CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

A Study of the Life Cycle Requirements for an Information Model of the Components that are Incorporated in Process Facilities

By

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SUMMARY
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Title: *A Study of the Life Cycle Requirements for an Information Model of the Components that are Incorporated in Process Facilities*

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1. Abstract:

This paper reports the results of research that explores product modeling issues for components[1] that are incorporated in process plant facilities. To understand the business and technical challenges inherent in the development of component information models, the project:

- Studies the business issues of information exchange and the life-cycle information requirements for the components that are installed in process plant facilities.
- Identifies engineering tasks and coordination requirements that an information model should support.
- Investigates standards development for component and product information models.
- Implements a test case that explores integration of a component information model with a task based process model to provide decision support.

The information model and component selection test case is developed for one component type. It integrates an explicit description of product data and a task based process in a component information model. This model provides support for analysis and evaluation of component selection in an intelligent engineering application.

2. Subject:

This research seeks to identify the information requirements across the facility life cycle that component information models should represent to provide value added benefit for facility information use and sharing.

The key concepts of this research include:

- Definition of the business problems relating to component information exchange. These problems include the cost of information search, the cost of repetitive and

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[1] A component is a simple (single part) or complex (assembled part) item that is normally manufactured and sold by a vendor and becomes incorporated into the facility. The term "component model" is used to differentiate this information model from "product model" which is used to model the facility itself. The terms "part" and "component" are used interchangeably, though we prefer the latter because it includes complex assemblies of simple parts. Clearly, there is a strong overlap in the technologies used for modeling components and products, and there are times when this differentiation is not appropriate. The business issues for vendors (who sell components) and E/C contractors (who design and build plants) are, however, significantly different. This, and the need to identify the special information modeling issues for components, requires that a distinction be drawn between component and product models.

redundant engineering and analysis activities for component selection and specification, the cost to vendors of marketing and maintaining customer relationships.

- Identification of current limits of information products, services to satisfy the business requirements.
- Investigation of information requirements for knowledge based components.
- The value added benefit of developing component information models that include a representation of component form, function, and behavior, and which integrate with task-based process descriptions (related to components) to enable task automation, particularly for engineering analysis and evaluation activities.

3. Objectives/Benefits:

The project basis of the A/E/C industry leads to enterprise organization and information technology (IT) support systems that are fragmented. This problem manifests through communication problems, errors, delays, and increased cost for project participants. An important requirement for improving this business problem lies in the standardization of product data representation. This is the challenge of ISO STandards for the Exchange of Product data (STEP), and more recently the Industry Alliance for Interoperability (IAI). These initiatives provide a data structure and content foundation for software vendors to develop integrated applications that improve communication between enterprises.

Information integration through product data standardization solves only part of the business problem. It is also possible to formally describe processes, the things that individuals and organizations do with product data to achieve project goals. The integration of product and process description in an executable program can lead to software services that offer significant benefit through task automation, increased data and knowledge reuse, better decision making and improved coordination.

This research pursues these goals from the perspective of information and knowledge exchange between vendors and users of components that are installed in facilities. The test case demonstrates the usefulness of a component evaluation and analysis software system that interacts directly with the design model and provides support for component selection. It is hoped that this research can lead to technologies that improve business and technical process related to components throughout the facility life cycle.

4. Methodology:

The research method for this project consisted of:

- A search and review of information modeling literature and, in particular, the ongoing STEP efforts within the process industries. In addition the ISO 13584 Standard Part libraries (PLIB) was studied. Part of this effort included attending quarterly STEP meetings.

- An information requirements study that was conducted through interviews with participants in component information exchange, including product vendors, information integrators, engineering/construction professionals, and facility owners. Through this study the business issues and information requirements were identified.

- The implementation of a test case that integrates an explicit description of product data and a task based process. The test case is an information model for a component and a piping sub-system. It includes a behavioral representation that supports one engineering task, preliminary valve sizing and selection. This model provides support for analysis and evaluation of component selection in an intelligent engineering application.

5. Results:

To support and improve business process, component information models should be capable of representing component form, function, and behavior. In addition such product descriptions should integrate with formal process descriptions of tasks so that they may be automated. It is possible develop software services that encapsulate these models and thereby leverage corporate knowledge for greater productivity.

6. Research Status:

This research will continue as a Ph. D. dissertation project.

Plans for future work include further investigation into the integration of product and process description for component models. To validate and compare the findings for control valves, a second case study will be performed. From these findings, the research will investigate a task-based view framework for a conceptual data model that improves support for product and process model integration.

We also hope to understand the potential business impact of software services based on such models by developing a new test case that demonstrates component object transactions using the World Wide Web. The test case will show access, retrieval, and use of component information objects for design and procurement between a component supplier and a user. The objects that are accessed from the supplier will integrate seamlessly into the user's CAD system or a project database management system. The test case will be implemented in Java to enable the creation of component objects that support the behavior and process descriptions developed in this report.

A STUDY OF THE LIFE CYCLE REQUIREMENTS FOR AN INFORMATION MODEL OF THE COMPONENTS THAT ARE INCORPORATED IN PROCESS FACILITIES

A REPORT SUBMITTED TO THE

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

(in fulfillment of Grant 60NANB4D1699)

James Andrew Arnold, Paul Teicholz
Stanford University

March 1996

Abstract

This paper reports the results of research that explores product modeling issues for components[1] that are incorporated in process plant facilities.

This project begins with an information requirements study that identifies the industry stake holders, the business and technical processes involved in component information exchange, and the life-cycle information requirements of a typical process plant component, the control valve. The findings for the study are described through a review of the business issues, and through a process description of the 'life-cycle' of a valve within a hypothetical project context. Through this case study, the research attempts to identify data and engineering knowledge that should be included in a component information model to support and improve business process.

In the final phase of the project, an information model and component selection test case for one component type is developed. Based upon the results of the information requirements study, the test case explores the integration of an explicit description of product data (including form, function, and behavior) and a task based process in a component information model. This model provides support for analysis and evaluation of component selection in an intelligent engineering application.

It is proposed that the integration of product and process description in a component information model makes it possible to develop information exchange technologies that can effectively support and improve business process. This approach is compared to other efforts that are being pursued within the research community and industry, e.g., the STEP/EXPRESS initiative and related efforts.

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[1] A component is defined as a simple (single part) or complex (assembled part) item that is normally manufactured and sold by a vendor and becomes incorporated into the facility. The term "component model" is used to differentiate this information model from "product model" which is used to model the facility itself. The terms "part" and "component" are used interchangeably, though we prefer the latter because it includes complex assemblies of simple parts. In a process plant, the components consist of such items as pipes, valves, pumps, fittings, etc. Clearly, there is a strong overlap in the technologies used for modeling components and products, and there are times when this differentiation is not appropriate. The business issues for vendors (who sell components) and E/C contractors (who design and build plants) are, however, significantly different. This, and the need to identify the special information modeling issues for components, requires that a distinction be drawn between component and product models.

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Introduction

Timely and accurate exchange of information about the components that go into process plants is an important business problem. Vendor knowledge, contingent upon the quality of engineering requirements provided by the customer, often determines final component specification for facility design and engineering, and the procedures for component installation and maintenance. The specification process for components requires extensive information exchange between product vendors, plant designers and engineers. This information, in turn, requires considerable effort to access, interpret, validate and transform so that the relevant data can be used for project documentation and the necessary fabrication, installation, operations and maintenance activities. Failures in the timely and accurate delivery of component information causes delays and uncertainty in the performance of tasks which, in turn, result in poor component selection, incorrect specifications, time delays and re-work, increased change orders, etc. These coordination problems increase the transaction costs between component vendors and customers, and between the other parties who need the information in the course of the facility life-cycle. Thus, improved methods for accessing, storing and using component information can have a significant impact on design and construction cost, time and quality.

The A/E/C industry faces unique organizational and information technology development challenges. Whereas businesses in the manufacturing and service sectors focus economic organization and deployment of scarce resources towards the design and efficient mass production of products and/or services, A/E/C businesses vary organization structure in terms of size and the participant mix on a project basis to design and deliver one facility at a time. Project organization, facility design and construction processes differ for each project according to the type of contract, mix of participants, project requirements, and by site constraints. Such constraints highlight the importance of developing effective, accurate, and system independent information models for the exchange of product data

The business problem outlined above is summarized by the following points:

- Component vendor knowledge, contingent upon the customer relationship, often determines final component specification, installation and maintenance procedures;
- Considerable non value-added effort is required to access, interpret, validate and transform vendor information into project documentation;
- For the vendor, there is considerable marketing cost to distribute information and maintain customer relationships;

- On complex projects with many participants (the normal case), the added effort increases the transaction costs of data exchange;
- In a fragmented industry such as A/E/C, standardizing the format of information content can help to reduce communication and coordination costs;
- Current information products and services do not improve business process nor provide added value for information exchange. In particular, they do not add value to the owner of the project for use of the facility.

Objectives

To understand the problem described above for the process industry, the research studies the business issues of component information exchange and the life-cycle information requirements for the components that are installed in process plant facilities. A second goal of this research has been to prototype a component information model and software application that explores the business problem for component selection in an intelligent CAD system.

To ascertain the business problems, the report begins with a review of organizational issues in the A/E/C industry that affect communication and coordination amongst project participants. Section 1.3 reviews the modes of electronic information exchange, including STandard for the Exchange of Product data (STEP), that exist or are proposed to support project coordination and communication. Also in this section there is discussion of the emerging paradigm of interoperable information exchange that is gaining popularity among application developers for the A/E/C industry.

The review of Standards initiatives includes work in the standardization of parts library data that is occurring in the ISO TC184/SC4, the UN EDIFACT, CIAG and elsewhere. Several industry consortia in the United States (PlantSTEP, PDXI, CIAG) and Internationally (PISTEP, SPI-NL, CAESAR-POSC) are investing considerable resources to define STEP for the process industries. These organizations are collaborating to develop two STEP Application Protocols; AP 221, process functional representation and AP 227, spatial configuration of plant systems. Also third effort, AP 231, that covers process engineering data is approved for development. In Part 3, a modeling methods analysis places particular focus on understanding AP221 and AP227. In addition, a separate ISO standard for parts libraries, ISO 13584, Standard Part Libraries (PLIB) is studied[2].

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[2] See Appendix B for a list of organizations.

Part 2 investigates the information requirements for components. It describes the results of an information requirements study performed with participants involved in the exchange of component information for process plants. The investigation focuses on a representative test case for one component type, the control valve. The study gathers information from the review of product data standards initiatives for the process industries just described, and through interviews with representative participants involved in component information exchange over the facility life cycle. The findings are described within the context of a hypothetical project that describes the 'life-cycle' of a valve.

From the findings for control valves, the key business and technical processes are identified that require component information during design, engineering, procurement, construction, plant commissioning, operations, and maintenance. The product data and engineering process requirements are categorized according to life cycle tasks and a set of terms that may be useful for generally describing the requirements for components. The findings indicate that a description of component behavior is an important requirement that is not currently modeled in the STEP efforts described above. To date, the ISO/STEP initiatives for the process industries focus primarily on modeling the requirements for facility design and procurement. These standards support only component form (geometry) and function characteristics. Component behavior is not currently modeled.

Also, the research proposes that it is possible to realize added business value from component information models if they integrate a description of component data (properties and behavior) and related engineering process. Such an information model can provide support for automated component evaluation and analysis software services.

Part 3 describes a test case that integrates an explicit description of product data and a task based process in a component information model. This model demonstrates the partial automation of preliminary sizing for a control valve. The implementation uses and extends an intelligent design environment called the Semantic Modeling Extension (SME), developed by others at CIFE [Clayton, Fischer, Kunz, Fruchter 1995]. Also, in Section 3.1.4 the report analyzes how the modeling methods for SME, AP 221, AP 227, and PLIB satisfy the information requirements that are identified in Part 2.

The purpose of the test case is to demonstrate the value added benefit of integrating a product and process description, and of representing behavior in addition to form and function in a component information model. It is contended that information models that provide these features are key to the development of software applications which can automate sub tasks, increase data reuse, provide design decision support and improve business process.

Part 1. Background

1.1 The Process Plant and the Facility Life Cycle

Process plants are industrial facilities in which material resources are transformed through engineering processes into a product, or into a material used in the fabrication of a product. Process plants include petro-chemical, energy and power, pulp and paper, sewage treatment, and food processing facilities.

The primary phases of the process plant life-cycle consist of the following;

- **Facility Planning**: the business plan for the facility and an implementation plan for the project;
- **Conceptual Plant Design**: the design of the chemical and energy processes used for the plant and the approximate layout of the major plant equipment to achieve these processes;
- **Detail Plant Design**: the detailed process design, the detailed engineering design, including the electrical, mechanical and piping, structural, and civil engineering disciplines;
- **Procurement**: the procurement of components and equipment that are installed in the plant;
- **Construction**: The procurement of construction services and the materials that are necessary to construct the facility. This phase also includes the determination of delivery schedules, review of specifications for installation and startup, and the delivery of plant documentation and warranties of performance;
- **Startup**: the steps necessary to start and test the processes in the plant to ensure that all portions of the plant operate correctly and at the rated capacities. Training of plant operations and maintenance personnel is normally part of this step;
- **Operations and Maintenance**: the scheduling of maintenance, determination of operating behavior, and inquiry regarding availability of replacement components or purchase of new equipment.

In section 2.21 these phases will be described in greater detail.

1.2 Organizational Issues in the A/E/C Industry

1.2.1 Factors Affecting Project Organization

Project organization for the design and construction of process plant facilities varies widely according to the economic risks and the participants involved with each project. Some of the factors that affect project risk include:

- **Project financing**: The level of capital investment by the owner and the related lost revenue penalties and costs associated with construction errors and/or schedule overruns which are born by members of the project team;

- **Time to Market**: Facility owners are increasing the demand for faster project delivery. On capital intensive projects, project development time is no longer a variable. It becomes a constant that cannot be changed. This factor puts significant pressure on engineering and construction professionals to work concurrently and to use technology to speed their work without reducing or compromising quality;
- **Standardization versus innovation**: The degree of design standardization versus innovation required by the process. Projects with high innovation often involve increased coordination among the project participants. This, in turn, increases the risk of design errors that require rework and places increased pressure on project schedules.
- **Project complexity and size**: On larger projects, the cumulative costs of errors and delays can present significant financial risk for the participants;
- **Regulatory bodies**: Country, State, and local regulation requirements and permit approval processes;
- **Labor**: Engineering/construction labor availability, costs and quality of work.
- **Resource costs**: The prevailing costs for construction materials and the products that are installed in the facility;
- **Client Requirements**: The client can specify that particular vendors be used, that a given approach to contracts and procurement be followed, etc.

Generally, the impermanent nature of project work, the high costs of performing it, and the fierce competition of open bidding promotes industry fragmentation and specialization of design and construction service providers. For projects with less risk, project organization will be market driven. For instance, the E/C may sub-contract much of the detailed engineering work to low bidders. It is not uncommon for this work to be sub-contracted internationally to countries where engineering labor rates are considerably lower than domestic rates. As project risk increases, the transaction costs increase in terms of sunk resources into coordination efforts and contract governance. In this environment, project organization tends to become more centralized. For example, the E/C would perform all design and engineering services in-house. Joint ventures provide another organizational form that distributes project risk.

The variance in project organization models helps to explain why IT systems in A/E/C organizations have developed into "islands of automation", and subsequently, why product information exchange is problematic. As a result, current modes of exchange fail to capture all the information that is required to satisfy the life-cycle requirements of facility owners and operators.

1.3 Information Exchange in the A/E/C Industry

This section provides an overview of the information exchange problem in the A/E/C industry. It summarizes the business problems and challenges that affect information exchange in project based organizations, and it discusses the modes of electronic information exchange that support project coordination and communication. The two primary extant modes of electronic exchange are file exchange (IGES, .DXF, STEP) and electronic transaction (EDI). In addition, this section discusses the emerging paradigm of interoperable information sharing.

The interoperable application paradigm is gaining popularity amongst applications developers and professionals within A/E/C. This section highlights the Industry Alliance for Interoperability (IAI) that is working to develop this paradigm, and summarizes the nature of its work.

1.3.1 The Current Exchange Model

Figure 1-1 depicts the predominant model for project information exchange. Participants in the facility life-cycle develop information using in-house software systems that often are incompatible between disciplines. Frequently, hard copy constitutes the media of exchange. Such materials are static and not computer processable. Electronic information exchange is static also since there is no automated coordination (active change notification between contingent design elements and/or version management). In addition, electronic exchange often requires translation, which increases the risk of information loss between systems. The potential errors in node to node exchange is a problem of N(N - 1) complexity. The current model does little to improve support for the iterative, change oriented nature of design and engineering practice; nor does it reduce the redundant generation of design knowledge from project to project. This model is low on the scale of the automation steps described below.

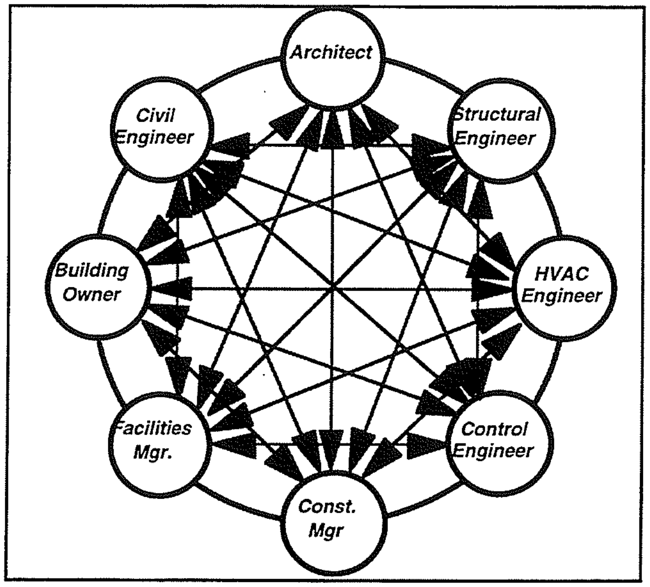

Figure 1-1. Node to Node Information Exchange

1.3.2 Levels of Automation

Figure 1-2 originates from a study on personal computer use performed by [Nolan, Norton & Co. 1987]. It describes four levels of automation and indicates its value added for business.

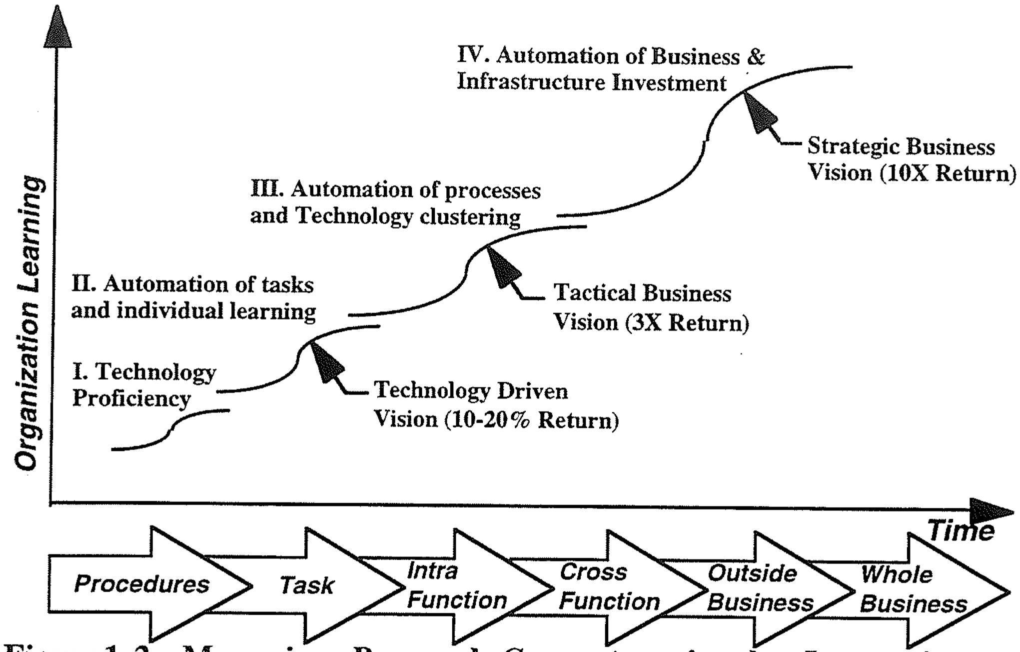

Figure1-2. Managing Personal Computers in the Large Organization, Nolan, Norton & Co.

The study advocates a monitored, incremental approach towards business automation to control risk. Nonetheless, the graph shows clearly that significant returns on technology investment occur at levels III and IV when organizations successfully automate work processes that cross functional and organizational boundaries. The current electronic information exchange model primarily supports level II automation. We shall see from the information requirements study that the status of component information exchange is consistent with this level of automation. Yet component information exchange involves the cross functional and inter-organizational communication where the greatest gains can be achieved.

1.3.3 Construction Component Information Services

To assess the status of electronic component information services, two providers, Autodesk®, Inc. and Information Handling Services® (IHS) were interviewed. In addition, the World Wide Web (WWW) was searched for on-line services. The following table highlight the benefits and drawbacks of these services:

The features of these services confirm that component information exchange products do not yet support improved business processes. The WWW search did show that component information is coming on-line. At this junction however, the available

Information Source	**Benefits / Drawbacks**
CD ROM	
IHS	18,000 mfrs. / 63,000 catalogs. Most are scanned images. No Structured Data except for electronic parts Searchable by Keyword
	Improves search time, but no value added for computer-based user work processes (IHS is working on ways to integrate their product data into work processes)
	Outdated information usage paradigm (bit maps of paper information cannot be understood by the computer)
Autodesk	AutoCAD serves as a productivity tool
	ME parts search able by component attributes
	.DWG format drawings available with component ID and specification attributes
	Value added limited to graphics and some product data
	Parametric generation of CAD drawings in future version
	Looking at on-line, but think market is not ready yet
On-Line	
A/E/C Info. Center	Structured documents, text, graphics Coverage; currently very low, but changing fast
Build.com	Integration with end-user work processes; low cost to access information
Others[3]	Interactivity; Medium. Users can control search, but can not do much with the acquired information
	Visibility; Low, Web sites can be difficult to find
Future	
Component Catalogs / Libraries with...	Interoperable objects with behaviors (foundation classes supported by industry and/or ISO standards)

Table 1-1. Construction Component Information Services

information does not integrate with end user systems or provide design decision support. With the phenomenal rate of WWW development and the advent of technologies that enable distributed, platform independent computing (e.g. Java), improved information services will be forthcoming.

