1997 ASME Fluids Engineering Division Summer Meeting
FEDSM'97
June 22 - 26, 1997

FEDSM97-3336

PRELIMINARY PUMP SELECTION AND CONFIGURATION IN AN ENGINEERED-TO-ORDER DESIGN ENVIRONMENT

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ABSTRACT

The majority of the market for pumping equipment utilize modular product families which are customized into Engineered-to-Order (ETO) design variants. In such a design process, the "best" design is not necessarily globally optimum but rather, one which technically satisfies all of the functional requirements, is delivered in the shortest period of time at the lowest total cost, and is produced within the environmental constraints of the manufacturer. The "front-end" design process is emphasized at which point the purchaser and manufacturer have the greatest control in fixing product costs and influencing the purchase decision. This paper defines the characteristics of a pump selection and configuration system used for ETO products during the preliminary design process. This system includes a novel system architecture, specialized optimization methods, a product configurator, and data exchange methods which have together improved productivity 38% and the technical quality of pump selections in 30% of the cases compared to traditional methods.

INTRODUCTION

Enterprises engaged in the application, design, manufacture, and installation of pumping machinery are operating in an environment of increasing worldwide competition. The competitiveness of the firm's pumping machinery is generally determined as part of the purchase evaluation. Purchasers expect manufacturers to design and produce high quality equipment which meet their defined pumping requirements. Alternative pump designs which meet the technical requirements are compared based on total cost. This is either a simple evaluation based on total equipment cost or a detailed analysis taking into account the cost of energy, maintenance, or other total lifecycle costs. Finally, preferences are given to manufacturers that deliver their product in the shortest leadtime with integrity to their promised shipment date. In summary, the three overriding criteria in the selection of pumping equipment are:

1. Satisfaction of functional requirements
2. Minimum total cost
3. Short delivery lead time

Many firms are looking to emerging computer technologies to improve performance to these selection criteria and thereby improve their competitiveness. Computer based applications are often used to aid in generating pump proposals or to check part inventory status. Design departments use CAD/CAM systems to shorten the design cycle and run simulations using structural finite element methods. However, the use of computer technology alone does not guarantee a measurable economic benefit (Chorafas, 1987; Kempfer, 1993). Organizational and process changes are usually necessary to achieve the benefits of computer automation. In response, many firms have adopted process focused design and manufacturing teams in the place of functional organizations. These teams are able to reduce queue time as information flows through the design and manufacturing process (Hammer, 1993; Carter and Baker, 1992). These process improvements often extend beyond a single firm with the formation of formal and informal alliances between engineering contractors, pump suppliers, and other equipment suppliers. These separate firms often join to form "virtual corporations" to address short-term market opportunities (Goldman et. al., 1995; Byrne, 1993).

These trends place a greater emphasis on the purchaser-supplier interface during the pump selection process. From the purchaser's perspective, the choice of pumping equipment has significant cost implications over the service life of the equipment. From the manufacturer's perspective, configuring the preferred offering of pumping equipment is crucial in securing a competitive advantage during the purchase evaluation.

The objective of this paper is to define the characteristics of a pump selection and design system used in the pre-manufacturing stages of the pump design process, in order to positively influence the purchasing decision. The success of such a system depends on the ability of the purchaser and manufacturer to effectively translate customer needs into functional requirements and finally, into the selection of an optimal pump design. The following contributions are described in this paper:

- The classification of pumping machinery as Engineered-to-Order (ETO) products which prescribe the use of standardized modular product architectures, adapted into flexibly configured variants, to meet specific customer requirements.
- A system design model complimentary to an ETO product and readily developed into a computerized design system.
- A structured information flow between the customer, design, and manufacturing functions to reduce complexity and decision making.

THE ENGINEERED-TO-ORDER DESIGN ENVIRONMENT

The Product Design Process

Researchers have categorized the product design process according to the characteristics of the product and the intended market. Ulrich and Eppinger (1995) have proposed 5 broad variants of the generic design process. The generic, or Market-Pull process is based on a known market opportunity in which the product is designed to satisfy a defined need. The converse of the Market-Pull is the Technology-Push process in which the firm attempts to find practical applications in the marketplace for a new technology. The other three variants are Platform Products, Process-Intensive Products, and Customized Products. Of particular interest are Customized products which are designed as slight variations from existing configurations, usually to satisfy specific customer requirements. This type of product development process is commonly used by pump manufacturers as well as turbine, motor, mechanical seal, gearbox, boiler, and other mechanical equipment manufacturers. These products and the design process used to produce them are hereafter known as *Engineered-to-Order*, or *ETO,* products and processes.

