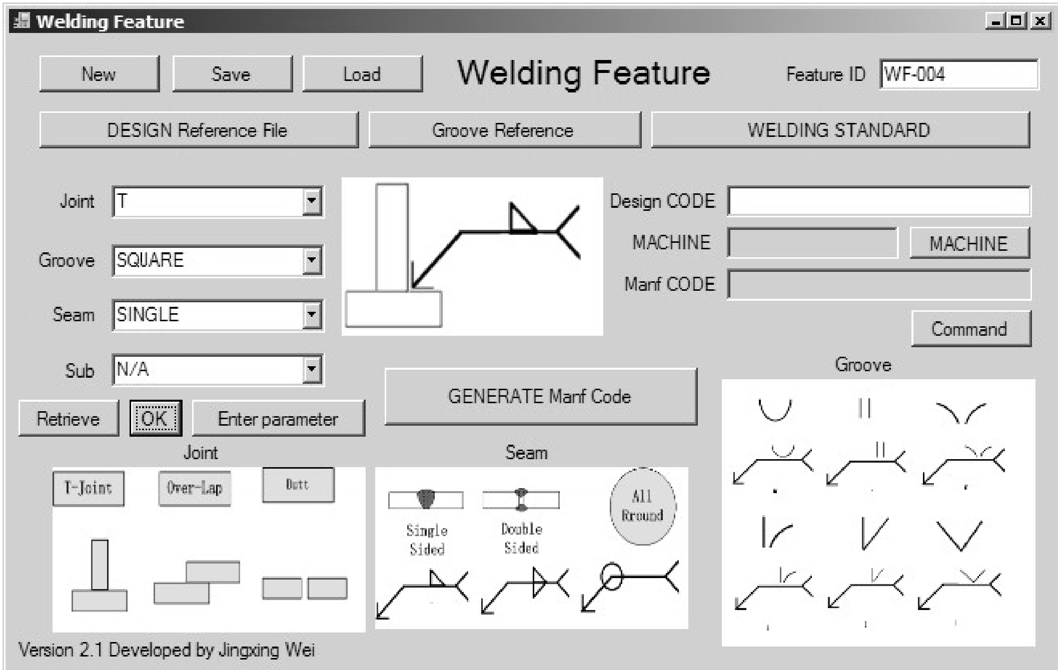


Figure 6-15 Welding Feature UI

After determining the type of welding required, further parametric factors need to be entered through the "Welding Parameter" module, as shown in Figure 6-16. This UI is used to manage detailed welding factors such as the length and height of the plate, start length and step length to be used. This module also includes feature requirements to manufacture the part. The system manages this information as weighted scores or levels. In this example, "WF-004" needs level 3 as a fixtures requirement, level 5 as a distortion requirement, and level 2 as a finishing requirement. The information will be matched with the machine capacity database (DB) stored in the ERP database user-defined tables. As for each type of welding feature, the parameters are different, as are the UIs. The system will load different UIs based on the different feature type selections stored in the database.