1.3.4 Business Concerns

Information Issues

The interviews conducted during the information requirements study also identified the business issues for the participants involved in component information exchange. The following table relates the issues to participants;

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[3] See the WWW home page for this project, URL: www-leland.stanford.edu/~jaa/ressum.html

	Participants			
Business / Information Issues	Vendor	Information Integrator	Engineer/ Contractor	Facility Owner
Component Data Standards				
Nomenclature	X	X	X	X
Semantics	X	X	X	X
Interoperability	X	X	X	X
Cost of Modeling	X	X	X	X
Security				
Proprietary Info.	X	X	X	X
Financial Transactions	X	X	X	X
Data Longevity	X		X	X
Time to Market	X		X	X
Cost of Marketing	X			
Improved Maintenance	X			X
Remain closer to client over facility life-cycle	X			X

Table 1-2. Business Information Issues

All parties perceive the benefits and costs of standardization. The responses are consistent with contingency theory that standardization of business language reduces communication ambiguity, decreases the need for redundant communication, and increases information processing capacity [Galbraith 1977]. Similarly, all parties recognize the business value of information security. There is less consistency amongst the participants with respect to the remaining issues. It is worth noting that all the issues are relevant to the facility owner who ultimately drives the information requirements.

The Business Barriers

The business barriers to effective component information exchange include:

- Industry Fragmentation
- No Standards for data exchange
- Long term benefits of detailed information modeling conflict with modeling cost and short term business goals
- Differing levels of automation;
  - Low automation for some processes/companies
  - Many companies are not on-line
  - Lack of interoperability
- Belief that competitive advantage lies in proprietary knowledge;
  - Engineer/Contractor: technical expertise and cost estimation knowledge
  - Vendor: technical marketing
- CAD systems do not meet user requirements
- Organizational inertia;

- Embedded culture resistant to change
- Risk aversion
- Lack of understanding and training in new business processes
- Cost of converting to new business procedures and standards

While the business challenges are formidable, technologies that automate inter-organizational information exchange between vendors and users of components can provide significant benefits. New methods for communicating and using product information will affect project team structure and relationships with product vendors. The boundaries between customer and supplier may change as emerging technologies encourage new work processes. The use of electronic networks, e.g., Internet, could allow widespread access to product data and knowledge. As an example, it may become advantageous for engineering professionals to allow product manufacturers access to conceptual design models of facilities. Conversely, product manufacturers would allow design professionals instant access to their product information and fabrication data so that they may accurately estimate costs and delivery schedules. In this capacity, engineering professionals and product manufacturers will collaborate as team members to effectively achieve project goals for design, cost, quality, and schedule.

The following section describes the current modes of electronic information exchange and presents the basic concepts of the interoperability paradigm that is gaining popularity.

1.3.5 Modes of Electronic Information Exchange: file exchange and transaction processing

Drawing file exchange between design and engineering CAD systems is limited primarily to product geometry. Figure 1-3 shows the communication model between heterogeneous CAD systems. The primary CAD file exchange formats are;

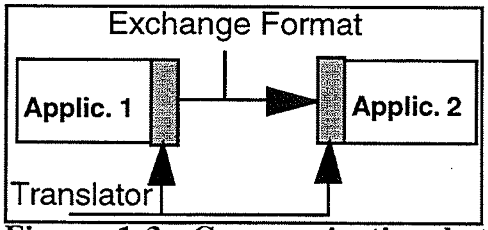

Figure 1-3: Communication between Heterogeneous CAD Systems

Initial Graphics Exchange Format (IGES)

IGES is an ANSI standard for the exchange of geometry and graphics data. The semantics are limited to geometric entities (lines, arcs, circles, etc.). Therefore, it is not capable of explicitly representing higher level objects such as components (doors, windows, control valves). As a result, usage problems stem from its semantic limitations. For example, 'semantic overloading' can occur when the same graphic entity represents two or more ideas.

Drawing Exchange Format (DXF)

DXF is a defacto standard published by Autodesk. It has gained widespread acceptance because of Autodesk's dominant position in the CAD marketplace. Like IGES, it is limited to geometry and graphics entities only. Also it shares the same semantic limitations.

AutoCAD Drawing (DWG)

In North America, Autodesk's penetration into the A/E/C CAD marketplace is so prevalent that DWG files are the predominant format for file exchange between parties who have AutoCAD. DWG files are smaller than DXF. For an AutoCAD only solution, all the information in the drawing can be retained during exchange. Some AutoCAD competitors have even added the ability to read and write DWG files. Nonetheless, DWG exchange has pitfalls as well. Since AutoCAD is highly customizable, it is very difficult to enforce guidelines or standards for drawing organization (layer names, line weights, font styles, block names, etc.). Thus, although DWG exchange is successful, the receiver often spends considerable time converting the drawing organization to an internal set of standards.

STEP

Recognizing the limitations of IGES, the ISO launched STEP in 1984 to replace it . Formally, STEP is described as;

> "...a neutral mechanism capable of completely representing product data throughout the life cycle of a product...The completeness of this representation makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing databases and archiving."
>
> [P.D.I.T. 1992]

Informally, STEP is a methodology and set of technologies for industry professionals to agree upon what to call things and how to describe them in an unambiguous, neutral and computer sensible format.

A STEP standard is defined by one or more application protocols (AP). An AP defines and scopes a specific industry need, documents the information requirements, provides a map from them to an EXPRESS [ISO IS 10303-11 1994] information model, and specifies software application conformance requirements for the standard. A suite of APs normally comprise an industry standard. AP 221 and AP 227 are the first two STEP standards for the process industry. For a list of APs related to A/E/C, See Appendix E. Figure 1-4 shows the relationship between the primary documents that constitute an AP and a STEP conformant software application.

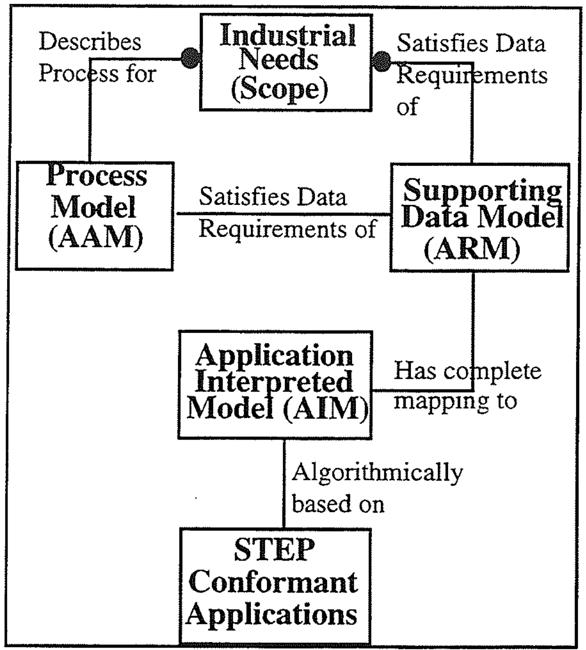

Figure 1-4. OMT[4] AP object relationships

- Application Activity Model (AAM). The AAM describes the processes for an industrial application. It is normally created using the Icam DEFinition method (IDEF0) [ICAM 1981] and is a tool for developing and validating the;
- Application Reference Model (ARM); an object model that defines the data, relations and constraints of semantic elements. It is normally created in NIAM or IDEF1x [NIJ 1989].
- Application Interpreted Model (AIM); an EXPRESS model developed from the ARM and the STEP Integrated Resources[5].

There is an explicit mapping between every ARM object and its AIM counterpart. The definition of the AIM from the Integrated Resources constitutes the basis for integration amongst a suite of APs.

Benefits and Drawbacks

STEP is a rational methodology for defining and agreeing upon nomenclature and semantics for domain objects, processes and resources. It provides a computer sensible, non-ambiguous and implementation independent representation of product data. To date, the scope of STEP standards within A/E/C are limited to descriptions of product geometry, function, and to some degree procurement requirements and product description change control. These features have the potential to improve communication through the exchange of product data semantics beyond product geometry.

STEP enjoys strong support in the aerospace, aeronautics, mechanical, electronic and automotive industries. In A/E/C, the process industry is developing STEP to enable data

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[4] Object Modeling Technique [Rumbaugh, Blaha, Premerlani, Eddy, Lorensen 1991]

[5] The Integrated Resources are domain independent EXPRESS schemas that may be referenced by an AP. The stage at which the they are brought into an AP is called Integration. This is a process during which STEP/EXPRESS experts analyze the ARM and apply the STEP Integrated Resources where possible.

exchange for all phases of the facility life cycle. STEP for architecture and construction lags these efforts. However work on information models for structural, HVAC, explicit shape representation and a construction core model is ongoing.

STEP follows an incremental development methodology and the design of STEP information models can support information sharing. However, STEP implementation tools primarily support static file exchange. The technology was initially designed for data integration, not data interoperation. It lacks support for concurrent design activities such as active change notification or automated constraint management. STEP file exchange does not guarantee against information loss. If two systems have a different conformance class approval, translation from the higher to the lower conformance class system will entail information loss. Last, STEP lacks support for object behavior, the formalization of design knowledge and object performance that is necessary for automated decision support and improved business process.

Transactions

Electronic Data Interchange (EDI) is a set of protocols for automating common business transactions. EDI is comprised of standard data forms, called Transaction Sets. Some examples follow;

Transaction Set No.	**Description**	Transaction Set No.	**Description**
832	**Price/Sales Catalog**	**810**	**Invoice**
850	**Purchase Order**	**856**	**Ship Notice/Manifest**
860	**Purchase Order Change Request**	**862**	**Shipping schedule**
830	**Planning Schedule**	**861**	**Receiving advice**
855	**Purchase Order Acknowledgment**		

Table 1-3. Transaction Sets

Along with Electronic Funds Transfer (ETF), transaction sets expedite the flow of information and funds necessary for the sale and procurement of products. Product information for EDI consists of product identifiers (catalog IDs) for inventory and control during a transaction. Transaction sets can explicitly model product data, however to do so requires customization between an individual supplier and purchaser.

To implement EDI two companies must agree to modify their existing procurement systems to a common format. Thus the motivation to comply is only as strong as the demand by a company's customers. Within A/E/C, EDI currently is limited to procurement of bulk items in large organizations. Nonetheless, at some point product model data may link to transaction set information to integrate the formal product description into procurement practice.

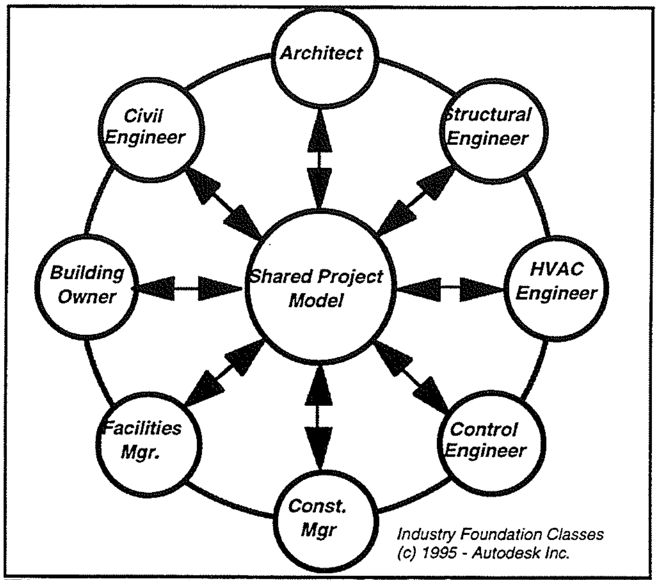
1.3.6 Interoperable Information Sharing

Object oriented software technology shows promise for providing the project coordination and design decision support features that are not yet available using file exchange technology. Several software vendors and A/E/C practitioners are working to move information models from geometry-based documents (or files) to design models comprised of real world objects. The 'interoperable information sharing' paradigm hopes to:

- Integrate object models by including in the object definition the geometry, relevant design and engineering knowledge, and industry-specific information.
- Support the life cycle information requirements.
- Share the project model between multiple software applications; Instead of file exchange, software applications will be able to access information directly from the objects that comprise the design model.
- Provide multiple views of the object data for various engineering and design tasks.
- Enable a dynamic project model. Constraint relations between persistent, integrated objects will make active coordination and control possible.

Integrated Object Models

Integrated objects will incorporate a description of form, function and behavior. These terms are developed in depth in Part 2 (see forward). Extending current STEP models that primarily describe form and function to a representation that includes object behavior, will enable automated design evaluation for a set of functional requirements. Behavior representations in information models will be a key feature for extending their business value by integrating them with design and engineering tasks and business process.



Industry Foundation Classes
(c) 1995 - Autodesk Inc.

Figure 1-5. Interoperable Information Sharing

Shared Objects

Sharable objects will support integration by allowing different software applications to access and use project data. To achieve integration, it will be necessary to understand and model the object content that satisfies the facility life cycle requirements. Published, standard programming interfaces to these models will be necessary as well so that software applications can add, delete and modify information. This is necessary for the representation of accumulated knowledge throughout the facility life cycle .

Dynamic Project Model

Automating coordination activities will be as important as information sharing. Explicit representation of relations and dependencies between design elements will support coordination goals. Consider moving a door. The position of the electrical outlet is dependent upon the position of the door. Normally, the change is handled manually. The architect moves the door symbol and the electrical engineer moves the outlet symbol. When communication involves a static model, an additional exchange is required. A dynamic information model would automate this dependency and, ideally, provide active notification for the change to the interested parties.

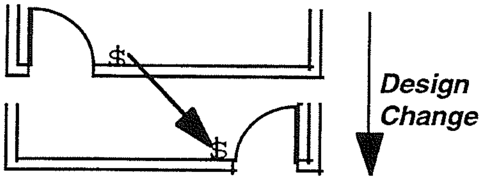


Figure 1-6. Design Change

1.3.7 Approaches to Interoperable Applications

Established in 1995, the Industry Alliance for Interoperability develops the Industry Foundation Classes (IFC) [IFC 1995]. The IFC are libraries of object classes that are commonly useful to an Industry. It is the hoped that they provide a “mechanism for object sharing, which (equals) interoperability across the boundaries of software applications” [IFC 1995]. The IAI enjoys growing industry support. Autodesk, which initiated IFC before spinning it off to the IAI, and Bentley Systems are members, as are several value added developers for AutoCAD and MicroStation. Over forty companies from several disciplines participate in the IAI and outreach to STEP, the Construction Specifications Industry (CSI), and several overseas organizations in Europe, Singapore and Japan is in progress. The IAI faces complex modeling challenges. Success depends upon the cooperative participation of all organizations. The key development concepts include;

Object Classification

This involves the development of a common nomenclature and semantics for real world design objects by teams of industry representatives and then published for industry. While the initial focus is on objects that encapsulate form and function, the ultimate goal is to include object behaviors that enable design evaluation. Success for IFC requires the involvement of industry and software vendors to specialize the core model. The IAI can benefit substantially from the A/E/C modeling foundation laid down within STEP, and extend it to support object behavior. Autodesk is developing IFC conformant products, as is Bentley Systems using Objective MicroStation technology. Further challenges that face the IAI include:

- Understanding the life cycle information requirements of industry domains (including the business issues and processes using this data);
- Understanding how behavior will be supported;
- Investigate technologies to extend and specialize core objects, and to link Mfr. data);
- Assure public object definition so that applications can access information from others that a user may not own;
- Develop standards for use and extension of class libraries with sharable interface to IFCs.
- Assure data integrity when transferring data models that are dependent upon libraries from one computer to another;
- Provide application compatibility across CAD platforms;
- Retain compatibility with legacy data and systems (if this can be done);
- Provide a mechanism to update class definitions as they become more mature over time.

1.4 Summary

Part 1 of this report describes the role of information exchange technology in the A/E/C industry. It is argued that distributed computing technologies (e.g. the Internet) and object oriented product modeling technologies may enable the A/E/C industry to overcome some of the problems associated with communication and coordination of information about components. For these technologies to have a positive impact, it is necessary that they be motivated by a strategic business vision in which the technology is used to automate task performance and change business process. To do this, it is necessary to understand the life cycle information requirements for the tasks and processes that involve components and to encapsulate the necessary design knowledge and object behavior in the object model. Models that explicitly represent such information are key to the development of software applications that can provide design decision support for task assistance and/or automation.

Part 2 reports the results of a study that investigates the life cycle information requirements for one component type, the control valve.

Part 2. Life Cycle of a Component

This case study describes a project scenario that identifies the product information for control valves that is needed during the various processes of the facility life cycle. The process descriptions that follow are important because they give insight into the information modeling requirements. These requirements can be modeled using various modeling methods. Part 3 of this report describes an implementation of a component model for control valves that satisfies a subset of the requirements identified below. It then is contrasted with other modeling approaches in light of these requirements.

2.1 Methodology for the Study

The study was conducted through interviews that were conducted with industry professionals who take part in component information exchange, and through ongoing dialogue and email exchange with individuals involved in the development of product modeling standards for the process plant industries. The primary participants involved in part information exchange for the A/E/C industry are shown in the diagram below;

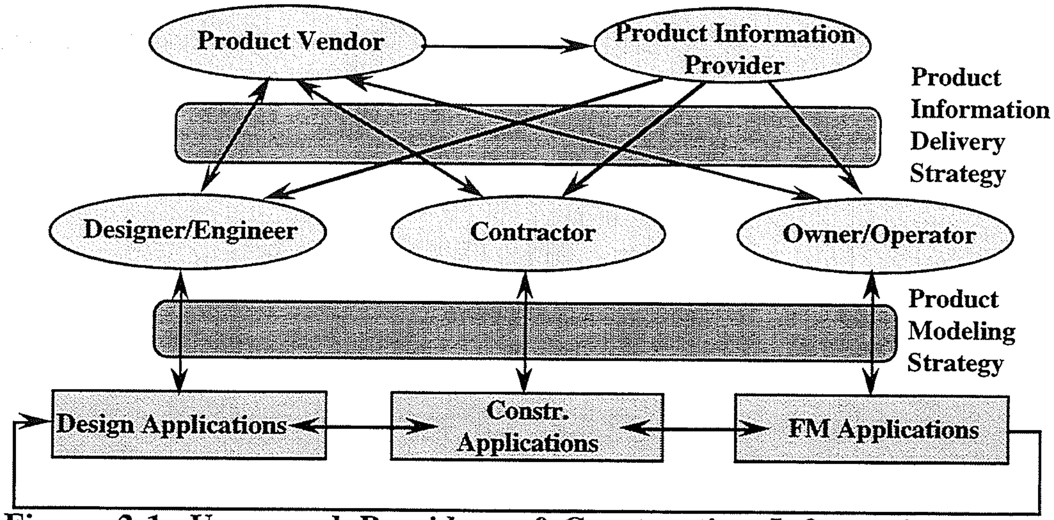


Figure 2-1. Users and Providers of Construction Information

2.1.1 Facility Life-cycle Coverage

The interviews were conducted with thirty-eight individuals representing 12 companies. They were conducted on an informal basis, guided by a question list developed for each company type. The intent of the interviews was to gain an overall picture of the relationship between business process and information development for the components that are installed in process plants. The interview questions included inquiries about tasks that the participants perform, the information they require, the views of the data that they have, how they use it, what media they use to exchange the information, and what software tools are used to process it. The responses were recorded in note form during each interview. The types of companies included in the interviews included;

- 3 engineering/construction firms that perform process plant work;
- 2^+ valve manufacturer/vendors (2 manufacturers, 1 vendor/distributor);
- 2 product information providers;
- 3 Facility owners;
- 1 EDI Vendor.

See Appendix A for a list of the companies involved in the study.

In addition, information was gathered through a survey of current industry initiatives to create standards for the exchange of product information. See Appendix B for a description of these initiatives.

2.1.2 Analysis method

The IDEF0 process modeling method [ICAM 1981] describes the processes. This diagramming methodology provides a process decomposition technique that characterizes processes and functions in terms of inputs, constraints, outputs and mechanisms.

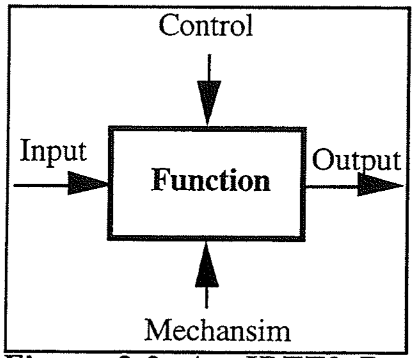


Figure 2-2. An IDEF0 Box

Within the IDEF0 framework, the top level diagram shows the entire process plant life-cycle in terms of six major processes. This diagram derives from the Integrated Building Process Model developed by [Sanvido, et al. 1994] and from the process model diagrams in the draft standard [ISO CD 10303-227 1995], Plant Spatial Configuration. The project scenario description decomposes five processes, Facility Design, Procurement, Construction, Commissioning and Maintenance to a level of detail where it is possible to identify the information characteristics necessary for valve sizing, selection, procurement, installation, commissioning and maintenance. This exercise identifies the processes, constraints, participants (in terms of mechanisms), and views of the data (in terms of inputs and outputs) that each participant has relative to part information exchange for valves. In

Section 2.4 the information requirements that are derived from this process description are categorized according to component properties, behaviors, task coordination dependencies and administration attributes.

2.1.3 Purpose

The case study describes a project scenario which identifies the product information in a broad sense (data, knowledge, behavior) that should be represented for valve components. This information should satisfy the requirements of the individuals who use the information during the various phases of the process plant life-cycle.

2.2 Case Study Project Description

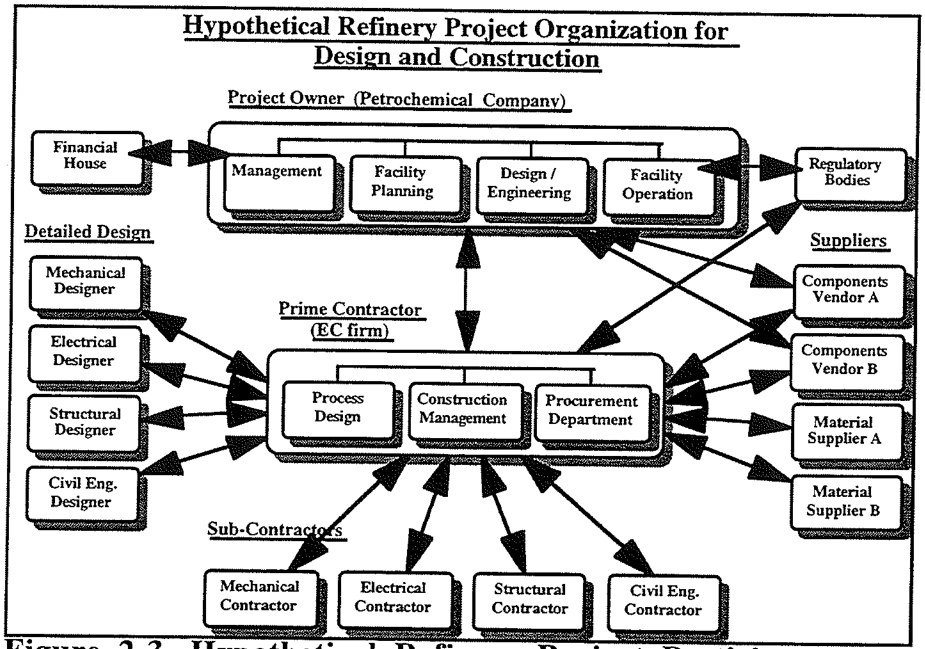


Figure 2-3. Hypothetical Refinery Project Participants

Based on the information acquired through the interviews, a Hypothetical Refinery Project (HRP) was created. The plant under design will be owned by a major petro-chemical company. Its purpose is to process crude oil into various fuels such as gasoline, jet and diesel fuels and as other petro-chemical products such as many types of lubrication oil. The plant is built on water-font land owned by the project owner. Figure 2-3 describes the top-level organizational structure that manages activities in the facility life cycle. The entire project is financed by a credit line provided from a bank to the project owner.