In order to understand the distinguishing characteristics of the ETO Process, it is necessary to first review the generic product design process and then relate that to the ETO Process. Generic models of the design process have been proposed by Ulrich and Eppinger (1995), Ullman (1992), Pugh (1991), Pahl and Beitz (1996), Welch and Dixon (1989, 1991, 1992) and Brown and Chandrasekaran (1984). A typical design process taxonomy has been adopted as shown in Figure 1.

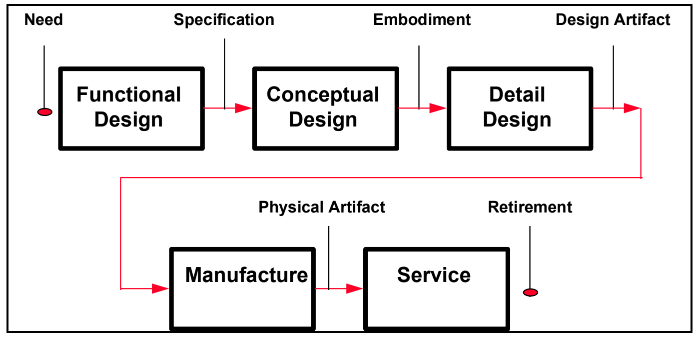

Figure 1. Product Design Process

Pugh (1991) further defines a spectrum of design processes which range between innovatory design and conventional design. Innovatory design is relatively unconstrained by prior practice and contains a high level of design synthesis. Conversely, the conventional design process is heavily constrained by prior practice and requires only a minimal amount of design synthesis. Pahl and Beitz (1996) estimate that conventional designs comprise about 75% of all design activity while General Electric claims that a full 85% of their design work is “purchase order” engineering (Whitney, 1990). Ironically, most design research is concentrated on the innovatory design process. Although this focus may appear more intellectually elegant, the rest of the world is toiling with challenging conventional design problems.

Certainly, the majority of actual product design activity performed in the pump industry is of the conventional type. This ETO design process is based on a *specific* customer need favoring the selection of an existing, proven design, which can be quickly produced in the shortest period of time and at low cost. This is in stark contrast to commodity products (i.e. Market-Pull, Technology-Push, and Platform products) or process-intensive products which are made to forecast and in medium to high volumes. Each ETO design variant must follow a regimented design process beginning with the customer need and concluding with the manufacture and service of the product over its complete life cycle. The opportunity facing both purchaser and manufacturer alike is the development of a simplified process for communicating product information in an ETO environment. This will be elaborated in the next two sections, from the perspective of both purchaser and the manufacturer.

Perspective of the Purchaser

Pumping equipment is used in a broad range of wastewater, sewage treatment, power generation, petroleum processing, pulp and paper, food and beverage, mining, fire pumps, marine, HVAC, and mining applications (Karassik, I. J., et. al., 1986; Stepanoff, A. J., 1957). Following the decision that pumping equipment is required, an Inquiry / Proposal process is undertaken following these general steps (Karassik, et al., 1986): (1) define system requirements, (2) select pump and driver, (3) finalize pump specification, (4) bidding and negotiation, (5) evaluate bids, and (6) purchase the selected pump.

The entire process is information intensive, with purchaser's requirements communicated in the form of an Inquiry (also known as a Request-for-Quotation (RFQ)) and Manufacture's proposals submitted in the form of a Proposal (see Figure 2). This information flow consists of both technical and commercial information. The technical information is comprised of a datasheet with performance and construction details of the pump. In many cases, a detailed product specification is submitted by the purchaser based on their past experiences. Recently, purchasers are seeking to reduce the engineering resources required to process this information without compromising the quality of the competitive evaluation.