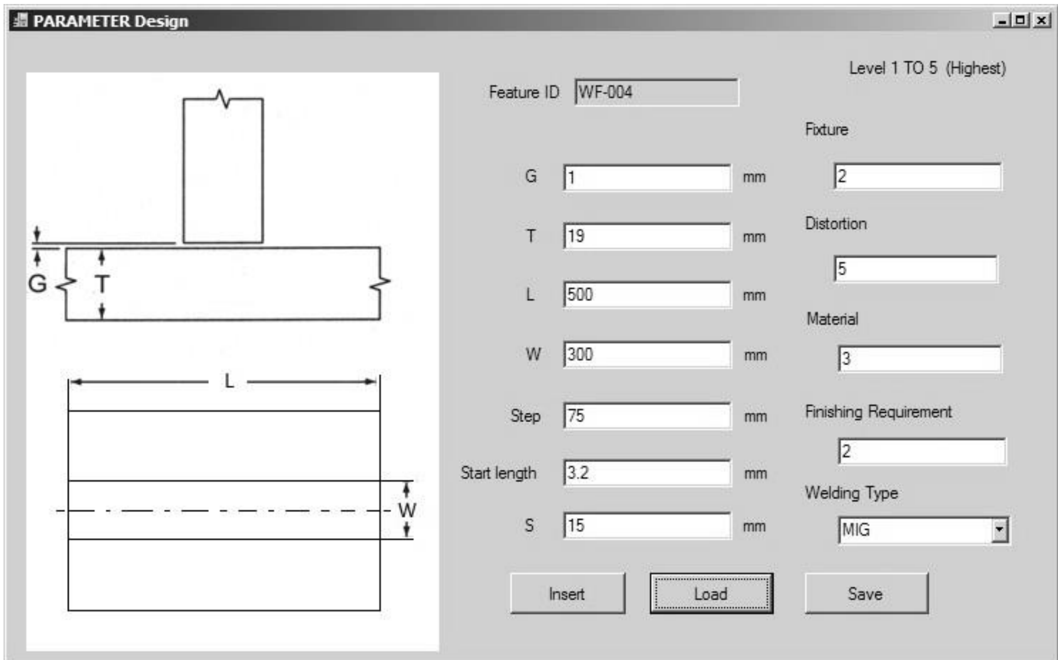


Figure 6-16 Welding Detailed Parametric Information

As a welding feature is determined, the module will match resource capacities with welding feature requirements. As shown in Figure 6-17, the module will go through the ERP database of each machine and search suitable machines. Then, the module will search the ERP scheduling module for current status information. If the machine is currently ideal, a status “OK” will be shown; otherwise it will be shown as “Busy.”

All the machine capability is stored in the machine module, which is shown in Figure 6-19. Operators’ information, such as license, level of experience, and name, is included in this module.

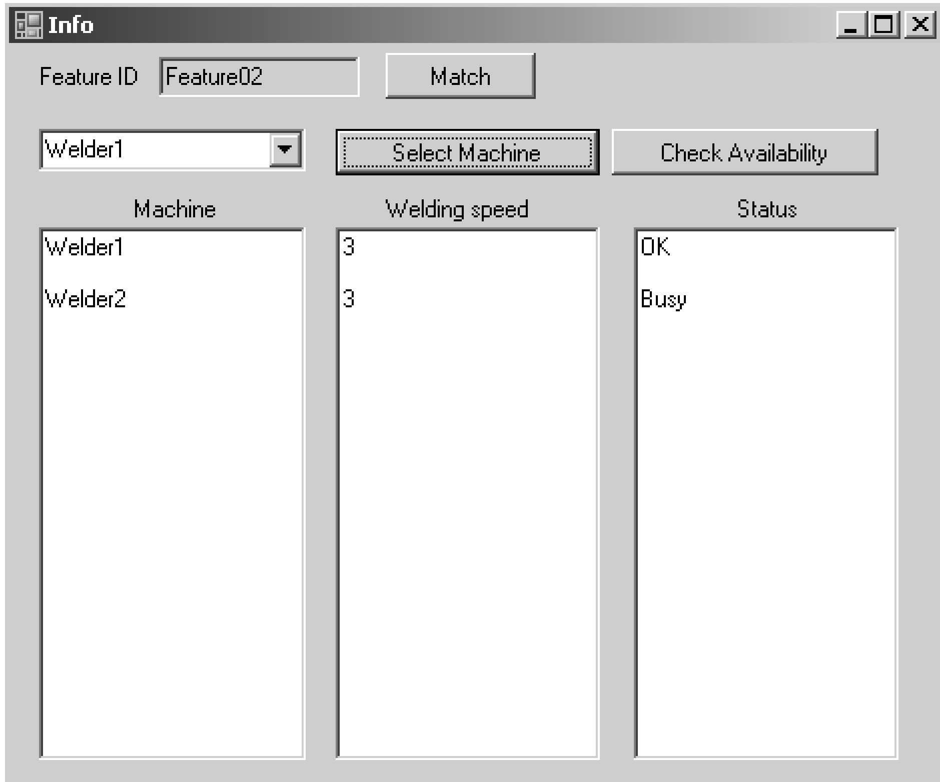


Figure 6-17 Capacity Feature Welding Feature Mapping Module

Detailed availability can be shown in Crystal reports in the report module as shown in Figure 6-18. The module also has the capability to show detailed machine information. As shown in Figure 6-19, detailed information about the machine and related pictures can be extracted from the ERP DB. In addition, current work orders placed on the machine are shown in the crystal reports by report module in Figure 6-20, with detailed labor and time tracking information of each operation included. This report links directly to the labor tracking system to reveal dynamic shop floor information.