The bank hires a consulting engineering firm to evaluate the economic and technical feasibility of the owner's plan for this project. The owner signs a contract with a large engineering firm that performs design and manages construction of the facility. During the design stage, the general engineering firm subcontracts the detailed design to specialty engineering firms in each discipline. The actual construction activities are performed by a general and sub contractors. However, the design engineering firm manages material procurement and coordinates the subcontractor's work. Upon completion of construction, the facility is handed to the owner for operation.

2.2.1 Functional Process Model

An IDEF0 process model for the HRP, see below, identifies the information requirements for each activity during the facility life cycle. The following section identifies the key stake holders in each phase of the process plant life-cycle. Section 2.3 analyzes the detailed activities in the design, procurement, construction and maintenance phases to identify the information requirements of each stake holder for valves.

Life-cycle of a Process Plant

Figure 2-4. IDEF0 node A0 (see forward) describes the entire facility life-cycle of the HRP. It consists of six phases; Plan Plant Project, Design Plant, Procure Components, Construct Plant, Commission Plant, and Operate and Maintain Plant. A brief description of the parties involved in each phase follows.

Plan Plant Project (Figure 2-4. IDEF0, node A1)

According to the business needs and general philosophy for the project, this phase defines the scope of the project and identifies the overall requirements for the facility to be built. The outputs of this phase include basic documents for the project such as a financial plan, a project execution plan, and the design scope.

The key stake holders in this phase include the management, facility planning team, process design and engineering team of the owner, the financial houses, bonding and local government agencies.

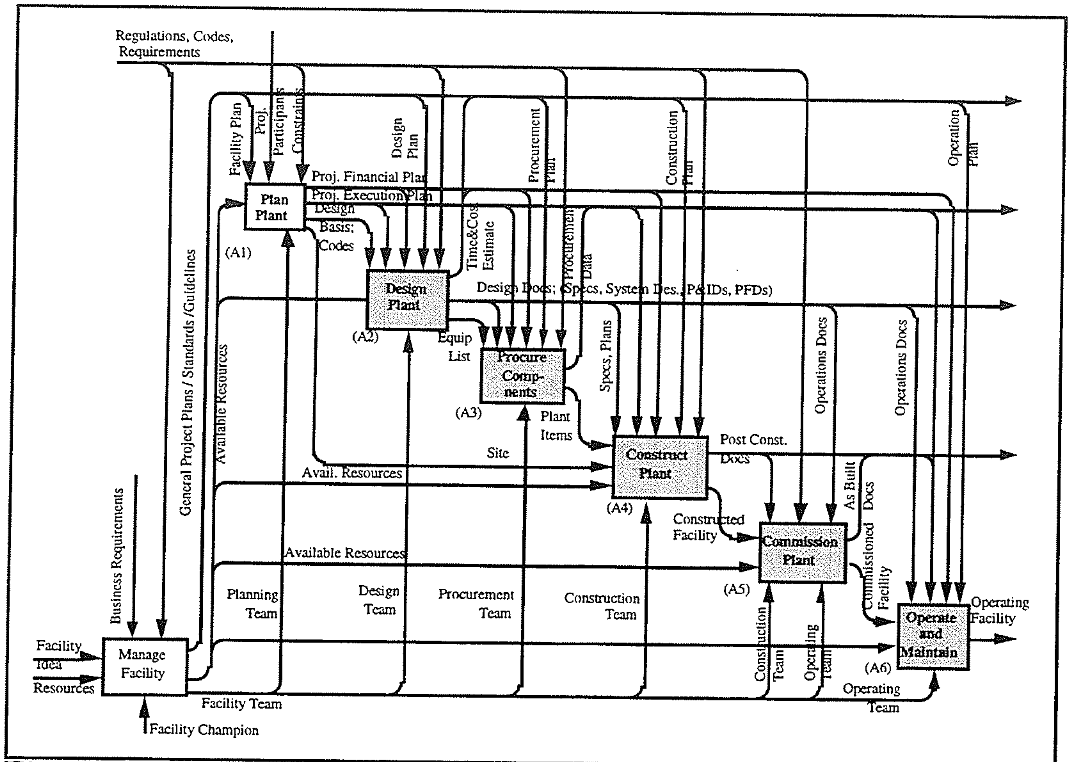


Figure 2-4. IDEF0 node A0, Provide Plant

Design Plant (Figure 2-4. IDEF0, node A2)

Based on the plans and the design basis produced in the planning phase, the design phase produces construction documentation for the facility. The facility is specified in detail, and the required components and equipment are identified. In section 2.3.1 the design phase is decomposed into four traditional sub-processes; conceptual and detailed process design, and conceptual and detailed engineering. The Design team performs the conceptual process design and solicits information about materials and components from vendors and suppliers to determine the process details of the plant. This phase produces an approximate plant design and the estimated cost and time based on the business requirements identified during the planning step. Once the schematic design is set, it proceeds into the detailed design phase. The detailed design team consists of the design and engineering function in the owner's organization and the design division of the selected prime contractor.

The prime contractor subcontracts the detailed engineering activities to specialized engineering firms. Various regulatory bodies provide constraints and guidelines for the design of the facility through standards, regulations and design codes. The output of this phase is a set of detailed plans, specifications, and a schedule.

Procure Components (Figure 2-4. IDEF0, node A3)

The procurement of components and equipment constitute a significant part of process plant projects. Normally at least 60% of the cost of the plant is represented by the material and equipment used for the plant. In this phase, the owner and/or prime contractor selects vendors and procures the components and equipment for the planned facility. The key stake holders in this phase include vendors, the facility owner, and the prime contractor's design, procurement and construction management team.

Construct Plant (Figure 2-4. IDEF0, node A4)

According to the design and the specifications, the procured items are assembled and installed during the construction phase. The output of this phase is the erected facility and post construction documents that contain the information necessary to maintain and operate the facility.

Stake holders in the construction team include the construction management team, the procurement department of the prime contractor, the specialized subcontractors, the component vendors and the material suppliers. The owner's construction management team includes the facility planning function, and the design / engineering functions. This team provides overall control and management services to monitor the prime contractor. Construction activities are regulated by the safety and construction codes provided by regulatory bodies.

Commission and turnover Plant (Figure 2-4. IDEF0, node A5)

During this phase the construction contractor must prove the operation of all plant systems defined by the detailed design specifications and reconcile any differences between the specifications and as-built conditions. Commissioning normally proceeds in stages from tests using inert materials to the use of the production stream. Upon satisfactory process unit testing, the plant owner accepts the facility for operation.

Operate and Maintain Plant (Figure 2-4. IDEF0, node A6)

The completed plant ready for operation is turned over to the owner's facility operation team. While running the facility the operation team provides necessary maintenance and retrofit services through vendors and contractors on a periodic basis and as needs arise. The operation of the facility is regulated by corporate requirements, standards and regulatory codes.

2.3 Information requirements for Valves

From the overall description of the facility life-cycle, the requirements study focuses on a functional description of control valve sizing, material selection, procurement, installation and maintenance. The goal is to identify the objects, object properties, stake holders, and processes that are necessary to characterize the requirements for a valve component information model.

Valves are devices that control the flow of a stream in a process system by introducing and modulating pressure drop within the valve body [Chevron corp. 1993]. The function of a valve is either to block flow or to control it by means of a throttling mechanism. The conditions under which a valve performs this function varies with the process under consideration, the environment in which it is placed, and the service requirements. The definition of the process, the system that supports it, and subsequently the specification of the equipment that meet the system requirements for process control, occurs within the phase labeled Design Plant (IDEF0, node A2) on Figure 2-4.

2.3.1 Description of the Valve Sizing and Selection Processes

Figure 2-5. IDEF0, node A2 represents the detailed activity decomposition for the design phase.

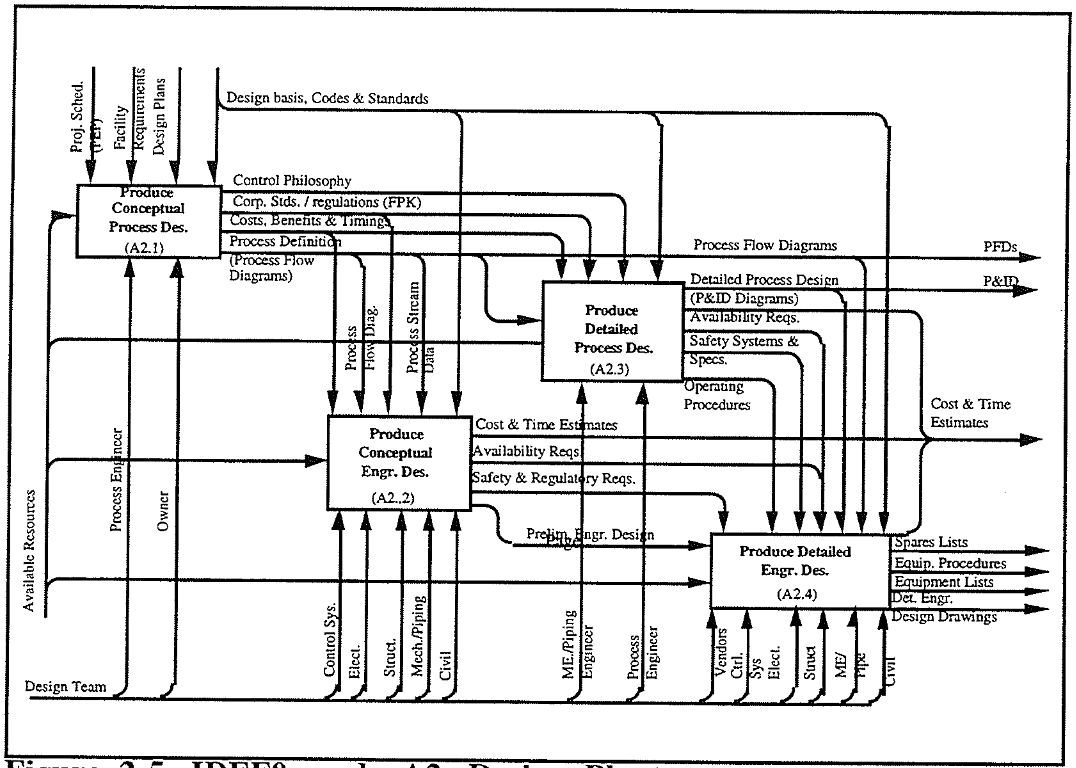


Figure 2-5. IDEF0, node A2, Design Plant

The design phase separates into four sub-processes; conceptual process design, conceptual engineering design, detailed process design, and detailed engineering design (IDEF0 A2.1-A.2.4) On a real project, one or more of these phases may be combined or compressed due to time to market constraints. For the purposes of the study, the four traditional sub-phases remain to articulate the work flow and the information needs and uses that are necessary to size and select valves.

The following discussion about sizing and selecting a valve is drawn from [ISA-S75.01 1991], [Chevron corp. 1993], and [ISA 1976].

Definition of Stream and System Data

During conceptual process design (IDEF0 A2.1), the prime contractor's process engineering group develops the technical definition for the overall plant requirements and identifies candidate processes that fulfill them. The outputs of conceptual process design include [PISTEP 1994]:

- the required unit operations for the plant;
- the process stream properties and composition;
- energy/mass balance equations for the system;
- the control philosophy;
- process flow diagrams which document the process definition, the stream definition, and the control philosophy;
- a cost, benefits and timings analysis;
- the safety and regulatory requirements.

The need for control equipment, such as a valve, may be indicated at this stage, but the specifics of how control is achieved and the equipment configuration that will enable control is not articulated until the following stage, detailed process design. Nonetheless, the stream data and the process definition developed in this phase provide the system requirements for sizing and selecting valves. For a given valve, this information consists of the stream data below.

Stream Information

- Chemical composition
- Phase
- Fluid pressure in pipe
- Vapor pressure
- Density
- Viscosity
- Temperature
- Specific gravity
- Min. steady state controlled flow rate
- Max. steady state controlled flow rate
- Max. flow rate to recover from a flow disturbance

Information Media

The media used to record the design information include the Process Flow diagrams in CAD format, process specifications (text documents), and a preliminary engineering equipment and project management database. The level of integration between these documents varies. Most engineering firms maintain links between a project equipment database and the CAD drawings. However, there may not be electronic integration with project management and procurement systems.

Participants in Exchange

The participants in the conceptual process design phase include the process engineer of the E/C firm, and the design/engineering and project management representatives from the owner team. These participants normally exchange the information in hard copy format. This form of exchange is typical of inter-organizational information exchange.

Valve Sizing

Valve sizing occurs in the detailed process design phase. Figure 2-6. IDEF0, node A2.3.X describes valve sizing.

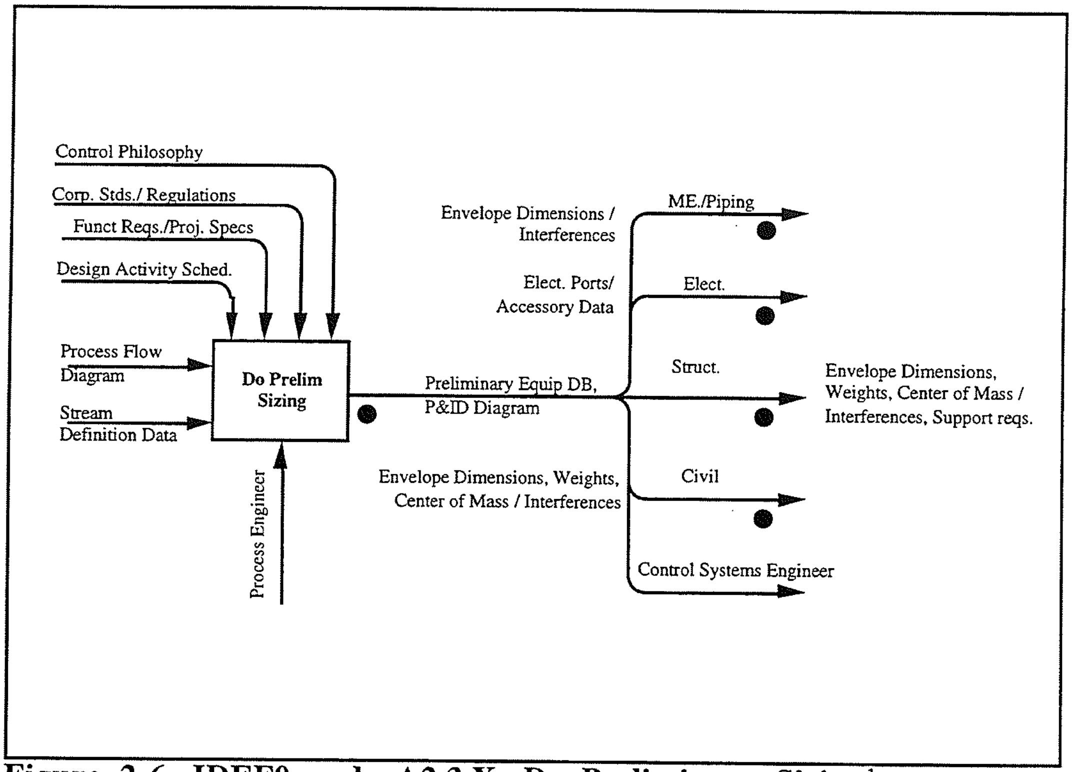


Figure 2-6. IDEF0 node A2.3.X, Do Preliminary Sizing[1]

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[1] The dots in the IDEF0 diagram indicate bi-directional information flow.

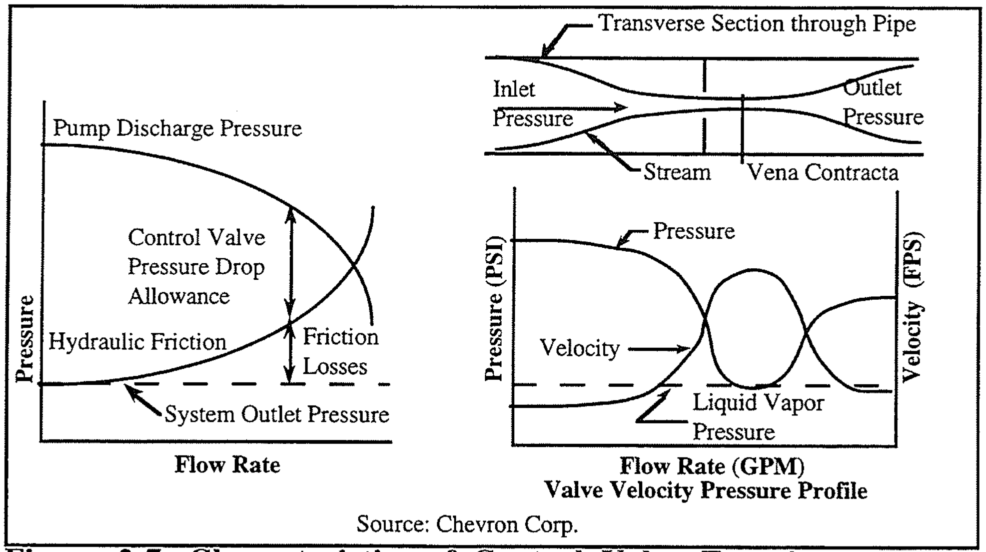
In this phase the specifics of the piping system are designed and the piping system equipment is identified and sized. In addition to the stream data, the pipe information that is necessary for sizing a valve includes:

- Valve inlet and outlet nominal pipe diameter and swages is applicable;
- Applicable design code (ASME);
- Piping specifications (schedule, class and flange rating) for compatibility of design;
- Environmental constraints in the form of electrical hazards, climate, atmospheric contamination, and plant procedures (wash down and decontamination).

Sizing Process

The process of sizing a valve involves understanding the valve's role as an energy consumer in a thermodynamic system. A valve functions by "consuming" the pressure of a stream passing through the valve body.

Usually an energy provider, such as a centrifugal pump, induces a stream to flow in a pipe by introducing pressure into the system. The pressure in the pipe is a function of the flow rate of the stream, the head to be overcome and losses due to friction. The pressure drop caused by friction losses increases with the square of the increase in flow rate.



Source: Chevron Corp.

Figure 2-7. Characteristics of Control Valve Function

A valve should be sized to consume "whatever pressure drop is available to maintain a system at a set point" [Chevron corp. 1993]. Looking at the diagram above, one observes that at high flows, a valve does not have to consume as much pressure to control the flow. This diagram demonstrates that it is necessary for a valve to operate across a range of operating flow conditions. To determine the correct valve size, the process engineer determines the required pressure drop capacity of the piping system for minimal, maximal and upset condition flows[2]. Then the engineer selects a valve with the right service characteristics and capacity factor that matches the requirements across the specified range. Normally, a valve will be sized to achieve effective control over a range from the minimum flow -5% to -10%, to the maximum flow +5% to +10%. This range is called the "rangeability" of the valve.

Engineering Considerations

Because the valve causes a pressure drop in the system for a given stream velocity, one must calculate whether the pressure drop will fall below the vapor pressure of the stream for its operating range of temperatures and pressures. If this occurs, cavitation or flashing may occur. Cavitation is a condition where the stream changes state from liquid to vapor in the valve (see Figure 2-7 above). When the system pressure recovers after exiting the valve body, the stream's vapor bubbles collapse, causing cavitation. If the valve outlet pressure stays below the stream vapor pressure, flashing will occur. Either of these conditions will cause noise, vibration and ultimately damage to the valve and pipe.

The capacity index of a valve for a given set of stream conditions is called the coefficient of flow, or C_V. There are standard calculations for determining the C_V for a valve dependent upon the type of flow (laminar, turbulent, or transition), the inlet and outlet pressures, the flow rate, the specific gravity of the stream, and upon any differences between the piping geometry and the valve body inlet and outlet diameter [ISA-S75.01 1991].

Process Summary for Control Valve Sizing

To summarize the valve sizing process, the process engineer accounts for a range of performance properties of the valve that are dependent upon the thermodynamic characteristics of the process stream and upon the piping system geometry. Thus the information that is necessary to support valve sizing should include the valve form (geometry and size), the valve function, and knowledge which describes valve behavior based on a range of functional conditions, or states, of the process fluid and pipe system.

Information Sources

When the process engineer performs the initial valve sizing, he/she may consult a part database maintained by the procurement department to obtain information about which valve to select. Alternatively, he/she may consult an in-house library of manufacturer's

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[2] An upset condition is a disturbance that causes one or more operating parameters to fall outside of its design range.

product literature. In addition, most valve manufacturer's and many database system vendors (e.g. Oracle) provide software applications that automate valve sizing and selection and link the results into the engineering management database system. Currently, these applications are not yet integrated into the CAD systems in which the engineering teams develop the process design and detailed engineering documents[3].

Information Media

When preliminary sizing is performed, a rough specification for each valve is developed and entered into an equipment list program linked to an engineering management database. In addition, the process and instrumentation diagram (P&ID) is developed during detailed process design and some valve information is indicated on these drawings. At this point each valve is given a unique project identification code that is referenced on the drawings. If further valve information is available at this stage, it is shared with:

- Mechanical engineering/piping: valve envelope dimensions and required clearances for maintenance.
- Structural engineering: valve weights, center of mass, mounting styles and positions.
- Civil Engineering: valve weights, center of mass.
- Electrical engineering: electrical ports and hookup requirements.

Participants in Exchange

Once the capacity of the valve is sized correctly for a piping system and stream, the process engineer hands the valve material specification to the control systems engineer who develops a complete specification for the valve with respect to its required service condition. In the HRP scenario, this hand-off would involve exchange of the piping system functional information through hard copy drawings and database reports, or by translation of the electronic data from the process design data management system to independent systems maintained by each of the detailed engineering sub contractors. Electronic translation of this information carries the data exchange risks described in Part 1. The process plant STEP development efforts (see Part 3) are addressing this issue.

Valve Material Selection

Valve material selection occurs during the detailed engineering phase. Figure 2-8. IDEF0 node A2.4.X details valve material selection.

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[3] The difference between these software applications and model based behavioral reasoning is explored in Part 3.