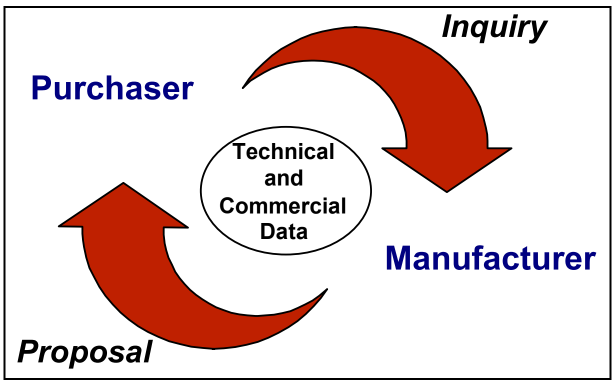

Figure 2. Purchaser Supplier Information Exchange

Perspective of the Manufacturer

The vast majority of the market for pumping machinery utilize *modular product families* customized into *engineered-to-order product configurations.* The design of these products represent a delicate balance between product standardization and product flexibility. Manufacturers are challenged to design pumping equipment which has the low cost, short lead-time characteristics of a standardized, off-the-shelf product, while providing ample flexibility to customize the equipment to meet a wide range of customer requirements. However, once the investment in a product range is made, the manufacturer seeks to maximize the return on those assets by applying that product to a wide variety of potential pumping applications.

Studies have shown that in new product development, 50-70% of the total product costs are committed during the design engineering phase even though the engineering costs represent only 5-10% of the actual costs expended (Chorafas, 1987; Ullman, 1992). These estimates were based on the design of made-to-forecast consumer products such as Ford automobiles and Xerox photocopiers. In an ETO product, engineering costs are made in two phases. The initial investment is made at the time the modular product range is developed. Thereafter, additional engineering costs are made to customize the product family to meet specific customer requirements. These ongoing engineering costs are expended during the Functional and Conceptual Design steps (Figure 1) or what is commonly referred in the industry as the Inquiry / Proposal Process (Figure 3). At the conclusion of the proposal stage, the manufacturer sets a total project price and is obliged to meet the associated cost targets with a minimum amount of risk. Thus, for an ETO design process, nearly 100% of the costs are committed during the "Front-End" Inquiry/Proposal Process in contrast to the 70% figure in the new product design process.

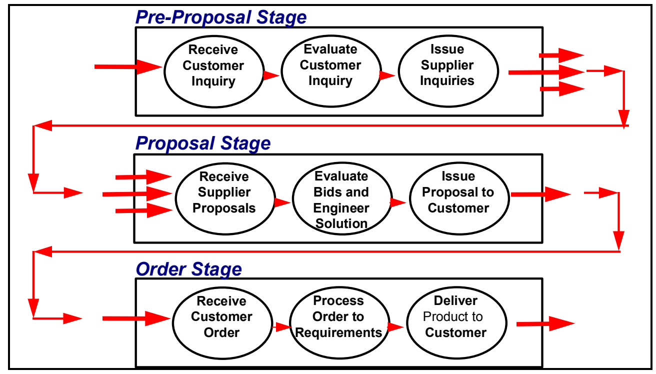

Figure 3. The Inquiry/Proposal Process

The ETO Inquiry/Proposal process, represents approximately 10-25% of the total product cost for the pumping equipment. The reason this is higher than the 5-10% estimate cited before is explained in the following example. Suppose the Operating Company gives three Engineering / Design contractors the opportunity to bid on an expansion of a chemical process plant. If each of these contractors issues three inquiries to pump manufacturers, a total of 9 inquiries are issued. Now, if each manufacturer issues 3 inquiries to their sub-suppliers, a total of 27 inquires are pending (Figure 4). In the end, only one contractor, one equipment supplier, and one sub-supplier actually receive orders to supply equipment for the project. Thus, only 3 inquiries out of 27, representing 11% of the total functional and conceptual design effort is useful work. These engineering costs are recovered only when equipment is actually purchased. The cost of the other 89% of effort by those participants in the Inquiry/Proposal process who did not receive a customer order are wasted and absorbed as a sales and engineering overhead. Simplifying this process is an attractive proposition for both purchaser and manufacturer.