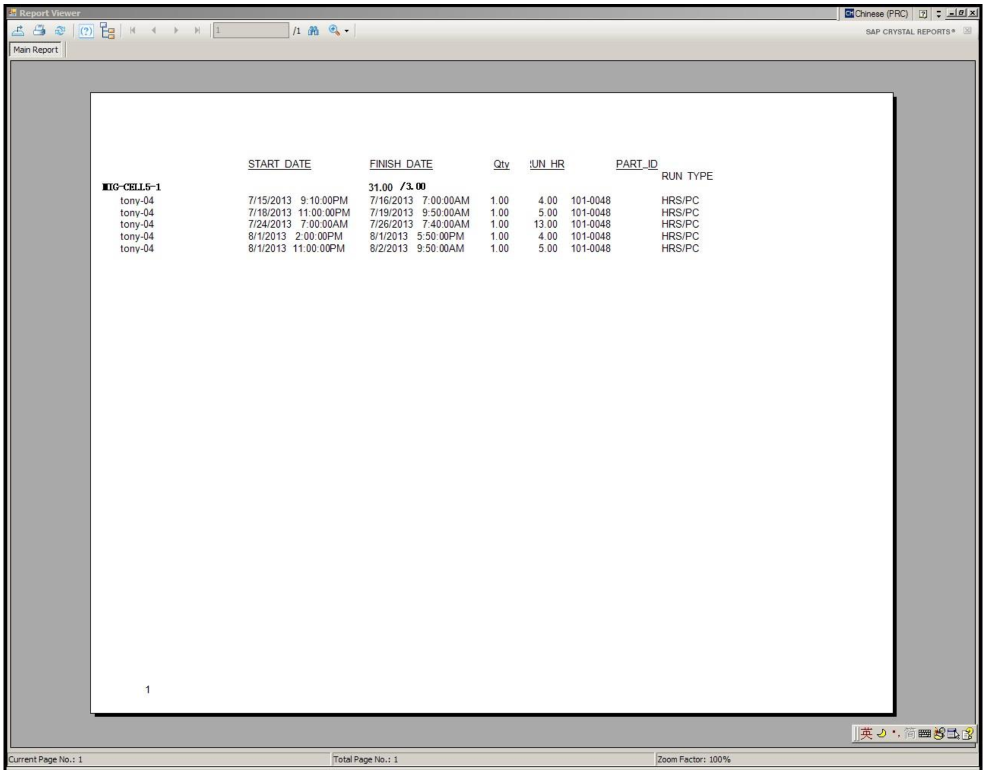


Figure 6-18 Production Schedule Report for Welding Resources

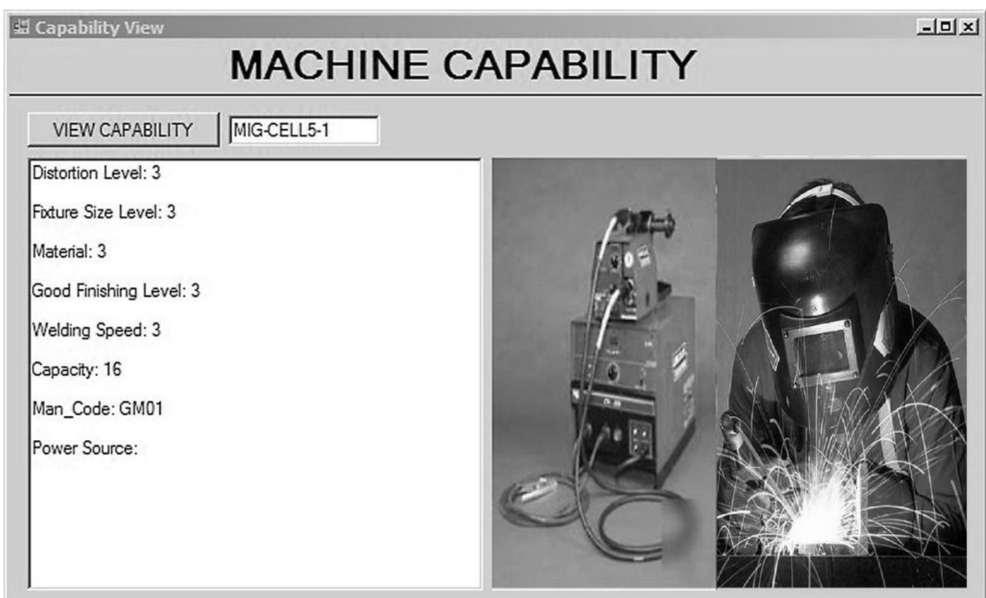


Figure 6-19 Machine Capability

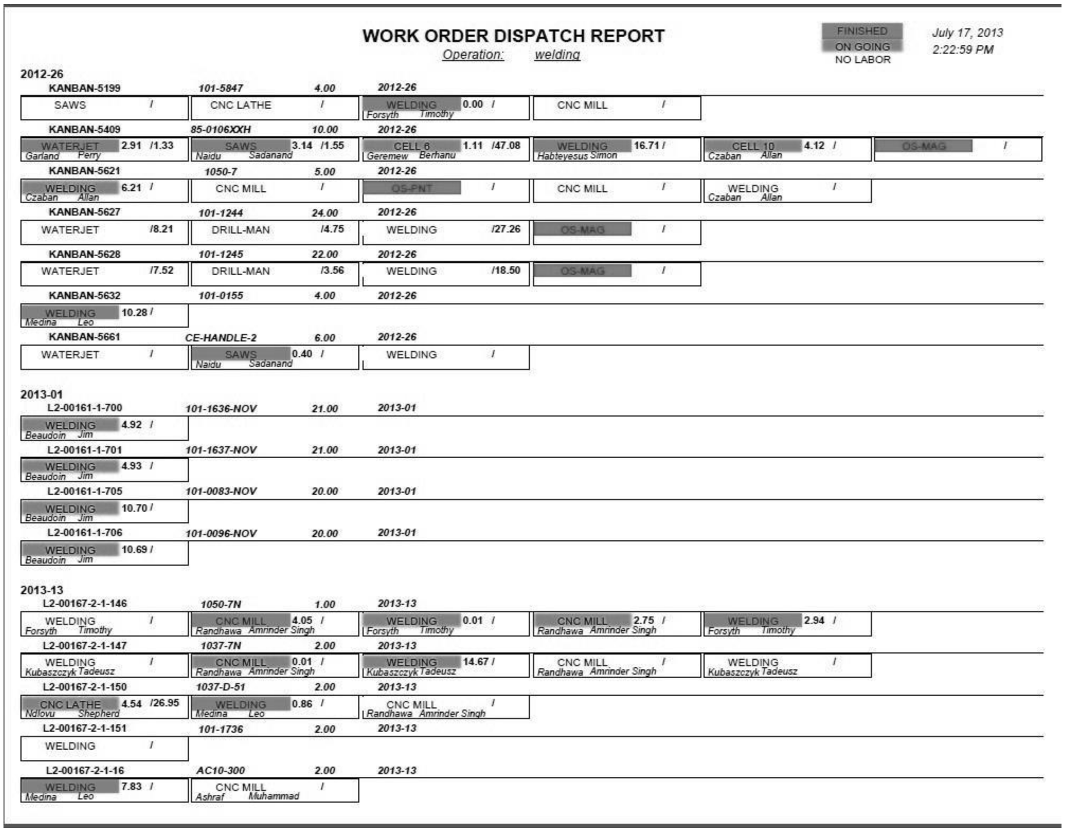


Figure 6-20 Production Dispatch Report for Welding Resources

After the machine is selected, the system will generate the manufacturing code (Manf-code) linking to the company welding standard DB and retrieve the detailed welding standard report, as shown in Figure 6-22. This report will provide detailed information on the suggested layer, path, amperes, and volts to be used. This report is a good reference for operators as well as production managers.