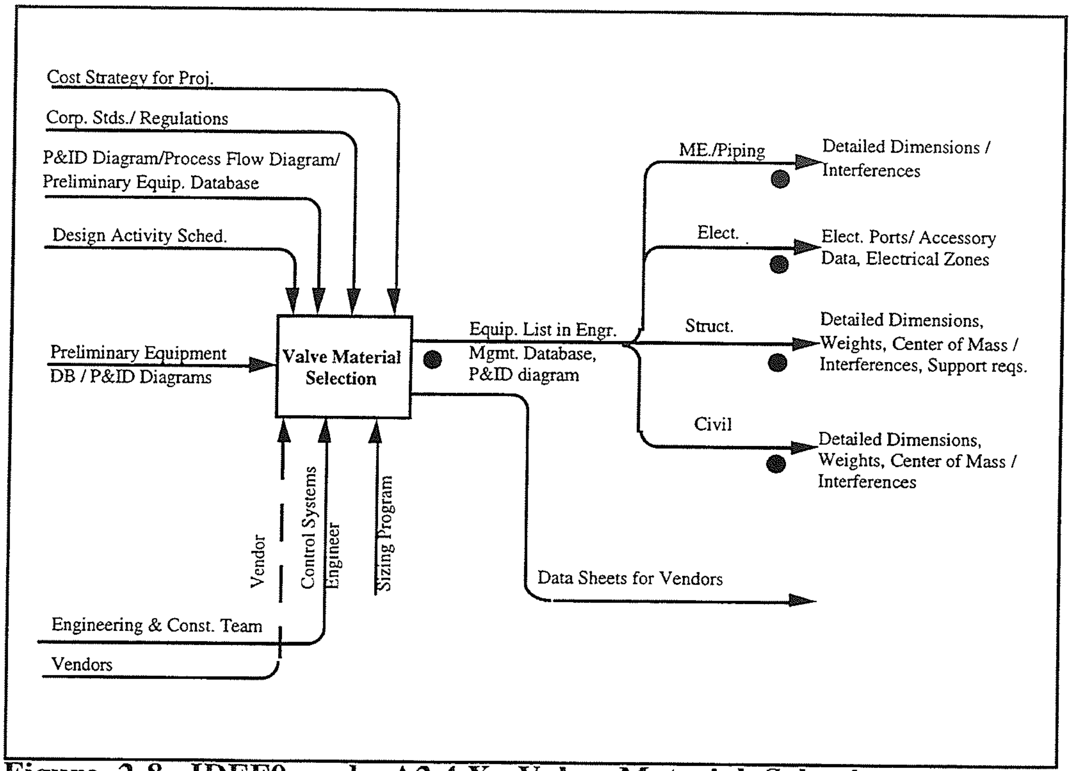


Figure 2-8. IDEF0 node A2.4.X, Valve Material Selection

Valve material specification includes the determination of:

- **Valve body;** Id (Tag), nominal diameter, ANSI class, material, end connection type, no. ports, Travel direction to open, flow direction
- **Trim;** Id, cage material, bushing material, seat ring material, valve plug (material, guiding type, balance type), port size, opening characteristic (see trim discussion below), shutoff class
- **Bonnet**; style, boss size, packing (see packing discussion below), bolting, bonnet, packing Flange
- **Actuator**; size, style, air to actuator, valve action on air failure, hand jack position
- **Positioner;** type, input signal, accessories, valve action on signal increase
- **Transducer**; input signal, output signal, action, mounting, airset, certification, explosion-proof approval, intrinsically safe approval
- **I/P Positioner**; certification, explosion-proof approval, intrinsically safe approval

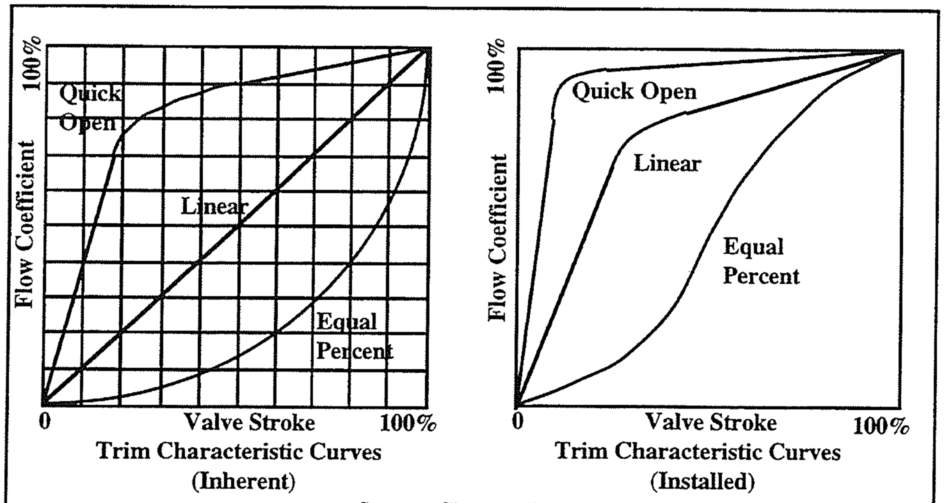
Several of these items depend upon the service requirements for the valve. The thermodynamic portion of the system requirements have been discussed above.

The valve material should satisfy the requirements of the process fluid for resistance to corrosion and erosion. Normally, the valve body material will match that of the process pipe material.

The selection of trim is critical for establishing the type of control the valve shall provide. Trim are the materials within the valve (the plug, seat and cage) that come into contact with the process fluid and provide the control function based upon the change in position (travel) of the trim within the valve. Valve travel ranges from fully open to fully closed. There are three primary trim characteristics for control valves [Chevron corp. 1993]:

- Quick opening trim is used primarily for on-off service. It enables a maximum change in flow rate at low valve travel.
- Linear opening trim provides control where the flow rate change is directly proportional to the valve travel.
- Equal percent trim provides control where equal increments of valve travel produce equal percentage change of flow.

The diagram on the left below shows the ideal, or inherent, flow characteristics that result from each type of trim;



Trim Characteristic Curves (Inherent)

Trim Characteristic Curves (Installed)

Source: Chevron Corp.

Figure 2-9. Ideal versus Actual Control Valve Performance

In reality, friction losses in the system due to rust accumulation produce different behaviors once the valve has been installed and the system is up and running nine months or more. The diagram on the right shows the installed characteristics. With time, equal percent trim behaves more like linear trim. Linear trim, in turn, behaves more like quick opening trim. Depending upon the "burn in" time for the system and the relative cost of different trim characteristics, it may be advantageous to select equal percent trim for a service condition which requires linear flow control. The change in flow control performance due to trim deterioration demonstrates that the information requirements for selecting materials include the representation of the changes in the material's behavior across time as well as inherent behaviors when first installed.

There are further considerations for selecting valve trim that are not be discussed in this paper. What is important to note however, is that the rationale for material selection is based upon design criteria that, in turn, are predicated upon assumptions concerning the required service conditions and upon applicable business rules (environmental standards, etc.). This point is also valid for the other materials listed above. As an example, a brief discussion concerning the factors that affect the selection of the valve packing material follows.

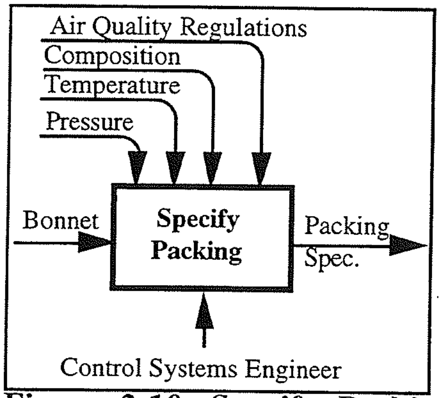


Figure 2-10. Specify Packing

Valve packing prevents leakage of process fluid past the surface of the valve stem or shaft. In addition to the fluid composition, and the operating temperature and pressure, the material construction of the valve stem should be considered when specifying the packing material [Chevron corp. 1993]. The selection of packing material is particularly important with respect to federal regulations for fugitive emissions imposed by the Clean Air Act of 1990. The specification of packing materials for valves in petro chemical applications are largely driven by these regulations. This example demonstrates another example of how government regulations affect the design assumptions required for a set of service conditions.

Material Selection Summary

These examples demonstrate how an information model, to effectively provide design decision support, should be capable of explicitly representing assumptions about service conditions, the applicable business rules, and also, how changes in these factors over time affect design criteria.

This discussion of the parts which comprise a valve also make it evident that an information model, to effectively support the maintenance and operations life-cycle phases, should explicitly represent a component's constituent parts. Section 2.3.5 discusses some of the typical problems affecting control valve component parts and the information requirements that should be satisfied for the maintenance phase.

Information Sources

When selecting valve materials, the control systems engineer consults vendor product catalogs and often contacts a vendor sales representative directly for decision support. In most circumstances, the information exchange occurs via hard copy. In some companies, vendors are beginning to provide this data in electronic format however, as described previously, no product data exchange standards exist yet to facilitate exchange.

Information Media and Exchange

The control systems engineer records the valve specification onto a data sheet and also may enter the information into the engineering management database. Valve class sheets for a project are generated from the database. This system will normally be linked to an integrated project management system that tracks procurement and field management functions. While these database management systems enable the information to be shared within the prime contractor organization, it should be remembered that exchanging it with sub-contractors requires translation to separate systems for each participant. The specified valve information is shared with each of the engineering sub-contractors:

- Mechanical engineering/piping: detailed valve dimensions and required clearances for maintenance.
- Structural engineering: final valve weights, center of mass, mounting styles and positions.
- Civil Engineering: valve weights, center of mass.
- Electrical engineering: electrical ports, hookup requirements, and safety requirements for electrical zones.

After valve selection is complete, the procurement department uses the information to expedite the procurement process. The following section describes the procurement phase.

2.3.2 Process Description for Valve Procurement

Figure 2-11. IDEF0 node A3 depicts the procurement phase of the facility life-cycle that relates to control valves. With respect to valve information requirements, the emphasis in the procurement phase is the exchange of technical data between the engineering firm and the valve vendor to successfully negotiate and transact a purchase agreement. Ideally, no new process data or project planning information is required during this phase.

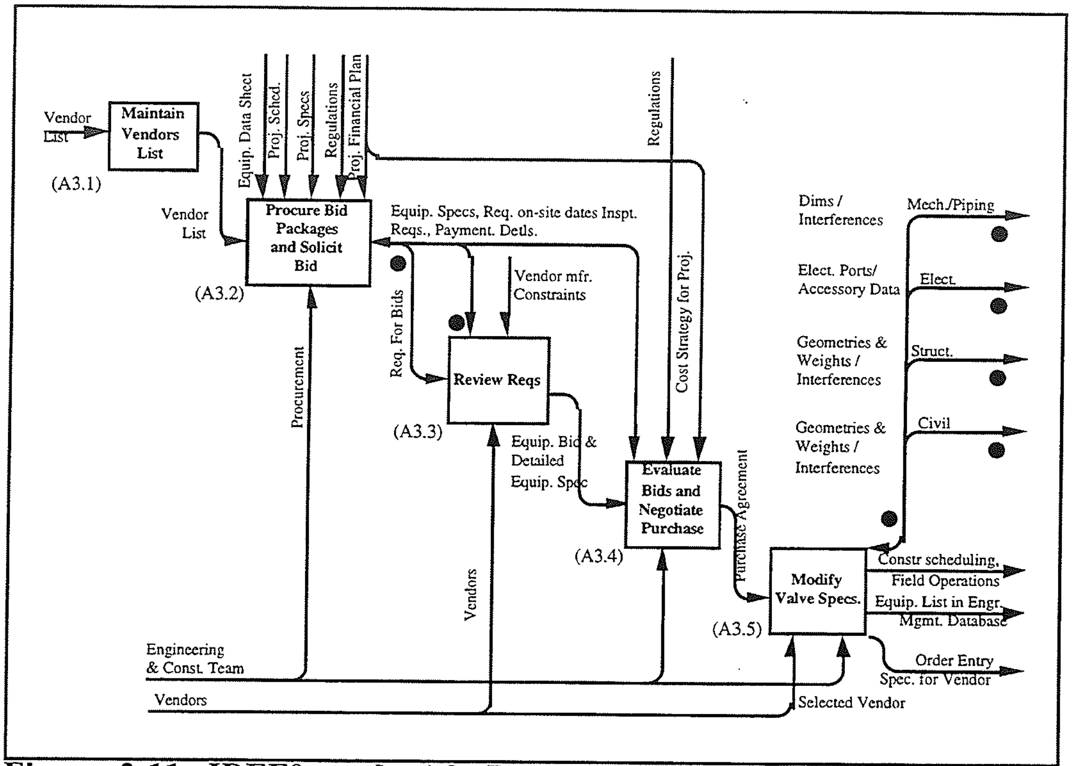


Figure 2-11. IDEF0, node A3, Procurement Process

Nonetheless, both the engineering firm and the vendors allocate resources to validate the information they receive from one another. In addition, it shall be shown that the specification for the valves used in the project often changes as a result of vendor review of project documents. The validation effort by both parties and the re-specification of valves by the vendor represent non-value added or redundant effort. Historically, this double work is due to the open bidding process and design responsibility liability for the design engineering firm. The entire procurement cycle for valves can consume from eight to twelve weeks of project time. Some firms are correcting this problem by instituting new procurement procedures, in the form of vendor alliance agreements, to eliminate the non-value added effort. Such agreements have been shown to reduce valve selection and procurement costs by half. These agreements redesign the procurement cycle by shifting responsibility for valve specification and selection onto the vendor. However, some firms have not yet entered into vendor alliance agreements. In addition, these work process changes have not yet carried over to interoperable exchange of electronic design documents and interoperable IT systems. Such automation has the potential to effectively place the vendor knowledge on the desktop of the design engineering firm.

Within the traditional procurement phase five sub processes are identified. They are briefly described below:

Maintain Vendor List (Figure 2-11. IDEF0, node A3.1)

The E/C firm's procurement division maintains a list of vendors with which the company does business. One aspect of maintaining this list is to keep an updated database of vendor pre-qualifications, product offerings, product availability, technical data sheets, and prices.

On many projects the facility owner specifies an approved valve vendor to assure consistent standards for plant equipment. In this case, the E/C works directly with the vendor to specify the valves for the project and forgoes the traditional bid process.

Procure Bid Packages and Solicit Bids (Figure 2-11. IDEF0, node A3.2)

When no vendor is mandated by the facility owner, the procurement department assembles the valve specifications (data sheets), the project specifications, the process flow diagrams and process and instrumentation diagrams (PFD and P&ID), the project schedule, and the regulatory, test and contractual requirements into a Request for Bid package. The bid package is the information exchange media used to solicit bids from qualified vendors.

Review Requirements (Figure 2-11. IDEF0, node A3.3)

After the vendor receives the bid package, it thoroughly reviews the valve data sheets and develops a bid based upon the information provided. Currently, most of the data exchange between the engineering firm and the vendor is accomplished using hard copy. Some valve manufacturers are developing systems that facilitate electronic exchange of the technical data for order entry, and they provide some product information back to the prime contractor in electronic format. However, once again, there are no published standards available yet to guide the development of these systems.

Evaluate Bids and Negotiate Purchase (Figure 2-11. IDEF0, node A3.4)

After the vendor submits a bid, the prime contractor reviews it. The procurement department receives the bid from the vendor and passes it to the design team consisting of the engineering firm's control system engineer and construction management personnel, and the owner's technical representatives. After reviewing the bids, the team selects a vendor.

Modify Valve Specifications (Figure 2-11. IDEF0, node A3.5)

Finally, after a vendor is selected, the interested parties finalize the order entry. Since the vendor specializes in knowledge about the product, it often recommends changes to the valve specifications. This can be an iterative process between the engineering firm and the vendor.

Analysis of the Procurement Process

Within the traditional procurement process one observes that valve specification may occur up to three times; during plant design, during the RFP vendor revue, and last, when all the parties agree to the final order entry. Alliance agreements effectively redesign the procurement process to reduce much of the redundancy. These agreements are driven by the fact that often vendor knowledge, dependent upon the quality of the documents provided by the engineering firm, ultimately determines component specification.

A life-cycle information model for components that can represent technical project data, component behaviors, design criteria and the business rules that determine product selection, may ultimately enable the encapsulation of vendor knowledge into information objects. One day, such objects may be capable of reducing errors, compressing component procurement time, and automating product specification on the engineer's desktop.

2.3.3 Construction Phase

IDEF0 Diagram node A4 represents the process model during the construction phase. Through the five activities shown in the diagram, the plans and specifications produced in the design phase are translated into a built facility. Throughout construction, the participating parties require different views of the information for valves that have been outlined thus far. In addition, the information requirements for valves extend from data about their inherent properties, to data that is necessary to facilitate purchase, transport product, support installation, and monitor progress at the construction work face. The focus turns from product description and specification to governance of the terms of exchange, installation procedures, and progress measure.

The following section focuses on two activities within the construction phase, the delivery and installation of valves. The following functional descriptions identify the exchange participants and their information viewpoints.

Deliver Valve (Figure 2-12. IDEF0 node A4.2)

The delivery of valves consists of a sequence of activities starting with order placement by the prime contractor's procurement team. According to the data sheets, the vendor fabricates the valves, and ships them to the site by contracting with an independent shipping company. When the valves arrive at the site, the construction team inspects them. Then they are stored in an on-site inventory until they are installed.

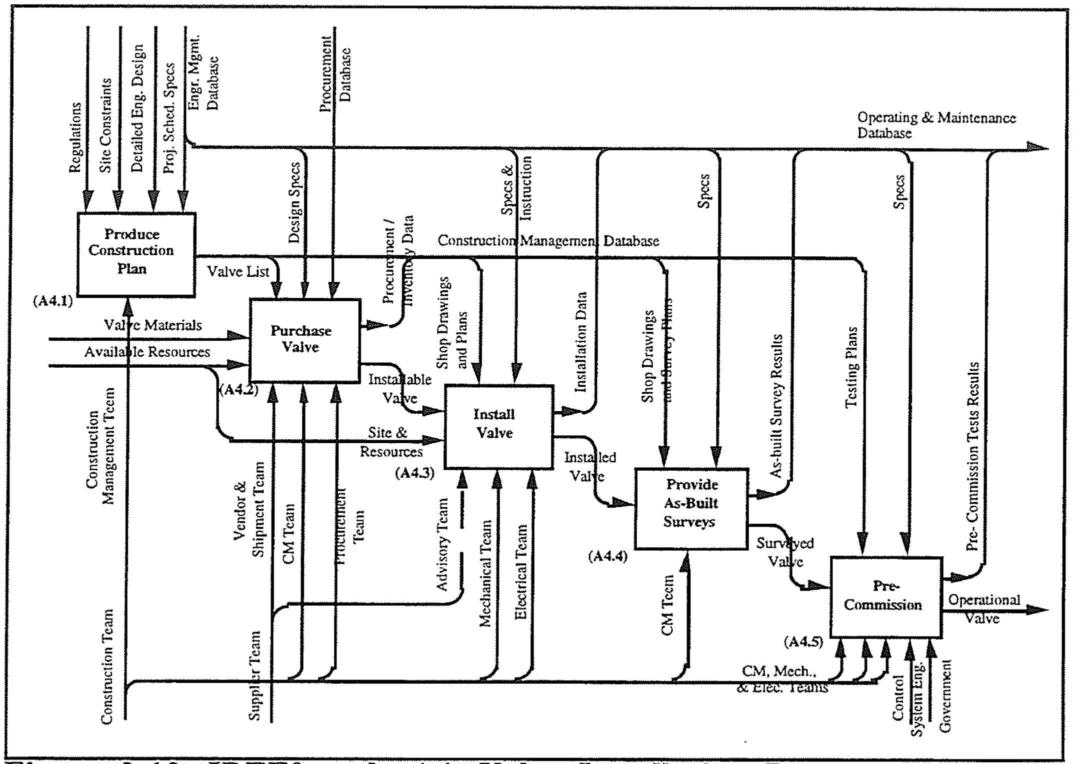


Figure 2-12. IDEF0 node A4, Valve Installation Process

The information required for this activity includes the detailed construction schedule, the valve data sheets and the purchase price. Upon placing an order, the procurement department stipulates a delivery date from the vendor and sends the information along with the order form to the construction team. This is normally done by entering the data into an integrated project management system that tracks equipment transactions. Therefore the order data are stored electronically in the prime contractor's procurement system and the procurement information is accessible for the construction team. Between the procurement department and valve vendor, however, the information is exchanged by mail and fax. The media are hard copy documents.

The information on the order form is then entered into the vendor's inventory control system which handles the manufacture and shipment of the valve components. The vendor requires the ID numbers of the valves along with the name, type and specification for each valve. During manufacture, the prime contractor may review vendor progress, and generate progress reports to assist the design and field activities. The prime contractor also issues stage payments based upon vendor progress toward fulfilling the order. The prime contractor schedules the valve shipments.

Before shipment, the valves are tested for casting defects by the vendor periodically in the presence of the prime contractor. The results of the tests are documented and attached to the shipment manifest. These quality verification documents also contain information about the physical properties of the valve materials. The valves that pass the quality tests are released for shipment by the prime contractor and furnished to a shipping company for delivery. A shipping list serves as an order form for shipment. The above information is exchanged by conventional information systems such as mail, telephone and fax. All the information is in the form of text documents.

The delivery of the valves are handled by the independent shipping company. Its primary information interests are the weight of each valve and the size of the packing boxes. The form of information and method of its exchange is the same as described above.

Upon arrival of the shipment, the prime contractor conducts an inspection to assure that the order form, shipment form and the valves match. The valves are then stored and maintained in an on-site inventory that is tracked by an integrated project management database controlled by the prime contractor until they are installed.

Delivery Process Summary

At this stage the information requirements for representing valves change from data that describe the design of an engineered artifact, to data useful for monitoring the status of a physical object. The information requirements for the Delivery process emphasize data for controlling production, monitoring quality and assuring compliance with the project schedule. These information requirements are normal for manufacturing processes and are well understood. In fact, EDI standards already exist that formalize and automate these procedures.

It is worth noting that EDI transactions for non bulk items have not yet penetrated the construction product procurement processes for the A/E/C industries. This is probably due to the fact that the standards are still relatively new and they are designed primarily for transactions of commodity, not engineered items. In time, EDI transaction sets may contain pointers to product information models based on STEP (or other) standards that provide the necessary detail to enable electronic transactions for complex, engineered products.

Install Valve (Figure 2-12. IDEF0 node A4.3)

The valve stored in the on-site inventory is eventually installed by the construction team according to the construction schedule. Valve installation occurs in the following sequence.

Structural erection: The structural contractor erects the support structure for the piping system. This includes the construction of concrete members, structural steel members, brackets, and tie rods that support the pipes and valves. The structural contractor is interested in the dimensions and specification of the structure, the physical support mechanisms for the valves, and their positions. The information is provided primarily in structural drawings and is exchanged by hand and informal communication. Typically, the structural contractor is not interested in the properties of a valve. However, he often must refer to the mechanical and electrical drawings when the information on the structural drawings is not sufficient. The information media and exchange methods are the same as describe above. In addition, the contractor sometimes refers to scaled 3D models to resolve spatial coordination ambiguities between the structural members and the mechanical piping and components.

Mechanical Installation: The mechanical contractor is responsible for the installation of valves along with the piping and HVAC system. His information requirements for valves include the valve specifications (class sheets, drawings and diagrams), their size and weight, and type of connection. The information is provided in a set of specification documents and mechanical drawings, and is exchanged by hand and informal communication with other parties. The activities are also controlled by the construction plan for valve installation. The construction schedule is provided by the construction management team in document format as well as informally through job meetings. As with structural erection, the mechanical contractor may also obtain vital information concerning spatial coordination by examining a 3D scale model if the detail design engineer develops one for the project.