Common Objectives

Both purchaser and manufacturer in the Inquiry/Proposal Process are striving to enhance their competitiveness by reducing costs through process oriented productivity improvements. *Intercompany* productivity gains are the obvious point of action. However, the "ripple effect" on the total cost across multiple firms is a significant cost and represents a relatively unexplored opportunity for *Intracompany* productivity gains. Some of the strategies include the following:

Intracompany Strategies.

- Form alliances to streamline the Inquiry / Proposal process across multiple firms.
- Reduce the number of participants in the process by defining a preferred set of customers and suppliers.
- Move the pump selection task earlier in the design process by allowing the purchaser to participate in the conceptual design decisions.
- Structure the flow of information between companies to reduce ambiguity and enhance common work processes.

Intercompany Strategies.

- Reduce the time required to produce a proposal.
- Improve the conversion ratio (ratio of won proposals vs. issued proposals) through optimal selections.
- Improve the conversion ratio by generating proposals only when there is a reasonable probability of success.
- Reduce decision making through a systematic design process based on an understanding of intercompany capabilities and costs.

These common objectives represent strategies for improving productivity and associated cost reductions in the Inquiry / Proposal process. The next section describes a tactical approach toward achieving these objectives.

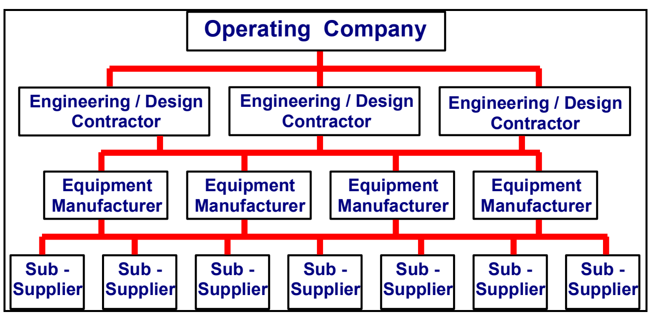

Figure 4. Multi-Firm Information Flow

THE PRELIMINARY PUMP SELECTION AND CONFIGURATION PROCESS

System Requirements and Objectives

This section describes an integrated system developed by one pump manufacturer to satisfy the proposed intercompany and intracompany objectives for the preliminary pump selection and configuration process. Specifically, this system is intended to fulfill the following functions. First, to generate an optimal pump *selection* for a given set of customer requirements considering any pump model within the company's portfolio of strategic product lines. Second, to rapidly develop preferred pump *configurations* such that detailed performance, construction, and pricing details are defined. Finally, to *communicate* these technical and commercial design details in a systematic, unambiguous way to both the customer (purchaser) and the manufacturer.

Two crucial advances were required to achieve these functions.

1. The development of a system design model conducive to an ETO product and process, and readily developed into a computerized design system.
2. A structured information flow between the customer, design, and manufacturing functions to reduce complexity and decision making in the Inquiry / Proposal process.

System Background

Current Solutions. The primary tool which pump manufacturers traditionally use during the Inquiry / Proposal process is commonly known as the *Pricebook*. A Pricebook brings to mind a simple price list which sales engineers use to quote pumps. In the simplest case, this is true. In most cases, however, the Pricebook is a manual which contains extensive pump performance curves, materials of construction, engineering data including dimensions and cross-sectional drawings, a plethora of guidelines on proper application of pumping equipment, and pricing information. Essentially, the Pricebook is an engineering design, specification, and pricing manual used by ETO product manufacturers during the preliminary design phase.

A trained pump applications engineer uses a Pricebook as the information base to convert a customer's inquiry into a customized proposal. Proposal documents are produced and include datasheets, performance curve, general arrangement drawings, and a price quotation including terms and conditions. In many cases, alternative selections, comments to the customer's specification, or other supplementary information are provided. The diverse array of information and expertise to develop a customized proposal has prompted the need to systematize the selection and configuration process using computer-aided tools.

Areas of Research. A significant amount of research began in the late 1970's and early 1980's in the area of systematizing the mechanical design process. At the time, these methods were aimed at delivering advanced systems using digital computers. Today, the ubiquitous personal computer and design workstation are a necessary ingredient in any modern design strategy. Yet, the results of this research in the preliminary design phases have not parlayed into widespread use in the pump industry.