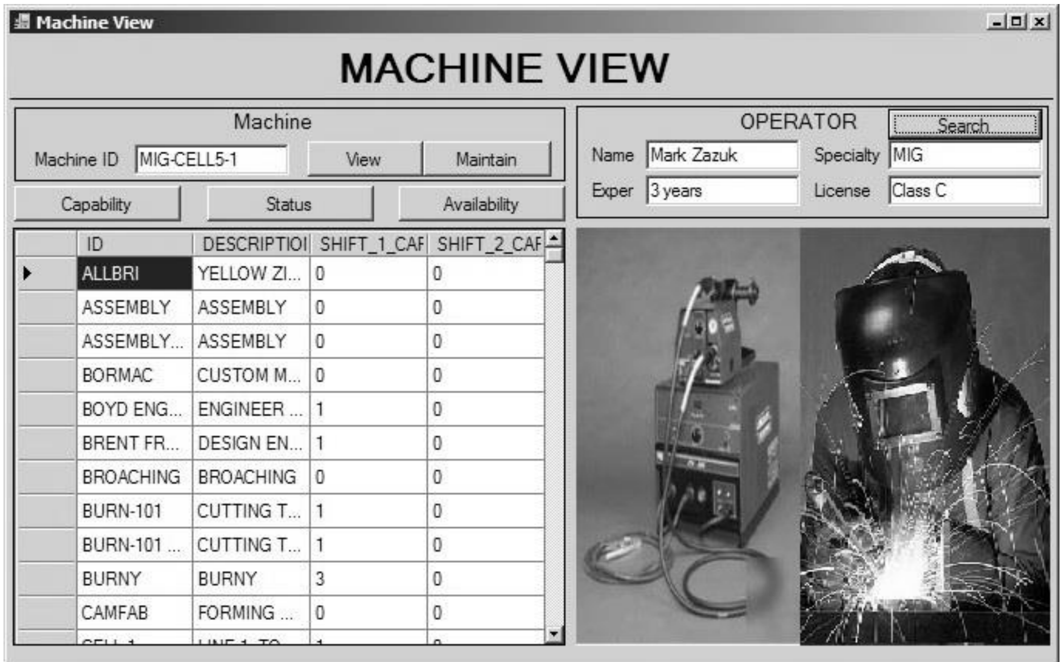


Figure 6-21 Machine View User Interface

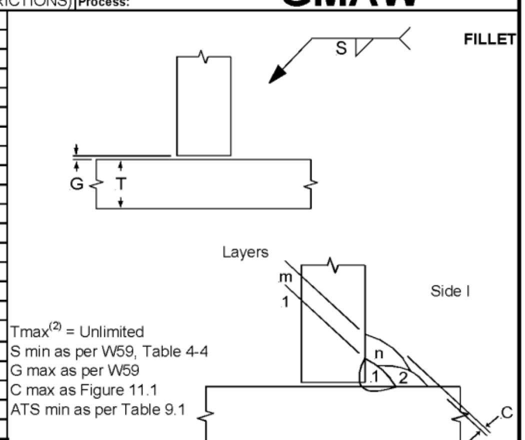
Base Metal: **Coating:** NONE
W59, TABLE 11-1, GROUPS 1, 2 & 3, or
Table 3.1, GROUPS 1, 2 & 3 in this WPS

Filler Metal / Classification
Table 3.1 in this WPS, or
CSA-ISO 14341: B-G 49A 2 C G3, B-G 49A 3 C G6
AWS A5.18: ER70S-3, ER70S-6

Thickness Range: 1/8 in (3 mm) to UNLIMITED$^{(2)}$
(SEE TABLE 2.1 FOR RESTRICTIONS)