Electrical Installation: After completion of structural and mechanical work, the installed valves are handed to the electrical contractor for wiring. Electric installation requires information about the required electrical voltages to operate the valve components, and safety requirements for special electrical zones. The information is provided with the valve specifications and is on the electrical drawings. The method of information exchange is the same as that described for the other installation activities.

Inspection: Upon completion of each of the activities described above, the construction management team inspects each contractor's work. The inspection involves examination of the work for conformance to the specifications. For this, the construction management team needs all the information identified above for the three stages of valve installation. In addition, the methods and criteria for the inspections are furnished in an inspection plan, government codes, and regulations. The information media and the exchange methods are the same as described previously.

Installation Process Summary

In this phase the information requirements involve reference to design data generated previously and to construction management information for coordination requirements between the disciplines. The specialization of the construction trades is reflected in the data views which require only the information that is necessary to perform a specific task. This point illustrates another requirement for a component information model. It should be capable of furnishing multiple views of the knowledge and information it contains. These views should be organized according to the requirements of users. In turn, the construction trades pass information regarding work face progress back to construction management so that it may monitor progress.

2.3.4 Commission Plant

The purpose of this phase is to prove the operation of the plant as defined by the construction documentation and project specifications by introducing process materials into the plant and operating it under test conditions. Concerning control valves, there are five primary activities that occur prior to plant handover;

Perform Trip Tests

Conduct safety tests that force trip conditions. These tests evaluate the loop between control instrumentation and valve actuator response for upset conditions.

Perform Cold Commissioning

Cold commissioning tests the process unit circuits using inert feed stock materials.

Perform Hot Commissioning

This activity performs operational tests using production feedstock materials. Hot commissioning verifies that the process transformation of feedstock to product proceeds as designed.

Tune Control Systems

Process circuit tuning occurs during the commissioning tests.

Perform Acceptance Testing

Finally, plant testing occurs under operating conditions. During this activity, operators establish benchmark performance characteristics for the plant under varying production conditions. At this time it is possible to establish benchmark performance measures for the installed equipment, including control valves.

At the conclusion of acceptance testing, the facility is turned over to the owner. At this time the prime contractor furnishes the as-built drawings, operating procedures and manuals, and the acceptance test results. The turnover process is formalized by the acceptance of a turnover certificate by the owner.

2.3.5 Operations and Maintenance Phase

This section summarizes the maintenance information requirements for control valves. The discussion of maintenance issues is drawn from the interviews and from several articles on control valve maintenance [Fitzgerald 1990], [Maintenance Technology 1992], [Emerson 1990] provided by Fisher Controls.

Upon completion of construction and plant commission, the facility owner takes control of the plant for operation. Plant operators attempt to optimize process efficiency while minimizing risk and plant down time. Plant maintenance becomes a strategic factor that affects the bottom line. While valves are relatively simple and rugged compared to other process control equipment, they play an essential role in the plant control system and their maintenance is critical to plant operation.

Performance Requirements

The maintenance criteria for valves differ with the process in question. In a petro chemical facility such as the HRP control valve overhaul occurs on a rotating schedule every three to four years for a process unit. During an overhaul, a process unit is taken off-line and all the valves are disassembled and rebuilt. Typically a process unit will have from 100 to 150 control valves and the service cost per valve is roughly $3,000.00 (line removal, disassembly and inspection, re-assemble and replacement on the line). This activity for one process unit costs from $300,000.00 to $350,000.00 for valves alone. Multiply this cost times the number of process units in the plant and the that valve maintenance costs can become significant depending upon the frequency of the disassembly cycle. This example represents just the out of pocket cost for valve maintenance. There are four primary performance requirements concerning valve maintenance:

- Process efficiency: process yield, quality and energy consumption are the measures. Control loop variability can result in control valve response that is inaccurate or jerky. These effects can cause the quantity and purity of the process to be sub-optimal, which results in production inefficiency.
- Process reliability: This factor affects plant down time, which is critical. It is estimated that "...each year, control valve problems alone cost the average nuclear power plant $2-3 million in lost revenue" [Emerson 1990];

To reduce downtime, plant designers introduce design redundancy such as block and bypass valves around each control valve. While effective for maintaining production, these systems increase plant design, construction and maintenance costs;

- Fluid containment: There are two types of problem, internal and external leakage. Internal leakage results in reduced process control, lost product, and process composition variability. External leakage also results in lost product. Perhaps more important, it can result in fugitive emissions that endanger workers, surrounding communities and the environment;
- Maintenance costs: The plant operator seeks to optimize process efficiency while minimizing maintenance costs. It is necessary to maximize the value of dollars spent to increase the return on the maintenance investment.

Typical Problems

- Positioner/Control Loop variability: Friction from corrosion of the plating surfaces on the stem can cause sticking and jerky operation. Alternatively, excessive friction can be caused by tight stem packing. When this occurs the valve operator builds up high pressures to force a control change. Instead of continuous control, the positioner jumps. The valve tends to operate in jerks. Often, it jumps past the intended set point and the controller continues to operate, trying to correct the position. When this occurs, variability as a percent of span goes up and the process does not stay at a set point;
- Improper seating: A poorly adjusted actuator can cause plug seating problems. There are two primary sources of sub-optimal actuator performance; Air leakage from a pneumatic actuator and actuator spring fatigue. A small air leak can increase response time, while a large leak can prevent the valve from opening or closing fully. A poorly adjusted spring can also prevent the valve from achieving a full stroke.

Some typical maintenance problems are due to disruptions in the quality assurance feedback loop between the customer and valve vendor, and/or a lack of control over the materials used for maintenance and repair. These problems originate from two sources;

- Plant operators use local, on site, or nearby off-site repair vendors instead of the original supplier for maintenance activities. When the owner/operator uses its own shop, the original supplier does not get accurate maintenance data that may be used to improve product;
- Plant maintenance engineers use 3rd party replica parts. While perhaps less expensive, such parts may be low quality. Such materials skew the maintenance data. Material traceability is lost and it becomes impossible to track where the part was acquired, who acquired it, what the failure rate is, etc.

Maintenance programs

Facility operators have three maintenance program options;

Reactive

Some facility operators wait until there is a problem before performing valve maintenance. The reactive maintenance strategy addresses the major problems. Unfortunately however, minor problems that affect production efficiency can go unnoticed.

Preventive

The preventive maintenance strategy is the most common. The HRP maintenance scenario presented above typifies this approach. While preventive maintenance reduces risk, it often involves unnecessary work that increases maintenance expense. During a petro chemical process unit overhaul such as the one described above, typically only one quarter to one third of the valves actually require disassembly.

Predictive

There is technology that enables operators to monitor control valves on a regular basis and predict their useful service life by comparing current data with historical performance data. This procedure, called signature analysis [Fitzgerald 1990], does not require valve disassembly and is gaining performance evaluation sophistication. It can augment a preventive maintenance program by helping to prevent unscheduled down time and by identifying sub-optimal valve performance before visible problems occur. The valve signature method "measures valve stem travel in response to the instrument signal while simultaneously measuring instrument air to the positioner, supply pressure and actuator pressure."[Fitzgerald 1990] From these measures, any two of the following parameters can be analyzed and compared to an optimal case [Fitzgerald 1990]:

- Actuator spring rate and bench set;
- Valve stroke and friction;
- Stroking speed;
- Seat load;
- Stem-nut adjustment;
- Air supply pressure;
- Positioner calibration, linearity and hysteresis;
- I/P calibration linearity and hysteresis;
- Packing friction.

Summary of Maintenance Issues

The requirements discussion shows that maintenance activities are tightly linked to business objectives for product production. An information model that explicitly represents the constituent parts and accessories of a control valve can contribute to preventive maintenance and the development of predictive maintenance capability. Explicit representation of the constituent parts should support these views of control valve parts:

Part identification and property description

This information includes a unique part and supplier identification, the material description, test approvals and the part properties that characterize geometry, material and function.

Part functional behavior and performance evaluation logic

This information includes the engineering knowledge necessary to derive part behavior. In addition, to support predictive maintenance goals, the information model should be able to represent the benchmark evaluation knowledge that is derived from the functional data. This would entail encapsulating "signature analysis" functionality within the information model.

Maintenance management information

The model should support maintenance management goals by tracking time-based data of the pertinent information described above and maintenance operations. Such data includes a history of valve signature indicators, who performs maintenance, the valves that are overhauled, the materials/parts that are changed, etc. This information makes it possible to evaluate the efficacy of maintenance strategies and decisions concerning the purchase of replacement parts.

An information model that is capable of providing these services can be used effectively in a program to re-engineer the business process for maintenance activities.

2.4 Analysis of Information Requirements

The level of analysis for the requirements can range from the determination of data types for computer sensible representation, to the necessary business models for electronic inter-organization information sharing. While each level of analysis is important, the conceptual emphasis of this case study is the identification of component information that the project participant wants to communicate with others.

Project participants want to describe components, understand how they perform and use this information for various activities across the facility life cycle. Users also need to manage procurement transactions involving components. For this they need to record and monitor the who, what, when, where, how and why of a transaction. Furthermore, users want to know process information concerning components that assists in the coordination of activities.

2.4.1 Component description

Appendix C contains a matrix that lists 150 life cycle information requirements for control valves grouped amongst 15 major tasks. For reference, figure 2-13 (see forward) reproduces the portion of the matrix that covers the preliminary control valve sizing activity.

Phase	Task	Information Requirement	Assigned	Design Req.	Design Std.	Measured	Computed	Administration	
Detailed Process Design									
	Preliminary Valve Sizing								
		Pipe							
		Nominal diameter		X					
		Applicable design code (ASME)		X					
		Class (material)		X					
		Flange rating (pressure rating)		X					
		Pipe geometry factor factor (Fp)	X						
		Stream (Min, Max, Upset functional cases)	**Same as flow rates above**						
		Inlet pressure at valve		X					
		Outlet pressure at valve		X					
		Pressure drop across valve		X			X		
		Pressure differential shutoff		X	X				
		Valve							
		Stream		X					
		Nom. diameter		X					
		Valve style modifier (Fd)	X						
		Noise level (db)				X			
		Liquid recovery pressure factor (Fl)	X						
		Laminar flow factor (Fs)	X						
		Coefficient of flow					X		
		Coefficient of flow, laminar stream (Cvs)					X		
		Coefficient of flow, transitional stream, (Cvt)					X		
		Coefficient of flow, turbulent stream, (CvTrb)					X		
		Reynold's number (Re)					X		
		Reynold's number factor (Fr)					X		
		Cavitation factor (Kc)					X		
		Predict Cv for service cases					X		
		Search for acceptable valve options					X		
		Valve Geometry (envelope dims)	X						
		Valve weight	X						
		Center of mass	X						
		Electrical Ports	X						
		Elec. hookup Requirements	X						

Table 2-1. Example from requirements matrix in Appendix C

The matrix divides the information requirements vertically by life cycle phase and task. Columns four through nine categorize the user requirements that are described informally above. Formal definitions for each category follow:

Properties

- Assigned: A characteristic of a component that is measured or observed. The nominal diameter of a control valve is an assigned property. The assigned properties of a component do not change;
- Design Requirement: A characteristic of a design context that is independent of a component but applies a design intent to it. Design requirements can and do change. The required outlet pressure of a fully open control valve is a design requirement;
- Design Standard: Similar to a design requirement, however a design standard does not normally change. Corporate design standards, government regulations or requirements pertaining to specific design criteria represent design standards.

Behaviors

- Computed: a value derived from reasoning about a component. The form of reasoning may vary (e.g. heuristic, analytical, stochastic). The Instrument Society of America (ISA) coefficient of flow formulas enable the derivation of a value that indicates the flow capacity of a control valve for a given set of functional conditions. Behaviors that derive from the application of design requirements to the model of a given structure or form for a component may also be called *predicted behaviors*;
- Measured: a value that is recorded from observation or measurement of actual component performance. Control valve diagnostics are measured behaviors. Time may also be a characteristic of measured behavior. For instance, control valve signature measurements are analyzed at time intervals. Such behaviors may be called *actual behaviors.*

Administration

Information that supports the flow (coordination and control) of information and resources for transactions (procurement, etc.). Formalization of transaction information currently falls within the EDI and ETF domain described in Part 1 and is largely beyond the scope of this report. For convenience, transaction information is grouped within Administration. However, there is project and material identification information associated with components that does not describe properties of them. Such identifiers (project numbers or material handling serial numbers) are grouped within Administration.

2.4.2 Task Coordination

The IDEF0 diagrams show the primary activities and flow of information related to control valves throughout the facility life cycle. Three types of task coordination requirement are implicit in these diagrams:

Design Contingency

The information interdependence between project elements. For example, the detailed specification for a control valve depends upon the stream definition. [Eastman 1995] shows it is possible to define contingency constraints between design elements and assign constraint violation functions for them that monitor and control design change within the product model.

Change Notification

Given a design change, this term characterizes the act of notifying the appropriate project participants. There is ongoing research in the development of design process support tools that enable active notification [Khedro, Genesereth, Teicholz 1993], [Eastman 1995] for product model changes.

Task responsibility

The assignment of ownership and accountability for tasks.

Other Factors

Time contingency and resource availability are additional critical factors in the determination of coordination requirements. They are not represented by the IDEF0 diagram technique. Time contingency is normally indicated on Critical Path Method (CPM) schedules. Resource availability is also monitored using CPM or other tools such as GANTT charts.

A component model that references vendor manufacturing information could provide input to a project process model for some of the coordination requirements listed above. Specifically vendor data for manufacturing schedules and product availability would be valuable. In addition, component models could contain software hooks for the establishment of design contingency and change notification relations with other objects once the component is referenced in a product model.

2.4.3 Purpose of Categorization

Categorizing the information requirements fulfills two goals:

- Generalization; factoring the specific requirements for control valves into a superset of information types assists in generalization the findings;
- Evaluation; these categories are useful criteria for evaluation of different modeling methods. In Part 3, several modeling methods will be described and compared with respect to the criteria.

2.4.4 Task Based Views

In the matrix, partition of the requirements by task suggests one of many possible views of the information. No individual project participant needs or uses all the information that is listed. Most participants work with a subset that is relevant to the task at hand.

From the decision support perspective, a component model should be capable of representing multiple views of underlying information for various work requirements. The work requirements vary depending upon the purposes for use and the time at which it is required or available. Similarly, the product model in which the component is referenced should also be capable of representing these views and of providing a design context for the characteristics of the component model that are functionally dependent on the design.

Some argue that support for engineering reasoning and decision support should be provided within software applications that access and manipulate an underlying information model. It is a research issue whether it is possible to develop a domain independent conceptual framework that supports view based knowledge and reasoning for engineering processes.

2.4.5 Tools and Media for Documentation and Exchange

It is clear that paper is still the primary documentation for most existing and many new facilities. Paper based information exchange is particularly prevalent for inter-organization information exchange. In a programmatic sense this information is informal. It is not represented explicitly and is not therefore computer sensible. Part 1 already addresses the problems associated with static information and the potential solutions for the representation of product information such as STEP. Nonetheless, many other forms of information developed for projects fall outside the current limits of STEP models. This is true particularly for documentation of project specifications and design standards. Information models for components will need to accommodate informal, text based knowledge representations along with explicit, computer sensible product information for some time to come[4].

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[4] Commercial technologies that enable the development of this information in symbolic format remain far on the horizon. Nonetheless, some promising technologies were encountered during the study. At CIFE [Howie, Kunz, Binford, Chen, Law 1995] report technology that enables the conversion of paper P&ID drawings to CAD graphics and an underlying, STEP compatable symbolic model of the process circuits, equipment and instrumentation. Within the NSF/ARPA/NASA digital library project [Phelps, Wilensky 1995] report the development of extended optical character recognition (OCR) technology that creates structured text in HTML format (complete with hyperlinks to related database information) directly from

2.5 Challenges

The detailed requirements identified in the case study represent the union of what was learned through the interviews, interaction with experts working on STEP information models, and a literature search. Despite these efforts that resulted in the identification of 150 separate information items, the enumeration of the requirements is assuredly incomplete. For example, most of the information is collected from E/C firms, information integrators, facility owners, and valve vendor representatives who participate in technical marketing. The information requirements study does not include detailed requirements from the perspective of the component manufacturer for component production and test procedures.

It has already been noted that each participant involved in information exchange about components has a specific perspective or view of the requirements dependent upon many factors, including the usage requirements and time at which the information is needed. Furthermore, no one participant has all the knowledge and expertise to develop a complete model. These factors point to the need for an information model that supports design schema evolution and enables the dynamic addition of information throughout the facility life cycle. This point has been expounded by [Eastman 1995]. One should not lose sight of the relationship between such capabilities and their importance for supporting business process. To achieve business goals, individuals and organizations access, manipulate, and transform information for a business purpose. This often results in new, derived information about a product. This study shows, to some degree, the broad range of information requirements for one component across the facility life cycle. Nonetheless, the findings of the study are informal. To validate them, it would be necessary to conduct similar studies that identify even more requirements, etc. An information model that has a general mechanism for schema evolution can support a complete representation of engineering design objects and their interrelationships [Phan, Howard 1993] without attempting, a priori, to fix and define a domain for which the information requirements inevitably change.

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scanned text images. Technologies such as these have exciting potential for overcoming the current information media barriers to electronic information sharing.

2.6 Case Study Conclusion

The life cycle information requirements for control valves begin with component design and specification. In procurement and construction the emphasis changes to identification of available products that match the design specifications, governance of the terms of exchange, installation procedures, and progress measure. From the plant commission phase through operations and maintenance, the focus becomes measurement and evaluation of component performance against production benchmark values and subsequent maintenance procedures.

With requirements that serve such diverse purposes, component information models should support multiple, task related views of the underlying information. Furthermore, an interface between the component and product model is required so that characteristics of the component that are functionally dependent upon a design context can be specified.

The case study focuses particularly on the information requirements for users to describe components, understand how they perform and use this information in various activities across the facility life cycle. The following information categories result from the requirements identified for control valves:

Component Description

- component properties
- component behaviors

Task Coordination

- Design Contingency
- Change Notification
- Task Responsibility
- Time Contingency
- Resource Availability

Administration

- Material identification
- Transaction processing

It is possible to improve the integration of component/product representation for design/construction process models by including an explicit representation of behavior and process related information. The incorporation of engineering knowledge and behavior in component models makes it possible to provide decision support for various engineering tasks, such as component selection and specification. The incorporation of enterprise manufacturing data related to components makes it possible to provide input to project coordination and control activities.

Part 3 presents a test case. It is a component information model for one component type, the control valve. The primary purpose of this model is to explore the modeling issues concerning the inclusion of a behavioral representation that provides decision support for the valve sizing and selection task. The information criteria from the case study are used to compare the modeling approach used for the test case with other modeling methods studied during the research project.

Part 3. Test Case

Introduction

Part 2 identifies several engineering processes that relate to control valves during the facility life cycle. To support these processes, the study describes the information requirements for a control valve information model and relates them to more general requirement categories. These categories include component properties, behaviors, task coordination dependencies and administration attributes.

Some of the processes are engineering tasks that require the application of engineering knowledge and reasoning to compute a performance property for a control valve. This reasoning is representative of design and engineering knowledge work, and particularly of tasks that involve analysis and evaluation of designed elements. Such knowledge translates project requirements and constraints into the designed product model. Automation of knowledge work is common in many software applications (e.g., finite element analysis programs). However, information models developed for standard product data exchange do not yet explicitly support this important task related dimension of design and engineering.

Modeling behavior in addition to the functional and structural properties of components makes it possible to provide analysis and evaluation software services for component selection and usage. These software services should formally describe and integrate a description of component data and related engineering process. In so doing, they would

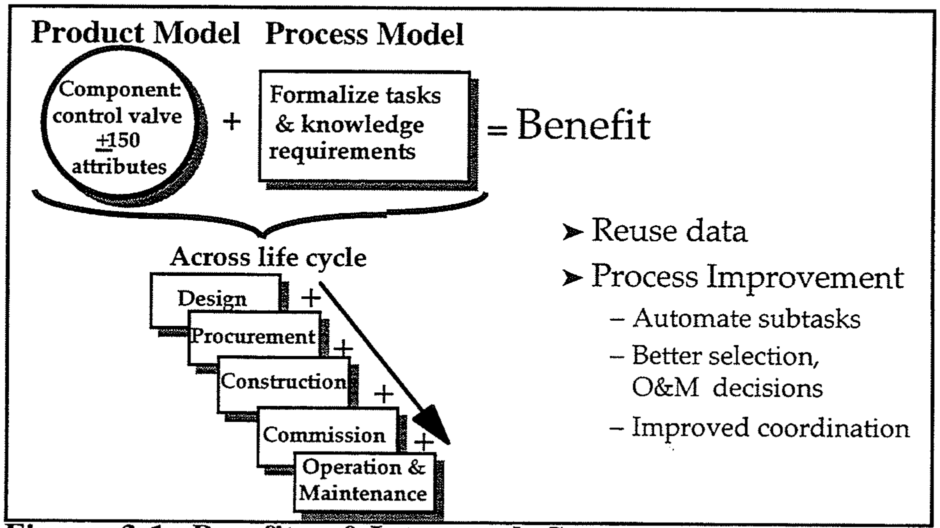

Figure 3-1. Benefits of Integrated Component and Process Description

offer value-added functionality for customers through the improvement and automation of existing process. Product, process information model integration can result in increased reuse of data, better component selection, improved decisions for operations and maintenance, and improved coordination between project participants.

Part 3 explores this concept through development of a test case that integrates an explicit description of product data and a task based process. The test case is an information model for a component and a piping sub-system. It includes a behavioral representation that supports one engineering task, preliminary valve sizing and selection. It uses the Symbolic Modeling Extension (SME) [Clayton, Kunz, Fischer, Teicholz 1994] modeling methodology that builds upon Form, Function, Behavior (FFB) [Kunz 1988], [Clayton, Fischer, Kunz, Fruchter 1995] concepts to model the control valve component and its placement in a piping sub-system of a P&ID product model. This model provides support for analysis and evaluation of component selection in an intelligent engineering application.

Current efforts to create standard information models satisfy some of the requirements identified by the study and highlighted by the test case. Other requirements remain out of scope for current efforts. Section 3.1 describes the test case information model, two process industry STEP APs (EPISTLE Core Model/AP 221 and AP 227), and ISO 13584 Part Libraries (PLIB). It analyses how these approaches satisfy the requirements. In Section 3.3 the test case implementation is described.

3.1 Comparative Modeling Methods

3.1.1 Preliminary Note

Elucidating the differences and similarities between FFB/SME and the other approaches assists in a better understanding of each, and hopefully demonstrates how FFB concepts can contribute to established modeling efforts. While the information requirement criteria from Part 2 apply to each modeling method, it is important to place each one in a relative context with respect to its scope and purpose.

Each modeling method focuses on a set of functionality that serves different purposes. STEP serves current industry practice by enabling the exchange of product data in a neutral, implementation independent, standard format. PLIB provides a component and component library representation structure for a similar exchange function between component suppliers and designers/procurers.