However, one class of conceptual design tools which has found widespread use in the industry are pump selection programs. These are procedural programs which use specialized mathematical algorithms to predict pump performance from a database of potential pump models. Optimization routines which automatically select the "best" pump are rarely used in these systems, mainly because the problem domain is represented by highly non-linear objective functions with constraints defined as both continuous and discrete variables. Optimization methods which address these Mixed Integer Non-Linear Problems (MINLP) are improving but are still impractical for industrial problems (Ramaswamy, Ulrich, Kishi, and Tomikashi, 1993). Also, the multi-objective nature of the selection process and the need to deal with uncertainty are beyond the scope of conventional optimization methods (Bradley and Agogino, 1993). Nonetheless, there are over 30 different pump selection programs used in the industry today (Cotter, 1996). With few exceptions, most pump selection programs have been specially developed by each pump manufacturer using proprietary mathematical programming methods and custom developed systems.

In addition to pump selection programs, product configurators are of particular interest to manufacturers of ETO products. Product configurators are tools which aid the designer in configuring a design according to a prescribed product configuration model. These product models are based on *design rules* and *configuration rules* which limit configuration choices (Shah and Mäntylä, 1995). Ultimately, configurators enforce product standardization and reduce configuration errors

An all inclusive review of the "front-end" Inquiry / Proposal systems used by pump manufacturers, much less all manufacturer's of ETO products, is not readily available. Nonetheless, the following section is intended to describe an extensive system implementation initiated by one pump manufacturer which describes the salient features of a "front-end" pump selection and configuration system. The system architecture is intended to be broadly applicable to any ETO product or process.

Description of the Implementation

In the late 1980's, a pump selection program to choose the optimum pump model from a database of pre-engineered product lines was developed. This program was a procedural program, written in FORTRAN, which used specialized mathematical algorithms to predict pump performance from a database of potential pump models. This program accepted as input, basic pumping requirements such as required flow, head, and fluid properties. The selections were constrained according to the purchaser's specifications for pump construction, materials of construction, and minimum performance. Later, the development of an interactive program to configure and price a given pump model was undertaken. Customized pump curves, datasheets, and priced quotations were automatically generated from the program (Dahl, 1990). The major features of this system are described below.

Engineered-to-Order Process Design. The overall scope of the system includes the Functional Design and Conceptual Design processes shown in Figure 1 which transforms the knowledge state from customer need through specification / selection and concluding with a defined design embodiment. This process requires a flow of structured and unambiguous information between the customer, sales engineer, and product/manufacturing engineer. A crucial requirement of this system is its ability to transport the knowledgebase to the earliest stages of the inquiry / proposal process. This allows purchasers to make informed design decisions and trade-off analyses at the point when costs are "designed-in" to the pumping system.

System Architecture. The relevant components of the system are depicted in Figure 5. The predominate "front-end" design process is handled by three modules which operate in series. The *Hydraulic Module* captures customer needs and selects the optimum pump for defined application. The *Feature Module* is invoked next, inheriting the performance and operating characteristics of the pump selected from the Hydraulic Module. The user interactively chooses the desired configuration *features* at the conclusion of which, an entire pump embodiment is defined. The *Order Entry Module* validates the complete pump embodiment such that all information required to process an order at a specified manufacturing plant are satisfied.

Two utility modules are used. The *Output Module* accesses the proposal database at any stage in the design process to generate custom proposal documents such as performance curves, datasheets, General Arrangement (GA) drawings, or a Price Make-Up (quotation). The *Assistant Module* contains a broad range of unstructured technical information such as cross-sectional drawings, engineering data, or quality information. This information is available using hypertext links and keyword search techniques to quickly access relevant information. The combination of all 5 modules (Figure 5) completely embody the information contained in a traditional Pricebook. Other program modules not described include a remote communication system which ensures each remote computer system is updated with the current product line knowledgebase. Each knowledgebase is produced by a domain expert using a *Knowledgebase Toolkit*. The same engineers responsible for designing and processing customer orders are also responsible for the maintenance of their product line knowledgebase.