Process: **GMAW**

Shielding Gas:	TABLE 9.1
Gas Flow Rate:	TABLE 9.1 & 40 CFH
Electrode Stickout:	TABLE 9.1 & 3/4"
Metal Transfer Mode	SPRAY
Process Mode:	SEMI-AUTOMATIC
Position:	FLAT, HORIZONTAL
Joint type:	TEE, LAP, CORNER
Penetration:	N/A
Eff. Throat Thickness:	ETT = 0.7S
Preheating Temp.:	TABLE 7.1 in this WPS
Interpass Temp.:	260ºC (500ºF) MAX



SEE TABLE 9.1 FOR PARAMETERS OR BELOW FOR B-G 49A 2 C G3 WITH 85% AR / 15% CO2 @ 35 CFH

Maximum Thickness, T mm inch	Side	Layer	Pass	El. Size inch	Current Polarity	Amperes ± 0%	Wire Speed - 0% + 10%	Volts - 0% + 14%	Min ATS - 0% + 30%
19$^{(2)}$ 3/4$^{(2)}$	I	1-m	1-n	0.035	DCEP	210-235	475 in / min	30.0	11 in / min
19$^{(2)}$ 3/4$^{(2)}$	I	1-m	1-n	0.035		280-295	800 in / min	31.5	17 in / min
UNLIMITED$^{(2)}$	I	1-m	1-n	0.045		330-365	425 in / min	30.0	9 in / min
UNLIMITED	I	1-m	1-n	0.052		325-360	300 in / min	28.5	6 in / min

Figure 6-22 Welding Standard Report

Chapter 7 Conclusion

As the concept of unified feature-based informatics provides a foundation for cross-domain information integration, this study has extended its application scope from a product engineering domain to a process engineering domain.

Firstly, this study proposes a conceptual framework for integration between the product domain and the process domain. A feature-based order acceptance and scheduling (OAS) module derived from a commercial enterprise resource planning (ERP) system has been developed based on this framework. To facilitate the integration, a comprehensive unified inter-domain feature management system is designed. A new category of feature, the customer feature, is defined as a class structure. With the given definition, engineering data are modeled and managed in objects; process domain features can collaborate with product domain features using an appropriate semantic modeling method. It also supports integration with existing manufacturing systems and reduces the overall cycle time for customer-oriented manufacturing. The OAS module has been programmed in a pilot effort and embedded into an ERP system, and users can access both product and process intelligence for decision making in order to gain an unrivaled competitive edge.

Secondly, further steps implementing the OAS module based on the proposed framework are achieved in the integration between the product and process domain by integrating manufacturing capacity information into an enterprise's entire information workflow based on unified features. To facilitate the integration, the welding process is redefined and classified into information patterns; the capability of the manufacturing resources is also redefined, using information patterns to implement the matching between resource capacity and manufacturing process requirements. Two other information patterns, the capacity feature and welding feature, are defined as class structures to transfer information between OAS and ERP. A theoretical definition of the welding feature elements is proposed with a detailed classification method (feature recognition method). The newly defined capacity feature and welding feature map with each other and interact with the previous proposed customer feature with pilot programming efforts, which help better model engineering information. The mapping results should provide sufficient input for later manufacturing activities. Manufacturing resources will then be well allocated and capacity-related information can be better addressed and reviewed through enterprise-wise software packages. A feature-based capacity mapping module is developed as a pilot effort.

The candidate believes that the concept of unified feature-based informatics provides a foundation for cross-domain information integration, and that this study takes a significant step in expanding the application scope into the process engineering domain. The given case of real world examples study has essentially validated the information framework and demonstrated the information sharing and integration between design configurations and ERP modules. In terms of academic research, the proposed method has been proven in principle. Note that the emphasis of this study is not the details of the OAS module development; rather, the prototype proves that the proposed method can integrate ERP order management with design configuration features through a consistent information framework and data structure design such that cross-domain feature information interactions are enabled by data associations. However, the scalability and sustainability measured from the angles of implementation efficiency and convenience of maintenance require further testing and enhancement.

Endnotes

Part of the thesis has been published. Jingxing Wei 2012. Proceedings of the 8th IEEE International Conference on Automation Science and Engineering. 968-973.

Part of the thesis has been accepted for publication. Jingxing Wei 2014. Computer in Industry. 65:64-78.

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