In contrast, the SME is a research prototype that is scoped to address a specific aspect of an information modeling problem. To date, SME demonstrates the integration of product and process models to provide intelligent decision support tools for the analysis phase of designing (see forward). Whereas STEP supports current work process, the goal of SME is to change work process by attempting to increase decision power through increased modeling power [Koskela 1995]. Yet, SME has limited scope. It is by no means a complete solution nor is it subject to the rigors and problems of scale and validation encountered in commercial implementation.

In addition, it is also important to frame the information requirements satisfied by STEP within the constraints of an incremental development strategy. As stated in section 1.3.5, STEP standards develop as a suite of information models (Application Protocols) categorized by domain. This strategy enables a life-cycle model to emerge as APs are approved to the international standard. Information that is lacking currently in a suite may be added eventually in a new application protocol. In addition, there are ongoing improvements to the expressiveness of the STEP information modeling language, EXPRESS [ISO IS 10303-11 1994]. Thus the modeling power and content development of STEP is a moving target. The incremental development strategy is correct given the size and complexity of the modeling challenges. In addition, industry needs and interests justifiably prioritize AP development.

Nonetheless, an incremental development strategy that satisfies distinctly different requirements can make it challenging to achieve unified, consistent results in a timely manner. The challenge becomes more complex within an organization composed of several groups trying to satisfy different industry sectors. The speed with which STEP delivers useful solutions to industry problems is a key factor for its acceptance. Given the complexity of the mission and the constraints on resources required to achieve success, it is vitally important that STEP identify and address the areas in which it can provide the biggest benefit for industry. While behavior and engineering process representations with STEP models would increase the complexity of STEP modeling and validation efforts, hopefully this report indicates that such functionality can provide significant new benefits.

3.1.2 Modeling Method Description and Analysis

Table 3-1 below summarizes how well the modeling approaches satisfy the information requirements categories that are identified in Part 2 of this report. The columns are the various modeling approaches, the rows are the criteria categories and the cells are evaluations (no support, poor, good, very good, etc.).

The table indicates that the 'state of the art' of product modeling covers assigned properties and design requirements very well. Design standards receive poor coverage primarily because the content is not yet available in a computer sensible format. Currently, design standards, codes and regulations are referenced as external documents. Behavior representation is out-of-scope for STEP models whereas FFB/SME and PLIB support its representation. STEP support for task coordination is static and therefore it is rated poor. Task coordination is out-of-scope for FFB/SME and PLIB. Identification is 'very good' for each method, however integration with procurement transactions is not explicitly represented by any of the modeling methods shown.

FFB/SME explicitly integrates a product and process model to automate analysis and evaluation tasks. PLIB explicitly supports the product selection process and could probably be adapted to support other engineering processes. The other models have no formalism for integrating product and process descriptions.

			Process Plant STEP Models		
Component Descriptions		**FFB/SME**	**AP221**	**AP227**	**ISO PLIB**
Data Properties	Assigned	++	++	++	++
	Design Req.	++	++	++	++
	Design Standard	-	-	-	-
Behavior	Computed	++	0	0	++
	Measured	0	0	0	0
Task Coordination	Design Contingency	0	-	-	0
	Change Notification	0	0	0	0
	Time Contingency	0	0	0	0
	Accountability	0	-	-	0
Administration	Identification	++	++	++	++
	Transaction	0	0	-	0

Legend (State of the art for product models)

++ Very Good **+ Good** **- Poor** **0 No Support**

Table 3-1. Satisfaction of information requirements by different modeling methods.

The following description and analysis of each modeling method explains in detail the evaluations summarized by the table.

3.1.3 Form, Function, Behavior (FFB) / Symbolic Modeling Extension (SME) Conceptual Model

FFB/SME has antecedents in formal symbolic modeling [Kunz 1988], [Dym and Levitt 1991], the design process framework of [Gero 1995], and in particular, Interpretation

Objects developed by [Clayton, Fruchter, Krawinkler, Teicholz 1994]. Interpretation Objects are realized in SME. It was extended for this project.

A model is a type of representation that simplifies organizes and abstracts the perception of an artifact or phenomenon. Models assist in the description, analysis and solution of problems concerning various phenomena and artifacts. A fundamental concept of a model is the distinction between an object or phenomenon, and its representation. The choice of representation is dependent upon what is being modeled, the purposes for which the model is developed, and the assumptions held by the individual(s) who create the model. This definition enables the representational capacity of a model to be evaluated in terms of business as well as technical purposes that are realized through work process.

The formal symbolic modeling approach contends that, while model semantics vary according to modeling purposes, most modeled systems can be represented explicitly in terms of the modeled system's structure and functional behavior [Kunz 1988]. Similar concepts have been elaborated and extended by others. [Gero 1995] uses the terms function, structure, and behavior to describe model characteristics. [Clayton, Fischer, Kunz, Fruchter 1995] articulates the product model in terms of the form, function and behavior of system elements:

- *Forms* are the geometry and materials of the artifact;
- *Functions* are the required and desired qualities of the artifact. Synonyms for functions include *goals*, *intents*, *requirements*, and *purpose;*
- *Behavior* is the performance of the artifact under particular conditions.

Modeling Process

Through reification of FFB, symbolic models enable the explicit representation of the internal states of a system. [Gero 1995] elaborates a causal relationship between FFB elements and incorporates them into a design process framework in which the interaction of form and function constraints determine behavior. The comparison of predicted behaviors with intended functions can necessitate 'reformulation' of form and function characteristics to satisfy behavior constraints. Contrary to intuition, there is no explicit causal relationship between form and function. An artifact with a given form can be used for several, functionally independent purposes. Through the activities of designing[1] the designer reconciles form, function and behavior to provide an acceptable solution for a

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[1] Gero uses the word 'designing' to signify the process of creating an artifact and 'design' to signify the description of the designed artifact.

design problem. Gero maps the form, function, behavior relationships to the following activities of designing:

- formulation;
- synthesis;
- analysis;
- evaluation;
- reformulation;
- production;
- design description.

These activities define the steps for the application of design knowledge and reasoning to the definition and refinement of a product model. They represent the value added service provided by design and engineering professionals, yet the knowledge content of these activities is not fully or explicitly represented in current information models. The full value of the design and engineering service is not captured at each stage of the design project nor is it passed to the facility owner.

The creative element of design formulation and synthesis is beyond the capability of current computing technology, however model based reasoning for the analysis and evaluation phase of designing is possible using symbolic models that explicitly represent the constraint relationships between object form, function and behavior [Luth, Krawinkler, Law 1991], [Clayton, Fischer, Kunz, Fruchter 1995].

Views

The model definition provided above stresses the usefulness of a particular model for a given purpose or user intent. The content of a model should be parsimonious to the extent that it contains only the information necessary to fulfill a modeling purpose.

In relational databases, views limit the visible fields of a relation. [Law 1992] explores object definition and management for topological views of structural elements based on underlying relations. View development for the design context and designing activities in an A/E/C product model is challenging due to the complexity and diversity of information perspectives for the various disciplines. Yet, product model views are necessary to provide a context for model based analysis and evaluation.

Integration of Product Description, Process and View

[Clayton, Fruchter, Krawinkler, Kunz, Teicholz 1993] propose a method, called Interpretation, for the real time assignment of views to a product model. They emphasize designing as a visual process in which practitioners informally draw ideas before semantically interpreting them into symbols that are subject to analysis and evaluation. Relating this perspective to Gero's work, interpretation further clarifies the difference between 'formulation' and 'analysis and evaluation'. To model the work process, they argue for interactive interpretation as another activity of designing. [Clayton, Fischer, Kunz, Fruchter 1995] reifies the interpretation of design shapes (walls, doors, etc.) through Interpretation Objects. An Interpretation Object relates design forms with a functional issue (e.g., cost estimation, energy, egress and spatial requirements analysis) in the SME prototype. Interpretation objects then may be 'critiqued' according to interpretation specific constraints. A Critique generates predicted behaviors for a functional issue that is associated with a set of forms. It then evaluates the predicted behaviors in terms of the functional requirements and furnishes an analysis to the user. Each Interpretation is a view of a product model[2]. Clayton calls the run-time association of Interpretations to a CAD representation a "Virtual Product Model".

Analysis

SME demonstrates dynamic annotation of CAD graphics with interpretation (view based) product model information. Equally important, through the integration of *critique* objects into the product model, it shows that model based analysis and evaluation, and thus automated engineering process, is possible for architectural design.

The FFB modeling concepts that underlie SME are well suited to product description. However, the term *form* currently encapsulates both geometry and material. In retrospect this definition may be suitable for certain system level design analyses. However, for piping products such as control valves and process media, the geometry and material properties are sufficiently distinct to merit a separate classification category for each. In the future, it may be appropriate to designate a modeling metaphor called Form, Material, Function and Behavior (FMFB).

In addition, it is clear that task coordination and administration requirements are out-of-scope for the SME prototype. FFB is a strong metaphor and organizing principle for describing the product model. SME describes work process and encapsulates engineering knowledge. However, a different set of intrinsic metaphors should be developed for the other requirements.

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[2] Interestingly, the application of set operations (intersetion, union, difference) to a collection of Interpretations leads to insights about shared information between them. Clayton's SME implementation begins to explore this through user interface tools that allow the user to perform set operations on available interpretations.

Despite the scope limitations, the product, process integration features of SME/FFB are sufficiently strong to demonstrate an incremental, but significant value added service of information models. The control valve test case uses the FFB/SME approach and explores whether it is suitable for computer assisted support for control valve sizing.

3.1.4 STEP/EXPRESS Models

The EXPRESS Information Modeling Language

STEP models are bounded by the representational limits of EXPRESS. It provides a rich set of features for developing an information model design, including the schema, the entity, the type, and the rule. It also has processes, functions and expressions. From these basics, it offers object inheritance, derived values and constraint management at STEP file compile time. Nonetheless, EXPRESS is not a programming language. It does not support input, output, exception handling or other common features of programming languages. For a thorough discussion of EXPRESS see [ISO IS 10303-11 1994], [Schenck, Wilson 1994].

EXPRESS generates information models that have a fixed, apriori definition of model structure and entity relationships. It is not currently possible to programatically add, change, or modify an EXPRESS schema. (The EDM-2 system developed by [Eastman 1995] explores several research issues relevant to dynamic conceptual data models.) In addition, EXPRESS does not offer a generalized method capability[3]. It does not yet support object behavior. Therefore it is not currently feasible to formalize engineering analysis and evaluation knowledge using EXPRESS. In addition, it would be difficult to implement automated design contingency or active change notification at the conceptual data model level[4]. Last, there is no formalism within STEP/EXPRESS for the conceptual definition of task based views. This limitation currently makes it difficult to reference a view of a specific component representation (other than geometric representation; solid model, 2D model, etc.) for a particular design or engineering purpose within in a STEP conformant product model. Exploration of this issue for the integration of ISO 13584, PLIB and STEP is an action item for the STEP architecture committee ISO/SC4/WG10.

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[3] A new version of EXPRESS (due for draft standard vote in Q1 1997) will support events, processes and states. EXPRESS models will enable the definition of a method signature. Method invocation will be supported through Strategic Data Access Interface (SDAI) calls to an external function library.

[4] References to research in these areas include [Khedro, Genesereth, Teicholz 1993], [Petrie 1993].

The current limitations of EXPRESS[5] constitute the fundamental criticisms of STEP as a technology that satisfies the conceptual data model requirements for a life cycle facility model that changes and evolves.

Process Industry Application Protocols

Despite the limitations of EXPRESS, the following discussion of AP 221 and AP 227 shows the variation in the design of STEP models at the ARM level. The variance in modeling methods reflect different requirements, expectations and philosophy.

AP 221 and AP 227 are the first efforts of the process industry to establish STEP for the facility life cycle. At the time of this writing, they are in the Committee Draft (CD) review phase. A new application protocol, AP231, that defines process information is also approved for development. This discussion focuses on AP221 and AP227.

AP 221

AP 221 describes the functional definition of plant items that are represented in a P&ID diagram.

Content

The classes of data within the scope of the AP include [ISO WD 10303-221 1995]:

- the identification and classification of functional or logical items within a plant;
- the identification and classification of physical items within a plant;
- the composition and connectivity of logical and physical items;
- the characteristics of logical and physical items;
- the 2D and 3D schematic representation of the logical items and their connectivity.
- version control data;
- audit trail data;
- data which reference external documentation;
- approval status data.

Architecture

AP221 is based upon the Core Model adopted by the European Process Industries STEP Technical Liaison (EPISTLE) [SIPM ICG/2 1995]. The Core Model is a conceptual data model designed to provide a common underlying data representation for domain specific information models. The Generic Entity Framework (GEF) furnishes the conceptual basis

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[5] We will see that the design of AP 221 attempts to circument some of the limitations of the STEP modeling methods, but this design also introduces new risks for standard conformance class validation.

of the Core Model. It consists of "four sets of orthogonal subtypes" [ISO WD 10303-221 1995] that qualify a domain specific entity. A domain object can be placed in only one subtype of each of the sets. The four sets are:

- Subject; furnishes a conceptual definition for an entity. Top level subsets of subject include Material, Activity, Association, Token, Characteristic, Operation.
- Instanciation; the distinction between the type of an object and an occurrence of it. The GEF recognizes two types of instanciation; specific and typical.
- Life cycle; objects have different logical state conditions (actual, required, planned, predicted) that reflect their life cycle stage. These states may not be mutually exclusive.
- Reality; another dimension of state. An object either exists as a thing, or is fiction (e.g., a designed entity).

Beyond these entity classification qualifiers, the underlying concepts of the Core Model include.

Data driven model

The GEF provides a set of meta-entity relationships that define object classification and the definition of object relations. This enables classification and the assignment of object characteristics to be data driven. The AP defines a baseline set of classes, objects, and associations in a data dictionary that users may extend or change. The data dictionary seeks to obviate the need for a standard object hierarchy. This approach attempts to resolve the fact that organizations have different component and equipment functional classification schemes and that it is difficult, if not impossible, to capture all the information requirements in the structure of one information model. The intent is to provide a data sharing structure for which the contents can be standardized on a project by project basis and enforced through business relationships.

Object attributes (characteristics) are themselves objects. This enables their classification (classification by data as for any other object), and equally important it enables a characteristic to be shared by multiple objects.

Separation of logical and physical entity definition accommodates change

AP 221 separates the logical and physical definition of the object. The logical item provides an invariant service to the process plant. The physical item can (and does) change state. For example a pump (logical item) induces pressure in a system (invariant service), whereas the pump (physical item) can be replaced when necessary. Since all objects carry identification and version control data, this feature provides a mechanism for change control.

Analysis

The GEF permits a very general and flexible model definition by splitting object properties into four information axis that are related through explicit association. It mixes relational concepts with object oriented information modeling techniques. Association of characteristics to objects (rather than characteristics being intrinsic properties of objects) enables data normalization for characteristics and establishes the object role and semantics. The reification of characteristics, objects, and associations also enables the topological and class definition to be data driven.

The data dictionary approach carries increased risk for conformance class validation. Vendors must validate AP221 compliance for the exchange of project data between systems and for the exchange of class libraries. The fact that the class libraries are user extensible makes the definition of conformance classes more challenging. The PLIB standard (see forward) also enables user extension to a class library. However, PLIB also offers a feature that assures the integrity of library entries (absolute logical identifier), and it enables cross references to be made between library entries with different semantics (semantic dictionary). These modeling tools provide a method for enabling compatibility between different library customizations.

The general features of the core model overlap to some extent with the architecture and purpose of the STEP Integrated Resources. This overlap caused harmonization problems with AP 227 during development, but is being resolved during the interpretation process.

In terms of the information requirements, it is evident that the AP221 conceptual model describes product properties, functional requirements but not a plant item behavioral representation. This fact is a result of AP scope and the modeling limitations of EXPRESS described above.

The GEF circumvents the limitations of the static, a priori model definition described above for classic STEP. Nonetheless, like STEP it assumes that software applications provide data management services for a data repository rather than binding data management behaviors directly to the conceptual data model itself. For example, AP 221 and STEP models in general (through the Integrated Resources) provide schemas to indicate design change, design versions, and approval status for file exchange. Indicating change when a file is exchanged is helpful, but it is not equivalent to automated change management through constraint management at the conceptual data model level. [Eastman 1995] shows it is possible to define contingency constraints between design elements and assign constraint violation functions for them that monitor and control design change within the product model. Given the possibility for variation in software conformance to the standard, it remains to be seen whether the Core Data Model can successfully support life cycle requirements (such as the task coordination requirements) across software applications and therefore between organizations. The distinction between encapsulating behavior and data together or separating them represents a fundamental difference between object oriented and relational modeling concepts.

There is no formalization for a description of engineering process (tasks) within AP221.

AP 227

Content

AP 227 describes the shape, spatial arrangement and materials of plant systems. The data within the scope of the AP include [ISO CD 10303-227 1995]:

- The spatial arrangement of plant systems within the process plant;
- Explicit representation of the 3D shape of piping systems;
- Explicit representation of the 3D external shape of piping components and connected equipment of the piping system, that may include parametric, envelope, outline, and detailed representations of external shape;
- The spatial arrangement of piping components and connected equipment that comprise the piping system;
- The logical configuration (connectivity and sequencing) of the piping system and the relationship of the logical configuration to the physical realization;
- Basic engineering data as needed for spatial layout and configuration of the piping system;
- References to or designation of functional characteristics of piping components and connected equipment;
- The identification, shape, location, orientation, physical connectivity, and routings of components of plant systems, including HVAC, structural, mechanical, electrical equipment and raceways, and instrumentation and controls for non-piping systems, reserved areas, and space occupying architectural components;
- References to specifications, standards, guidelines, or regulations, for the piping systems, components, or connected equipment that may specify physical characteristics;
- Status of plant spatial arrangement, piping components, and connected equipment;
- Connections and connection requirements for piping components and equipment;
- Definition of piping components sufficient for the acquisition of the components;
- Change request, approval, notification, verification, delta tracking, and documentation of plant spatial arrangement, piping components, and connected equipment.

Architecture

AP 227 follows the classic STEP development model. It offers an a priori, fixed definition of object topology, definition and description. In contrast to AP 221, the domain independent features of AP 227 (change control, procurement specification, references to specification documents, etc.) are referenced directly from the STEP Integrated Resources. The architectural limitations of AP 227 are bounded by those of EXPRESS discussed previously.

Analysis

Because this AP is static there is always a possibility that the model definition lacks the objects and attributes to sufficiently satisfy usage requirements. The question must be answered whether an AP 227 file exchange that does not transfer 100% of the data is acceptable. This issue is being addressed through the definition of conformance classes for software vendor compliance to the standard. The definition of conformance classes should be less complex than for AP 221. If acceptance of the standard is hampered by the discovery of new information requirements, it will be critical to update the standard quickly.

In terms of the information requirement categories from Part 2, the coverage of AP 227 is similar to that of AP221. It represents component properties but does not describe component behavior. The limitations for task coordination are bounded by the limits of EXPRESS and by the AP scope. There is no explicit description of engineering process that describes the process design and engineering tasks which relate to plant spatial layout.

Functional requirements in AP 227 do appear to be described from a 'view' perspective, but the user perspective of the view is not represented explicitly. Information appears within different portions of the information model without a formalism for views (other than designed versus installed which conceptually are adopted from AP 221). Note the entities Functional_Object, Stream_Design_Case for stream data and Service_Operator_Case for equipment [ISO CD 10303-227 1995]. This 'view' related data (with respect to the notion that the information satisfies a particular set of requirements or perspective of the model) should be mappable to ISO13584, PLIB which has a strong formalism for views (see forward).

ISO 13584, Part Libraries

ISO 13584 Standard Parts Library (PLIB) is a conceptual model and set of implementation resources for information exchange between part libraries and between a part library and a product model. PLIB contains no description of component content. The specification for the PLIB information model is domain independent. This fact differentiates it from the STEP APs which develop information content for an industry domain and formalize it into an information model. PLIB describes:

- the information structure for parts and for an integrated part library that defines parts, part families, and their relationships;
- facilities for semantically describing parts families, for cross referencing them, and for accessing and selecting them;
- the minimum functional requirements for the software services that a library management system should provide for producers and users of part information.

PLIB provides a standard for the integrated and interoperable compilation, access and selection of part information from diverse information sources. The standard assumes that part information suppliers (manufacturers, standard organizations, etc.) furnish PLIB compliant information models that a user or an information integrator compiles into a part library. This is an information liability and validation issue. Information owners should maintain responsibility for the accuracy of library contents.

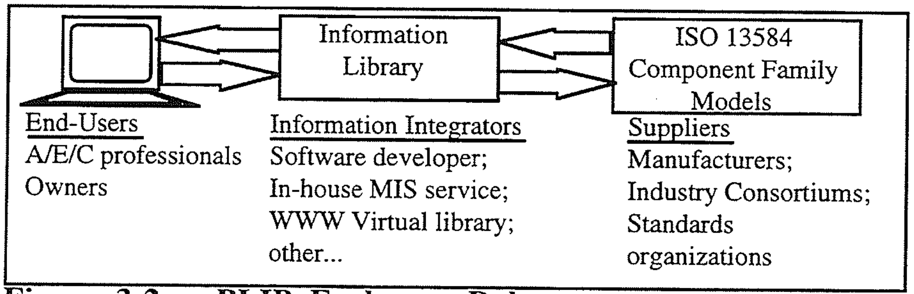

Figure 3-2. PLIB Exchange Roles

In addition to library compilation, the information integrator provides library management services such as integration with the user's database management and CAD system, and other library management services. This role can be in-house or furnished by an external provider. Within the PLIB framework, control of library content is an enterprise policy issue, not a technology issue.

Exchange Models

It was noted above that PLIB supports library to library exchange as well as library to product model exchange. The standard identifies three types of exchange:

Exchange by Value

The base case. When a user selects a part from a library, the system transfers an explicit part representation to the product model. If the user exchanges the product model with another party, the exchange of the part representation is subsumed within an ISO 10303 exchange process.

Exchange by Reference assuming consistent libraries

When a user selects a part from a library, the system transfers all or a portion of the part representation to the product model by reference. If the user exchanges the product model with another party, the library of the sender and receiver must contain the same part information for no data loss to occur.

Exchange by reference assuming inconsistent libraries

Exchange by reference. However when a product model exchange occurs, the system transfers both the product model (ISO 10303 exchange) and the necessary library information (ISO 13584 exchange) without making assumptions about the content of the library in the receiving system.

These exchange models are general descriptions. Despite the fact that they were devised prior to the advent of the World Wide Web (WWW), they remain applicable. Since the standard enables library to library exchange, one can imagine a user directly accessing a component manufacturer library, downloading component information directly into a user library and eventually importing a particular component description into a product model.

However, it should be remembered that these exchange models are proposals for ISO 13584 and ISO 10303 interoperability. There is no mechanism in place yet for assuring ISO 10303 compliant component representation within PLIB. Furthermore the two standards do not currently have an equivalent component representation schema. The mechanics of PLIB part instanciation in a STEP compliant product model is a current action item for the STEP Architecture committee, ISO/SC4/TC184/WG10.

Architecture

Figure 3-3 is an adaptation of the system architecture diagram provided by PLIB. For a thorough description of each sub-system, see [ISO CD 13584-10 1995]. The elements of the standard that are most relevant to the satisfaction of the component and process description requirements identified in the study include sub-system 3) Dictionary and 4) Data + Structure + Algorithms.