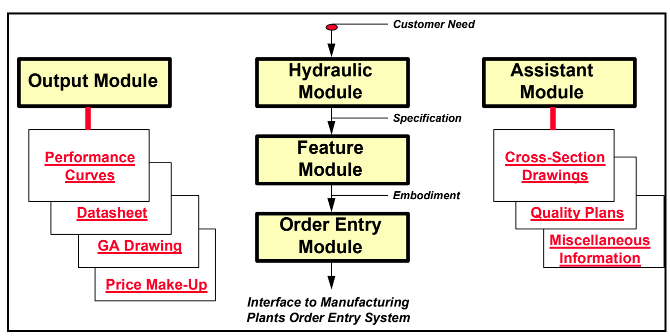

Figure 5: Major System Modules

Optimization Methods. Within the Hydraulic Module, the pump selection is based on optimization algorithms which capture the customer's functional requirements such as desired flow and head. Constraints may be invoked to limit selections which satisfy specific customer requirements such as API 610 compliance, minimum efficiency limits, suction specific speed limits, etc. At the conclusion of the optimization process, the user is presented with a list of pump alternatives. *Choices* satisfy all requirements. *Marginal Rejects* could potentially satisfy all requirements provided the customer is willing to relax a specification constraint. For example, suppose the Suction Specific Speed[1] (N_{ss}) for a given pump is 11,200. This would result in a marginal reject condition if 11,000 was the maximum limit for N_{ss}. Another case involves minor pump design modifications which allow the factory to satisfy the desired performance requirements (e.g. impeller underfile to achieve a 5% increase in pump head). Finally, pump's designated as *Full Rejects* are specified when the optimization program cannot configure the pump to meet the customer's requirements, despite minor specification changes or pump rework. The alternatives are presented in order of maximum pump efficiency or minimum purchase price, the two primary contributors in the purchaser's total evaluated cost model. The engineer then makes the final pump selection.

Product Configuration. A product configurator has been developed which describes abstract *configuration features* that completely describe the pump embodiment. Each design feature has 3 components. *Feature attributes* are assigned to each configuration feature which include a feature description, datasheet attributes, price, cost, and the influence on delivery lead time (e.g. the impeller wearing ring has material = cast iron, price = $300, and lead time = standard). *Configuration rules* dictate whether specific design features are allowed, not allowed, or required for a given application (e.g. wearing rings are required on all impellers). Finally, *design guidelines* further limit acceptable design features based on operating limits (e.g. open wearing ring clearances are required when the maximum pumping temperature exceeds 400°F). Once the configuration features are defined, abstract bills of material, total delivery lead times, and priced quotations are readily generated. When communicated through the Order Entry Module, these configuration features simplify the interpretation of the specified scope-of-supply.

Data Exchange Standards. Intracompany exchange of centrifugal pump technical data has been traditionally handled using the pump datasheet. Unfortunately, both purchaser and manufacturer have developed their own datasheet formats. Each datasheet exchange requires a laborious translation and interpretation of information from one datasheet format to another. With the implementation of computerized selection programs and bid-tab programs, this manual translation represents a lost opportunity to streamline the data communication process. In response, some firms have developed proprietary data exchange formats to leverage their own proprietary systems. Unfortunately, that approach has only shifted the burden to their trading partners who must develop special data translators. Consider that the total number of translators needed for M data exchange formats follows the relationship, M•(M-1). Therefore, 3 unique data formats require 6 translators while 10 unique formats require 90 translators. To halt this trend, a neutral data exchange specification was developed under the auspices of the American Petroleum Institute's Specification for Centrifugal Pumps (Dahl, 1995). This is used to exchange structured pump technical information reliably and efficiently between trading partners requiring each firm to develop only two translators (i.e. input and output) to exchange pump data. A number of purchasers and manufacturers are now starting to use the data exchange file during the Inquiry / Proposal phase.

LESSONS LEARNED

Results

The benefits of the pump selection and configuration system are based on a combination of improved sales opportunities and reduced costs (see Table 1). However, the benefits are difficult to measure quantitatively with confidence since the influence of all external factors cannot be readily isolated.