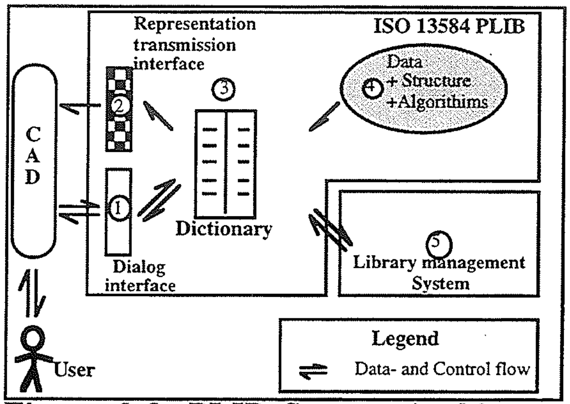

Figure 3-3. PLIB System Architecture
[ISO CD 13584-10]

Data + Structure + Algorithms

The information structure of ISO 13584, specifies three class hierarchies, General and Functional model classes and Views. These class hierarchies are tree structured with single inheritance [ISO CD 13584-42 1995].

General Model Classes

General model classes specify parts through the definition of a set of properties that uniquely characterize them. The structure of the general model classes consists of two sections. The higher section "classifies technical fields and also defines the first levels of generic families of parts. Generic families of parts are for classification purposes . They are not intended to be instanciated. The lower section splits these families into generic sub-families to obtain simple families of parts" [ISO CD 13584-42 1995]. Simple families are identified by a part supplier and normally correspond to a particular product line. A part from a simple family may be instanciated whether or not it belongs to a supplier or is defined as a "generic" part. Part identification occurs through the unique naming of a part supplier, and the simple and generic family properties.

PLIB recognizes that real world perspectives of the structure for part families differ, for example between two suppliers who sell competing products. Thus, in addition to the definition of a reference hierarchy for a part family based upon PLIB specified property characterization rules and guidelines, the standard also defines Class Valued Properties [ISO CD 13584-42 1995] that enable alternative family structures to be associated with a reference hierarchy. Thus, a product line organized according to a class hierarchy structure 'X' can be referenced in a PLIB reference hierarchy 'Y' as a Class Valued Property with a single value. This property is inherited by all the subclasses of 'Y'. This mechanism allows cross reference between different part family organization structures.

In STEP the Integrated Resources (IR) offer the Product and Product Definition entities that enable an equivalent definition of a General Model class structure. However, the STEP IRs have not implemented the equivalent of a Class Valued Property the enables one class structure to reference another. In this regard, the information modeling requirements for part library families are significantly different than those for a product model.

A part property may be an attribute (numeric, alphanumeric, boolean or derived value), another part, or in theory, an ordered list of parts. Based on these distinctions ISO 13584 categorizes libraries into levels 1, 2, and 3 respectively. A screw, for example is a part whose properties are attributes only. Thus a screw can be described in a level one library. A control valve on the other hand, is an component that is comprised of several parts (valve body, trim, actuator, bonnet, etc.). If a supplier wanted to describe a control valve that includes an explicit representation of the constituent parts, he would need to define a level 2 or 3 library. The choice between level 2 and 3 depends upon whether the supplier chooses to describe the parts as separate properties of the valve or as an ordered list. Thus Level 2 and 3 libraries support the description of assembled parts or components as they are defined in this report. However, level 3 libraries pose implementation difficulties for relational database environments. For this reason the level 3 library is not yet officially supported by the standard. Thus ISO 13584 does not yet fully satisfy the aggregation requirement for explicit representation of the parts that comprise a component. Multi valued attributes do not pose a problem in object oriented systems.

The standard supports a description of object behavior and thus satisfies an important information requirement of the study. Tables, rules or methods can provide derived attribute values. [ISO CDC 13584-20 1994] is an EXPRESS specification for the exchange of expressions that enables PLIB to support method exchange.

For specification of entries in the semantic dictionary (see forward) part properties are typed according to whether they are identification attributes, context parameters or behavior representation attributes. These types correspond closely to the component properties and behaviors identified in the study. The type system identifies component attributes that are independent of the product model, contingent upon it, or dependent upon it to describe predicted component performance. Thus conceptually, the standard furnishes the semantics to enable product selection through interaction between the library management system and a product model. In the base case the interaction would be manual assignment of values to component variables. In a system that includes a symbolic as well as graphic product model representation, programmatic interaction between the product model and a library system is possible for 'intelligent' product selection.

Functional Model Classes

Functional model classes define the properties for different representation categories (e.g. wire frame, b-rep, etc.) for parts. "The description of a functional model class is similar to the description of a parts family, except that it contains only context parameters, representation attributes, derivation functions (if any) and methods. The methods are associated with the view logical names, and possibly with the view control variables, which allow the user to request them" [ISO CD 13584-10 1995]. A part may be associated with several functional model classes and thus have multiple representations.

Views

"The view is the structuring unit for the data produced by an integrated library for output to the CAD system for the purpose of representing parts" [ISO CD 13584-10 1995]. There are two types: general and functional views. A general view represents a part in the product model data, whereas a functional view is an information model for a part representation category in a product model. The concept of view is unique to PLIB. It is not incorporated explicitly into STEP.

> A functional view refers to a general view;
> corresponds to a logical view name, and possibly to view control variable values;
> contains a set of view attributes [ISO CD 13584-10 1995].

Functional view classes define the representation categories for functional model classes. Consider the solid model representation category (or functional model). Functional views for this category might include plan, section, cut-away, elevation, isometric and perspective. Furthermore, the representational abstraction for each functional view might vary depending upon the zoom level for the view in a CAD system. Such factors are contingent upon the purpose for the view and the information that should be available to the user. An equivalent analogy can be made for other representational categories such as a procurement and engineering management database views. The PLIB authors developed the functional view class concept to support component selection. Nonetheless, the mechanism is general and could be extended for other processes.

STEP supports multiple representation categories (solid model, wire frame, etc.) for an entity, however these categories are currently limited to geometry. They do not incorporate the view concept for a perspective of a type of geometric representation or of a general definition for a task based view.

Currently, the concept of functional view classes requires further research, development and implementation. Component geometry is the first representation category to require a definition for functional views. However, PLIB has not yet developed an information model for the neutral representation of standard part geometry using EXPRESS. [Liset, Moen, Myklebust 1994][6]. To specify CAD geometric representation for semantic objects requires the development of an implementation independent parametric representation capability. Parametrics is a current STEP action item. Other class hierarchies, including view categories to support engineering tasks, would follow after the formalization of geometric representation categories.

Dictionary

ISO 13584 part families (class definitions and attributes) are entered in a Semantic Dictionary [ISO CD 13584-24 1995]. The dictionary is a table in which each entry is characterized in terms of an absolute identifier and a descriptor. The absolute identifier assures that each entry has a unique semantic meaning. The dictionary supports four formal semantic links between entries (is_a, is_case_of, is_part_of, and is_view_of) [ISO CD 13584-10 1995]. This mechanism enables cross reference between entries and thus between different supplier part families in the library. Furthermore, the separation of the logical identifier describing which elements are present in a part family from their semantic definition provides a mechanism for changing the logical description (through product catalogue updates, etc.) without affecting the semantic definition. The formal semantic links between dictionary entries provides a basis for software services to query the library for part access, specification, selection, etc.

Analysis

PLIB is still in development. At this stage, six of nine documents that currently comprise the standard are in the ISO development process (see Appendix F for a document list). Work items to develop geometrical view exchange protocols have not begun. In concept the standard offers many features for the representation and exchange of parts and part library information. These proposed features will:

- Enable information owners (manufacturers and standards organizations) to develop computer sensible, implementation independent library information models that represent part catalogues and part standardization schemas;
- Enable end users to compile supplier library information models into an integrated, standardized user part library;

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[6] The developers of PLIB have specified an Application Programming Interface [ISO DRAFT 13584-31 1994], based on a FORTRAN binding, that references an EXPRESS logical model for a target CAD system.

- Provide conceptual models to support data exchange from library to library and library to product model;
- Distinguish between a unique definition for part semantics and multiple classification schemas. This enables cross referencing between supplier products (including international language translation) and part standards;
- Furnish a mechanism for multiple, view based representation of parts for different modeling purposes;
- Support object behavior and methods to compute the predicted behavior of candidate parts for selection in a design;
- Provide semantic typing to distinguish between independent, dependent and behavior properties for parts.

Conceptually, the standard can support process automation for engineering evaluation and analysis tasks through a library management system that furnishes programmatic interaction between a product model and part library to automate part selection.

Concerning the information requirements identified in the study, PLIB provides an information model framework that is capable of describing component properties and behaviors. The framework does not attempt to explicitly represent process description. It depends upon part information providers to furnish the methods and functional views to model process (part search and selection), perhaps implicitly. Nonetheless, when a functional view class framework is in place and a part library is integrated with a library management system, the PLIB framework could satisfy the information requirement for integration of product and task based process description. Task coordination requirements and procurement transaction models are out of scope for PLIB.

It has been noted that PLIB is not integrated with STEP and that this topic is a current action item within ISO/SC4/TC184/WG10. PLIB is developed outside the traditional STEP architecture and implementation process. There is a proposal to reference PLIB as an external resource for the Integrated Resources through an interfacing schema. Since this mechanism would be new for STEP, it may require an extensive review of the STEP architecture and methods. To do this will be time consuming and a somewhat political process. The costs, benefits of this option need to be identified.

3.1.5 Summary of Methods

The review of AP information models based on EXPRESS indicate that the 'state of the art' for product models does not yet integrate a product data, behavior and engineering process description. PLIB may one day provide support for library management systems (non standard implementations) that can provide task automation services for part procurement.

However, presently PLIB does not offer an integrated link for graphical representation of parts and product models. In addition, PLIB does not explicitly model task process.

The existing models reviewed for this study are useful for improving product data exchange, but they are not intended to support the sharing of engineering knowledge and decision support reasoning capability. In this sense, they do not furnish an underlying IT capability to improve knowledge (as opposed to information) distribution, access, and use.

The scope of FFB/SME is limited to a small portion of the information modeling problem. Nonetheless, it supports features that incorporate an explicit representation of component behavior and engineering process in an information model. These features enable the development of a test case that offers decision support for a task and demonstrates the potential for such technologies to encapsulate corporate knowledge for reuse, better decision making and improved business process.

3.2 Implementation

3.2.1 Detailed Description

The valve sizing task is properly described as the analysis and evaluation phase for designing a control function of a process stream. The diagram below, adapted from [Kunz 1996] depicts a form, function, behavior view of the valve sizing task in light of Gero's design process framework and Clayton's interpretation objects. In step 1 the user manually 'interprets' a sub-system of the P&ID diagram. Through Interpretation, a symbolic representation of the component model links with a product model for which it provides the control function. The design decision support of the component model consists of its ability to predict and assess the behavior of a control condition for a given piping sub-system and set of functional requirements defined by a process stream. Step 2 shows the 'feature constraints for Behavior' and the 'Requirement constraints for behavior' relations between the relevant line and steam form and function objects and the predicted

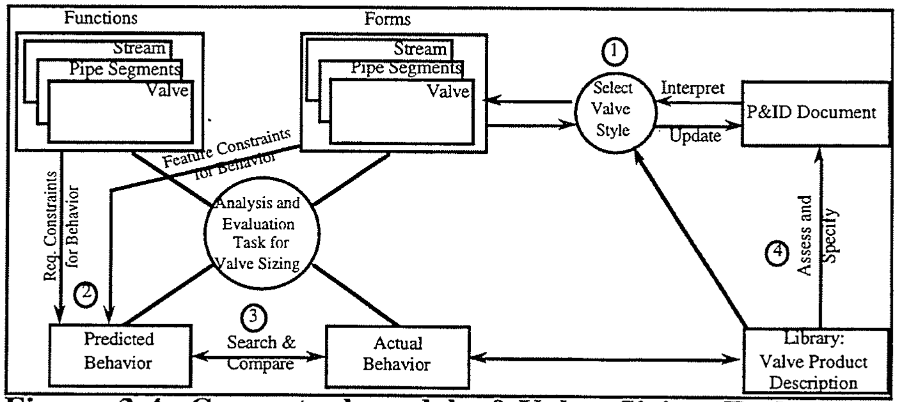


Figure 3-4. Conceptual model of Valve Sizing Task

valve behavior object. The predicted behavior represents the required performance condition, given the form and function constraints that are provided. Step 3 occurs during the 'Critique' phase. The predicted valve behaviors are computed and compared with the actual behavior of available valve products that are available in a component library. In step 4 the user assesses the products that match or exceed the requirements and selects a valve for the design.

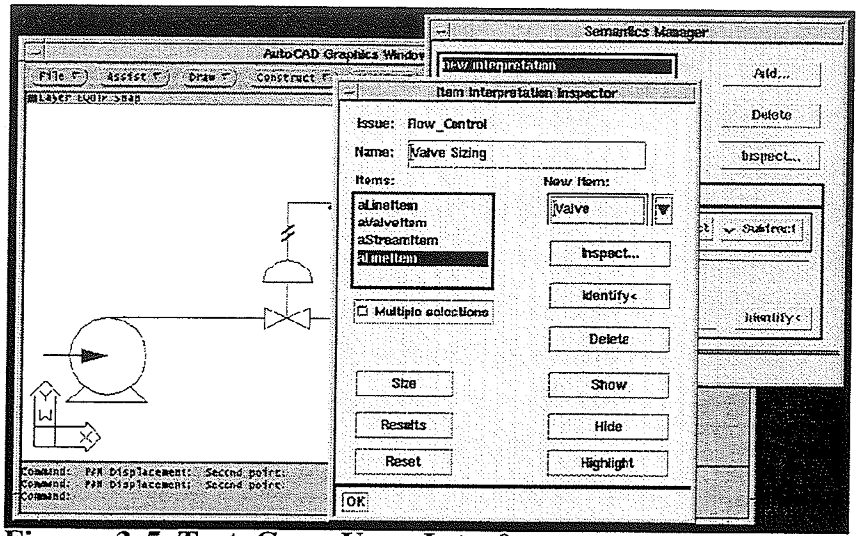
To perform this service, the model represents the valve's thermodynamic properties, the thermodynamic characteristics of the piping system in which it is installed and the process engineering knowledge for calculating a correct valve size. To support preliminary control valve sizing computation and analysis, the component information model incorporates [ISA 75.01 1991] standard sizing algorithms.

The test case performs this task for incompressible fluids. It does not represent a geometric valve description or its spatial configuration within a process plant. This modeling work has been performed within STEP [ISO CD 10303-227 1995]. In addition, the model does not yet represent valve trim, bonnet and actuator materials or other accessories. These elements are not necessary to perform preliminary sizing. However, as per the information requirements identified in Part 2, it would be necessary to represent these items if the reasoning functionality were extended to support valve material selection, specification, operations, and maintenance activities.

As mentioned above, many commercial software applications provide design decision support. Several programs assist users to specify control valves [Fisher 1993]. The difference is that the test case is model based. It reifies the valve behavior within the design model and captures behavioral state conditions of the valve under different functional load conditions. Conceptually, any project participant could query the product model to perform this analysis. Process and behavior information is incorporated into the product model and can be reused easily. Conventional software applications do not represent this information explicitly.

3.2.2 Application Description

Figure 3-5 shows the valve sizing *Interpretation Inspector* and the P&ID CAD representation. Each piping sub-system item in the list box named *Items* is associated with an element in the CAD drawing. When the user **Inspects** an item, an *Item* dialogue box opens (not shown) in which the user assigns properties and functional requirements. Once the annotation is complete, the user presses the **Size** button to invoke the *Interpretation Critique.* The user then views the *Critique* results by pressing the **Results**



Issue: Flow_Control

Name: Valve Sizing

New Item: Valve

```
Command:  P&N Displacement:  Second point:
Command:  P&N Displacement:  Second point:
Command:
```

Figure 3-5 Test Case User Interface

button. From the *Results* dialogue box, the user can select an appropriate valve for the product model. The implementation uses the AutoCAD R12, Sun workstation platform. The symbolic models are developed using the Intellicorp Kappa object oriented programming environment for Sun OS, UNIX.

3.2.3 Test Case Information Model

This section describes the test case information model structure using Conceptual Dependency Diagrams (CDD) that are generated from the Kappa object model. A CDD is itself an object model generated by an application written for Kappa. The CDD application extracts class objects, class object relationships, and methods from a source Kappa application (e.g., the test case) to show the class sub-class specialization hierarchy, the relations between objects that are not in the same graph, and the methods that are associated with each class. While less expressive than general diagramming techniques (EXPRESS-G, OMT, etc.), the CDD is useful because one can generate it directly from the Kappa development environment. CDDs do not indicate class instanciation. Figure 3-6 indicates how to read a CDD. Refer to Appendix D for an object model figure that shows the run time instances that are generated from a valve sizing Interpretation. Each run time instance is part of an Interpretation (explained below), and can be identified by its name suffix.

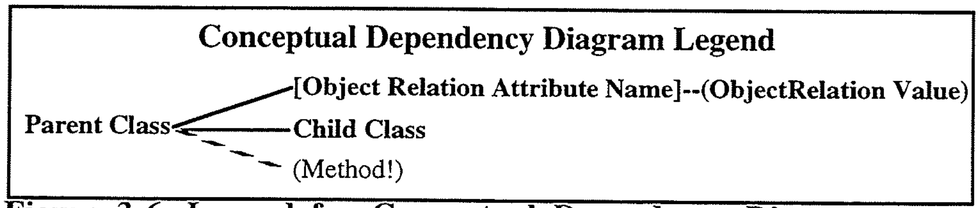


Figure 3-6. Legend for Conceptual Dependency Diagram

The suffix name is derived from the CAD drawing file with which the Interpretation is associated. For the diagram in Appendix D, the suffix is <@*testdwg*>. Figure 3-7 (below) shows the object named **Pipe_Sys_Item** (PSI). Subclasses of PSI offer logical representations of the plant items that are necessary to perform valve sizing for a given control valve placement. Child classes of the PSI include **Line** (pipe segment), **Stream** (process media), and **Valve**. When a valve sizing Interpretation is created, instances of the Pipe, Line, and Valve objects are generated. They link to graphical elements in the CAD system. The object relation attributes: PSI_Function, PSI_Form, and PSI_Behavior link the logical PSI objects to appropriate Form, Function, Behavior objects for each logical object type. The FFB objects are instanciated during the Interpretation process. The methods bound to the PSI objects perform object management for these relations.

The VPPM (Virtual Process Plant Model) object contains the methods for creating the link between the symbolic model in Kappa and the CAD representation. Figure 3-7 also shows the Valve Critique object. An instance of this object is generated each time the user invokes an Interpretation Critique (by clicking on the **Size** button in the Interpretation Inspector). It holds the valve sizing analysis and evaluation results for a given set of functional conditions (see forward). Figure 3-8 (see forward) shows the Form class objects. Instances of **Line_Form** represent different nominal pipe diameters, classification ratings and materials. These instances are predefined and are not generated at run-time. The association of the FFB object to the PSI logical object is transparent for the user. In the case of the **Line_Form** object, it occurs when the user selects a line diameter in the *Line Item Inspector*.

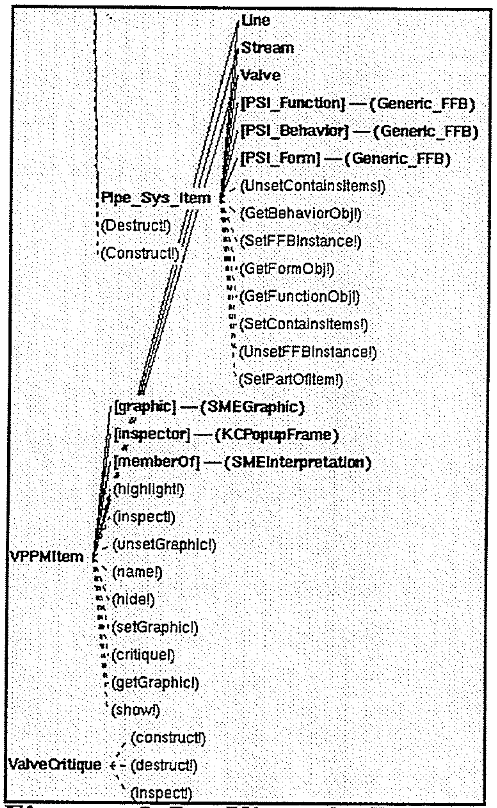


Figure 3-7. Virtual Process Plant Model Item (VPPM) & Pipe System Item Objects

A logical object **Line** can be associated with any one **Line_Form** instance. The methods associated with the **Line_Form** class furnish the piping geometry factor (Fp) when it is necessary to account for pipe swages. The sub classes of **Valve_Form** correspond to the different valve types that are distinguished by shape (geometry), not by function. Note that Valve Form objects provide constraints for valve behaviors through the object relation attribute *FeatureConstraintsForBehaviors*. These object relations reify Gero's assertions about the causal relationship between form, function, and behavior summarized in section 3.1.3. Much like instances of Line_Form, Valve_Form instances are predefined and cannot be modified by the user. The methods bound to the **Valve_Form** object are 'Get' functions for the following attributes: valve style modifier (Fd), liquid pressure recovery factor (Fl),and Laminar flow factor (Fs).

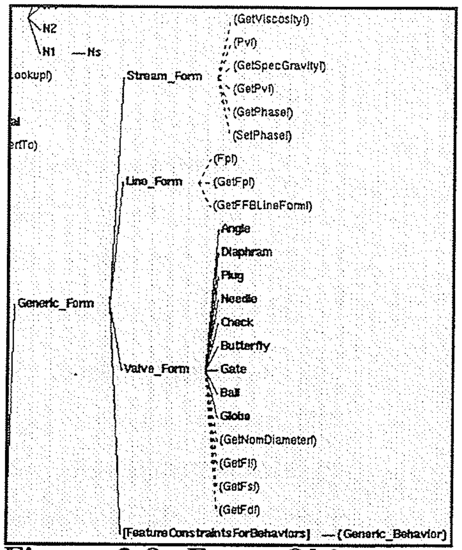


Figure 3-8. Form Objects

Figure 3-9 lists the Function and Behavior objects that relate to the Line, Stream, and valve objects. Instances of the **Line** and **Stream** function classes are generated at run time when the user enters the functional criteria for each functional case. For valve sizing there are normally three functional cases to consider: minimum, maximum and upset flow conditions. However, N functional stream instances can be generated for a given Interpretation. A Behavior instance is generated for each functional case when the user invokes an Interpretation Critique. Each function object relates to a corresponding behavior object through the object relation attribute *ReqConstraintsForBehavior*. The inverse object relation attribute is *DerivesFromReqConstraints*. The behavior methods bound to **Valve_Behavior** are of primary interest for valve sizing. They include:

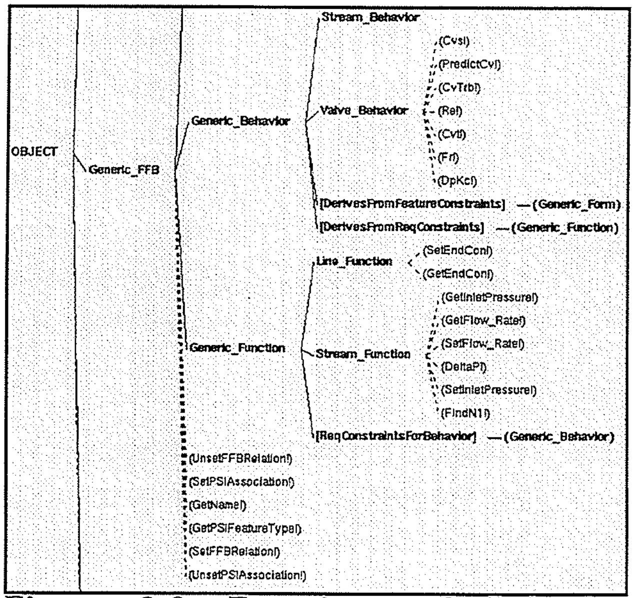


Figure 3-9. Function and Behavior Objects

- Coefficient of Flow, laminar flow(Cvs!);
- Coefficient of Flow, transition flow (Cvt!);
- Coefficient of Flow, turbulent flow (CvTrb!);
- Reynolds number (Re!);
- Reynolds number factor (Fr!);
- Predict coefficient of flow (PredictCv!);
- Determine whether a valve will Cavitate (DpKc!).