The following studies were performed to develop quantitative benefits. One study sampled nearly 100 pump selections made by manual methods using the Pricebook. Then, an applications engineer using the system re-selected each of the manual selections. From this sample, 30% of the original selections were considered sub-optimal such that another pump model was proposed with superior price or performance. In another study, it was found that the number of proposals issued per person increased 38% over a 2 year period. In another study, it was found that those applications engineers who regularly used the system statistically outperformed their colleagues in total sales (i.e. improved customer satisfaction) compared with those not effectively using the system.

Category	Improved Customer Satisfaction	Cost Reduction
Improved Quotation Productivity	x	x
Optimized Selections	x	
Adherence to Product Standards		x
Value Added Selling	x	
Standardized Proposal / Order Entry Systems		x
Reduced Distribution / Printing / Maintenance Costs of Pricebooks		x
Improved availability of Proposal / Quotation Information	x	x

Table 1: Benefit Categories of the System

[1] Suction Specific Speed in US Units = N_{ss} = RPM • GPM$^{1/2}$ / NPSHR$^{3/4}$ where RPM = pump speed in rpm, GPM = pump flowrate per impeller eye in gallons per minute, and NPSHR = net positive suction head in feet, all at the pump's best efficiency flowrate.

Hurdles

Organizations interested in adopting this methodology must consider a number of significant barriers to success. The first point is a major up-front development and implementation effort. The system modules described are not generally available as commercial applications, necessitating custom system development performed either in-house or via an external consulting firm. In addition, computer hardware and training are needed for all sales and applications engineers to effectively utilized the system. Secondly, the pump industry has a mature workforce which has enjoyed a long service record with their employer. This fact, combined with a relatively low influx of new engineers, has resulted in an early resistance to change. Another concern is young applications engineers often lack the grounding in pump fundamentals that their predecessors developed while manually preparing pump selections and proposals. On-going training programs for new applications engineers to develop fundamental pump applications knowledge is always necessary.

The final hurdle is actually achieving a seamless, structured information flow between the customer's and the manufacturer's sales and engineering functions. The availability of computer systems guarantees only that the infrastructure is in place to achieve the anticipated benefits. However, common work practices in both an intercompany and intracompany environment must be adopted. This requires re-visiting all of the design rules and guidelines used in the preliminary design of a product. In many cases, heuristics which govern good design practice must be fixed and codified in order to simplify the decision making process. In extreme cases, the implementation of the product line knowledgebase has forced designers to completely "re-think" their product structure and applications guidelines due to hidden conflicts.

CONCLUSIONS

In summary, a computer system has been described which has increased productivity and customer satisfaction during the functional and conceptual design phases of the Engineered-to-Order design process. Selection optimization has improved 30%, order interpretation errors have diminished, and proposal output per person has increased 38%. The development of this system has precipitated a number of advances in the state-of-the-art in order to fulfill the desired inter- and intracompany productivity gains. The first is the understanding that most pumping equipment is subjected to an Engineered-to-Order Design process. As such, manufacturers are challenged to satisfy the three overriding customer requirements: satisfaction of customer requirements, minimum total cost, and short delivery lead times. Based on these requirements, the ETO process was modeled and a corresponding computer system architecture developed to fulfill the requirements of that process. A structured flow of information between the customer, design, and manufacturing functions are a necessary ingredient towards reducing product complexity and decision making.

The development of this system has identified fertile areas for ongoing research and development. The availability and broad use of data exchange standards will allow robust exchange of technical information among trading partners. The combination of the API 610 neutral data exchange standards with an international standard such as ISO/STEP should further strengthen this ongoing initiative. Product configurators are only now becoming commercially viable but need to be developed for broad use by manufacturers. The Internet and other communication technologies suggest further opportunities to improve the preliminary design process as customers and suppliers adopt a preference toward business partnerships and more open exchange of design information. Finally, products which are readily configurable appear to be less complex and therefore have lower information content (Suh, 1990). Relating such a design structure to improved business performance would be an attractive methodology for ETO manufacturers to simplify their product structures.

ACKNOWLEDGMENTS

The authors wish to acknowledge the ongoing support of the Ingersoll-Dresser Pump Company and Ingersoll-Rand Company who have funded the work presented in this paper. In addition, the lead author acknowledges the inspiration of his Ph.D. dissertation committee at Lehigh University and his colleagues in Corporate Technology.

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