The method PredictCv! formalizes an engineering process. It is called from the Interpretation object method Critique! (see forward). PredictCv! encapsulates the engineering reasoning (logic) for valve sizing analysis by determining the proper way to compute the sizing algorithm based upon the functional conditions (laminar, transitional, or turbulent flow).

Figure 3-10 shows the Interpretation object called **Flow_Control_Interpretation**. This object furnishes the method Critique! which invokes valve behavior object instanciaton and sets the object relations described previously. From within the Critique! method, a newly instanced valve behavior object invokes the PredictCv! method described previously to perform the valve sizing analysis. Then, the Critique! method searches for a valve library object type (e.g., ButterflyType) that matches the users choice for the valve style (valve form object) and the valve type Search! method is invoked. Search! compares the predicted valve behaviors determined from invocation of PredictCv! with the actual behaviors of valve type instances that are predefined in the library. Figure 3-11 shows the simple library representation developed for the test case. It shows the logical object **ValveLib** with logical object sub classes for the various valve types. These valve types have instances that refer to the same FFB classes as the product model described previously. Run time generated instances of **Valve_Behavior** to compute candidate valve performance are

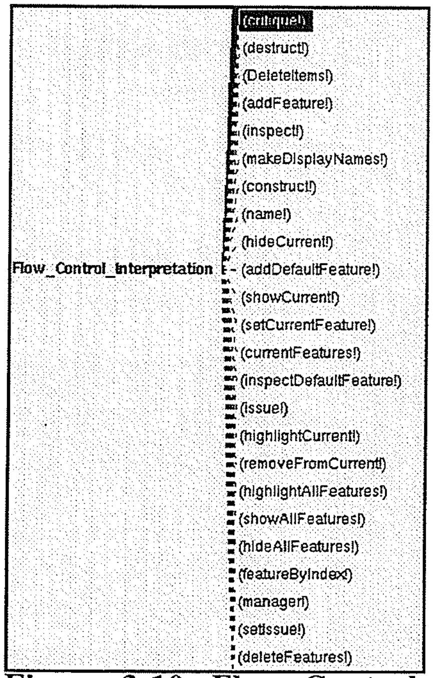


Figure 3-10. Flow Control Interpretation Object

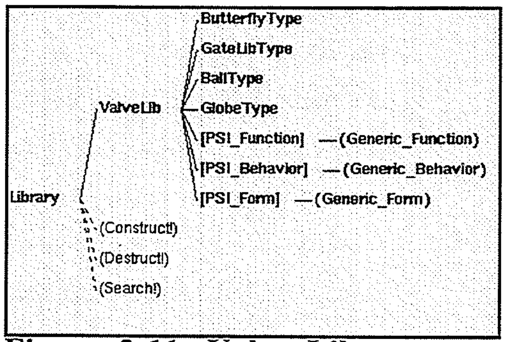


Figure 3-11. Valve Library

differentiated from predefined, library supplied behaviors through a naming convention. Predefined valve behavior instance names have the prefix <*Actual*>. Note that the object relation attributes have the same name as those utilized for the PSI objects. In a more robust implementation, the FFB objects and properties may be separated for the library and product models. For the test case, this implementation was expedient.

Information Model Summary

The information model for the test case reifies Form, Function, Behavior objects for each piping system component type and explicitly associates them to logical objects that represent a relevant portion of a piping circuit. Generation of the instances for Form objects are predefined from standard component descriptions. The user can select size or style options for each component type through the user interface. Function objects may be generated (e.g., stream functional cases) at run time. There are two types of behavior instance: predefined or *actual* behaviors that describe tested component performance, and *predicted* behaviors that are generated at run time during valve sizing analysis and evaluation. The valve sizing equations (ISA coefficient of flow formulas) and the comparison of actual to predicted behavior according to engineering analysis logic constitutes the 'reasoning' of the system. This behavioral reasoning is encapsulated within methods.

The SME approach enables two degrees of product model definition flexibility. First, an Interpretation can be developed for any evaluation and analysis reasoning that should be performed for a design. The dynamic annotation of Interpretation objects to a CAD representation allows the user to add semantic schemas as needed. Second, the separation and explicit association FFB objects to a logical product model enables further flexibility in the information model structure. The dynamic linkage of FFB types to a logical representation enables a range of functional and behavioral representations to be expressed according to constraints that are specific to form, function, and behavior properties.

It is understood that whether model semantics have an a priori, static definition or are assigned at run time, the issue of standard representation for semantics persists. Without agreement on the semantics of content representation, information sharing is not possible. Through the explicit representation of behavior and process in addition to form and function, SME/FFB adds two additional dimensions to the modeling challenge and thereby significantly increases modeling complexity. The fact that there is currently no conceptual classification of Interpretation (process description) or FFB objects indicates the relative immaturity of the approach and its current lack of generality and extensibility. This is a matter for further research.

Nonetheless, SME demonstrates the integrated representation of object form, function, behavior, and task based process. The test case implementation reifies the constraint relationships that are formalized in design process theory and indicates that they may be useful concepts for the development of model based evaluation and analysis software services. Such concepts and services are not available yet in the standard product data representation initiatives.

3.2.4 Concept Validation

To date, validation efforts for the test case have been informal. Nonetheless, the process model was described and the implementation was demonstrated to representatives of an E/C firm who had participated in the information requirements study. The response was positive. The formalization of process corresponded well to how engineers work. The concept of placing an analysis tool on the engineer's desktop that integrates with the design model was consistent with the business improvement goals for the company. After the demonstration, representatives from the company have indicated interest in participating and extending the project.

The engineering reasoning and valve sizing output of the test case was validated by comparing it with the output of a commercial valve sizing program for the same input parameters. This test was successful.

Part 4. Conclusion

The project basis of the A/E/C industry leads to enterprise organization and information technology (IT) support systems that are fragmented. This problem manifests through communication problems, errors, delays, and increased cost for project participants. The first requirement for correcting IT support for this business problem lies in the standardization of product data representation. This is the challenge of ISO STEP, and more recently the IAI. These initiatives provide a data structure and content foundation for software vendors to develop integrated applications that improve communication between enterprises.

Information integration through product data standardization solves only part of the business problem. It is also possible to formally describe processes, the things that individuals and organizations do with product data to achieve project goals. The integration of product and process description in an executable program can lead to software services that offer significant benefit through task automation, increased data and knowledge reuse, better decision making and improved coordination.

To understand the information content issues of modeling components for such services, this research has:

- Studied the business issues of information exchange and the life-cycle information requirements for the components that are installed in process plant facilities;
- Investigated standards development for component and product information models;
- Identified engineering tasks and coordination requirements that an information model should support for one component type and attempted to generalize the requirements;
- Implemented a test case that begins to explore integration of a component information model with a task based process model to provide decision support.

4.1 Accomplishments

4.1.1 Case Study Observations

The study of business and information requirements results in a detailed process description of the 'life of a valve'. In this description the major tasks associated with valves are highlighted across the facility life cycle. This exercise identifies several component information requirements that are not yet addressed by APs 221 and 227. In particular, it is necessary to describe the parts that comprise a component and develop a formal description of component behavior (predicted and observed) to satisfy the requirements for detailed process engineering, plant commissioning, and operations and maintenance activities. Such extensions would make information models useful for a broader range of business purposes, and in particular, the facility owner/operator would benefit.

The broad range of life cycle requirements, and the impracticality of capturing them for all modeling purposes also indicates the necessity for a conceptual data model that can support schema evolution. A complete a priori definition of complex engineering objects will be very difficult to achieve.

The study also focuses on a description of the engineering knowledge requirements for a specific task, preliminary control valve sizing. This is done to understand the requirements for describing a task based process and the interaction between process, product data and behavior during the activities of designing. The exploration of these relationships lead to another important observation of the study. An integrated description of product and process can lead to conceptual information models that support task automation.

Current STEP modeling efforts develop process models to gain an understanding of the information requirements that should be included in the ARM for an AP. However, AP development makes no effort to formally describe process and integrate it with the object models that are produced. There is no formal validation whether the information models actually satisfy the process requirements.

Furthermore, the modeling tools offered by EXPRESS limit the 'state of the art' for STEP information models. They do not yet support a description of object behavior or process, nor do they integrate a product data, behavior and engineering process description. PLIB does support the description of object behavior and it may one day provide support for library management systems (non standard implementations) that can provide task automation services for part procurement. However, presently PLIB does not offer an integrated link for graphical representation of parts and product models. In addition, PLIB does not explicitly model task process.

The existing models reviewed for this study are useful for improving product data exchange, but they are not intended to support the sharing of engineering knowledge and decision support reasoning capability. In this sense, they do not furnish an underlying IT capability to improve knowledge (as opposed to information) distribution, access, and use. While it is recognized that the scope of such an effort would be very large (and require more resources than are available), the current modeling efforts miss a business opportunity to support fundamental business process change.

4.1.2 Generalization of the Information Requirements

After investigation of the requirements for one component type, the research generalizes them for use in a broader context. Although the categories require validation for other component types, it is hoped that they are a useful starting point for component description purposes. Hopefully, they are valid also for describing component information that relates to process description for task coordination as well.

4.1.3 Test Case Implementation

The test case demonstrates an example of product and process description integration in support of task automation. It formalizes a description of the piping sub system elements that are necessary to perform preliminary valve sizing and, through the use of Interpretation and Critique objects, it formalizes the valve sizing task within the product model.

The test case performs work in a matter of seconds that interview respondents note may take several hours to perform manually per control valve given the time required for information search, analysis and incorporation into project documents. Most important, it demonstrates the usefulness of a component evaluation and analysis software service that interacts directly with the design model.

4.2 Challenges

4.2.1 Knowledge acquisition

First, knowledge acquisition is difficult and time consuming. It turns out that the engineering knowledge to understand and model control valves is technically complex and their specification can be as much art as science. The interview process turned up professionals who had spent their career studying and understanding the problems associated with control valve specification, usage and maintenance. In addition, control valve specification is not always an exact engineering problem. For functional conditions that involve process media in the transition phase, the sizing algorithms are inexact and require expert judgment given the actual design conditions. In addition, control valve engineering very often is dependent upon the upstream conditions of the process circuit. This creates a problem framework issue. It is quite possible for the component specification issues to develop into a configuration management problem which is overly complex and perhaps intractable.

4.2.2 Component Information Model Design

Review of the information model structure provided in Appendix D shows that the implementation is relatively ad hoc and lacks generality for the definition of the Form, Function and Behavior objects. Note that the purpose of the test case was to demonstrate the potential for an information model that integrates a component (properties and behaviors) and process description, not to define a canonical information model structure. Nonetheless, the object hierarchy for FFB objects jumps directly from "Generic" objects to sub-classes specialized directly for control valves. Without a set of common FFB primitives from which more complex objects can be derived, it will be impossible to share information between models and systems [Phan, Howard 1993]. A conceptual hierarchy for form, function, behavior objects is a matter for further investigation and research. In addition, there is no conceptual hierarchy to characterize the process description that is reified within the Interpretation object. Doing this would require extensive work to classify processes and decompose them into to sharable primitives as well.

Several information models were reviewed prior to developing the prototype. The concept of the pipe_system_Iitem object to represent the logical description of the pipe, stream, and valve entities was adapted from ISO AP 227. Further parallelism with other models was not attempted. It was decided that this would be too time consuming without direct contact and interaction with the persons who developed the other models. Even attribute assignment for the various objects was subjective. It was based upon best judgment at the time the implementation was developed. While the rationale for the model structure and properties was subjective, the goal was to be internally consistent with the definition of structure and assignment of attributes and behaviors.

The ad hoc nature of the test case and the general variance of modeling methods (e.g., AP221 and AP227), indicates the need for the development of "good" modeling principles and, vitally important, a set of metrics for the evaluation of information models.

4.2.3 Limits of FFB

In Section 3.1.3 and 3.2.2 it was noted that the FFB paradigm could be extended. Applying the substance properties for the process media to a Form object was not a natural or intrinsic way to describe process media. The Form properties associated with the process media had little relation to the Form properties for the pipe and valve. Resolution of this issue should be performed within an effort to develop a coherent and homogenous set of characterization hierarchies for FFB objects.

The FFB paradigm is clearly not applicable for the task coordination and administration information requirements that move beyond product description to data associated with a component class or supplier.

4.2.4 Conceptual View Framework

The SME work raises an important issue concerning the dynamic assignment of Interpretation objects to a product model. It is plausible to consider a library of Interpretation objects from which a user annotates the entities in a product model. However, predefinition of Interpretation information for the product description would improve the efficiency of design model generation. From the perspective of a component library, it would be necessary to develop a conceptual view framework to support multiple component representations for various design and engineering tasks. The PLIB conceptual model offers a compelling basis for this framework. It offers a mechanism for homogenous characterization of component attributes at the class level (General and functional classes). Also, it enables users to organize and access information according to domain specific practice (Semantic dictionary). Last it supports multiple representation (functional views) of components so that information access can be organized according to usage requirements. Other work that formalizes process description within the A/E/C industry includes [Levitt, Hayes-Roth 1989] who develop the OARPLAN construction planner. In addition, the computational organizational modeling literature contains references to research that investigates conceptual frameworks for process description [Malone, Crowston, Lee, Pentland 1993], [Lee, Yost, and PIF Working Group 1994]. This research discovered no work directly related to formalization of engineering and business tasks for the process industries.

4.3 Direction for Future Research

In the future it will be possible to offer interoperable software services for nearly any hardware platform over distributed networks. Design and engineering professionals will be able to tap information and task knowledge from a 'virtual' desktop comprised of resources available within the company and from external enterprises. They will be able to incorporate this formalized knowledge into project work directly and thereby leverage it for greater productivity.

To build towards this vision, plans for future work include further investigation into the integration of product and process description for component models. To validate and compare the findings for control valves, a second case study will be performed to either 1) understand the process requirements for another task related to control valves, or 2) understand the information requirements for design analysis and evaluation of another component type. From these findings, the research will investigate a task-based view framework for a conceptual data model that improves support for product and process model integration.

We also hope to understand the potential business impact of software services based on such models by developing a new test case that demonstrates component object transactions using the World Wide Web. The test case will show access, retrieval, and use of component information objects for design and procurement between a component supplier and a user. The objects that are accessed from the supplier will integrate seamlessly into the user's CAD system or a project database management system. The test case will be implemented in Java to enable the creation of component objects that support the behavior and process descriptions developed in this report.

Understanding the software management issues for interoperable, distributed objects will be another goal of future research. In this effort, it hoped that our work, which focuses on information content, representation, and process functionality, can be joined with CIFE work by others that investigates the network middle ware requirements for interoperation of legacy software applications that are developed using different languages and hardware platforms [Kunz, Law, Howie 1996].

Appendix A
Companies and Individuals Involved in Research Interviews

	Contact	Position
Owners **Chevron Corp.**	Stan Koloboff	Corporate R&D, Standards
Du Pont	Bob Pigford	Vendor Manager and ex-E&I consultant/design engineer
Merck	Susan Jones	Engineer
Engineering/ Contracting Firms **Bechtel**	Larry Damon Steve Lynch Pepe Edlinger Ken Cooke Dale Hauglum Dave A. van Staveren	Mgr., Engineering Technology R&D Mgr., Engr. & Const. Technology Manager, R & D Project engineering manager Manager, supplier quality Engineering Supervisor
Fluor Daniel	Chris Jorgensen Mark Murphy Randy Fix	Head of engineering systems Process engineer Engineering Technology Development
Brown and Root, Inc.	James Klein	Mgr., Engineering Systems Development
Valve Suppliers **Associated Process Controls**	Jim Carson Rick Ash	Director of Sales Technical engineer/marketing
Fischer Rosemont	Ray Michael Jerry Trout Bill Fitzgerald	Technical engineer/marketing Marketing Process engineer
Grove Valves	Jack Coulter	Engineering Manager
Information Integrators **Autodesk Inc.**	Ian Howell Ed Clapp Brian Cummings Kiumarse Zamanian Richard See	Dir. A/E/C and FM. Senior software engineer and Manager, data exchange group. Sales and Marketing AEC Market Group Product Manager, Interoperability Products
Information Handling Services	Jim Sutton George Thomas Bruce Black Bentley Smith	VP, Electronic product development Marketing Manager VP, Marketing Dir., Information Integration

	Daniel J. Burk Bruce G. Norton Mark Strandquist Jeanne Donohue Walt Bryant William A. Mass Jay Jordan Paul Kennedy Bernie J. Michalek	Dir., Information Integration Dir., Info. Management Vendor and GSA Senior Mgr., Vendor products Marketing, Vendor Products Component Engineer, Parameter Database Engineering Product engineer President and COO, US Operations Senior Director, Information Management VP, Marketing, US Operations
EDI Vendor **Sequoia Corp.**	Jim Pitts	Principal, Sequoia Corp.
Other Organizations **CIMIS**	Matthew Tatro Bill Knittle Joe Hetchman	Engineer/developer Co-chair, CIMIS Co-Chair, CIMIS

Appendix B

Organizations Involved in the Development of Product Modeling Standards for the Process Industries

CAESAR Offshore	**CAESAR Offshore** is a European consortium organized to develop products and methodologies which will enable European oil and natural gas industries to use digital information effectively in offshore development and operation, and to redesign work processes and organization around new information and communication technologies. Participants in CAESAR include "Statoil, Norsk Hydro, Saga Petroleum, Aker Dvaerner, Det Norske Veritas, The Norwegian Institute of Technology (NTH), The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF), and The Federation of Norwegian Engineering Industries (TBL).
CALS	***Computer Aided Logistic and Support Initiative*** Begun initially by the Department of Defense in the 1980's, CALS activities have extended from the defense contracting industries to manufacturing industry in general as companies realize the improved efficiencies through data standardization.
CIAG	***Construction Industry Action Group*** An action group for the Construction Industry Institute (CII/CIAG)
CIMIS	***Common Industry Material Identification Standards*** CIMIS is supported by the American Petroleum Institute/Petroleum Industry Data Exchange (API/PIDX), CII/CIAG, and the Pipes Valves and Fittings roundtable (PVF).
EDIFACT	***United Nations/Electronic Data Interchange For Administration, Commerce and Transport.***
ISO/TC184/SC4	**International Standards Organization, Technical Committee 184, Sub Committee 4**
EPISTLE	**European Process Industries STEP Technical Liaison Executive** The mission of EPISTLE is to "identify potential collaboration between parties (in Europe) involved in developing standards for the exchange of technical information, and to organize and deliver technical solutions to those problems" [SIPM ICG/2 1995].

PDXI	**Product Data eXchange Institute** PDXI has formed from the AIChemE. PDXI developed a process simulation data model that is the basis for AP 231 under development.
PIEBASE	**Process Industries Executive for achieving Business Advantage using Standards for data Exchange** A new consortium made up of all the consortia and companies involved in the development of STEP standards in the process industry. PIEBASE will function as a management and coordination body for the other efforts.
PISTEP	**Process Industries STEP Consortium** A UK based consortium of large plant owners and engineering contractors dedicated to the development of STEP standards.
PlantSTEP	**PlantSTEP** A US based consortium of process plant owners and engineering contractors dedicated to the development of STEP standards.
POSC & (POSC/CAESAR)	**Petrotechnical Open Systems Corporation** Based in Houston, the POSC mission is to develop standards for a Software Integration Platform for the oil (upstream) industry with a focus on subsurface information.
SPI-NL	**Cooperative Association for the Process Industry in the Netherlands** "Samenwerkingsverband Process Industrie-Nederland" (SPI-NL), a Dutch based consortium of large plant owners and engineering contractors whose charter is to promote the development of STEP standards.

Appendix C
Information Requirements Matrix

			Properties			Behavior			
Phase	**Task**	**Information Requirement**	Assigned	Design Req.	Design Std.	Measured	Computed	Administration	
Conceptual Process Design									
	Stream Definition								
		Stream							
		Chemical composition	X						
		Phase	X						
		Fluid pressure in pipe		X					
		Vapor pressure	X						
		Density	X						
		Viscosity	X						
		Temperature		X					
		Specific gravity	X						
		Min. steady state controlled flow rate		X					
		Max. steady state controlled flow rate		X					
		Max. flow rate to recover from a flow disturbance		X					
Detailed Process Design									
	Preliminary Valve Sizing								
		Pipe							
		Nominal diameter		X					
		Applicable design code (ASME)		X					
		Class (material)		X					

Flange rating (pressure rating)		X					
Pipe geometry factor factor (Fp)	X						
Stream (Min, Max, Upset functional cases)	**Same as flow rates above**						
Inlet pressure at valve		X					
Outlet pressure at valve		X					
Pressure drop across valve		X			X		
Pressure differential shutoff		X	X				
Valve							
Stream		X					
Nom. diameter		X					
Valve style modifier (Fd)	X						
Noise level (db)				X			
Liquid recovery pressure factor (Fl)	X						
Laminar flow factor (Fs)	X						
Coefficient of flow					X		
Coefficient of flow, laminar stream (Cvs)					X		
Coefficient of flow, transitional stream, (Cvt)					X		
Coefficient of flow, turbulent stream, (CvTrb)					X		
Reynold's number (Re)					X		
Reynold's number factor (Fr)					X		
Cavitation factor (Kc)					X		
Predict Cv for service cases					X		
Search for acceptable valve options					X		
Valve Geometry (envelope dims)	X						
Valve weight	X						
Center of mass	X						
Electrical Ports	X						
Elec. hookup Requirements	X						

Detailed Engineering Design

Valve Material Selection

Environment							
Electrical hazards		X					
climate (temperature range, precipitation)		X					
atmospheric contamination (corrosion)		X					
Plant procedures							
Washdown		X					
Contamination		X					
Valve body							
Project Id (Tag)						X	
Nom. dia		X					
ANSI Class		X					
Material		X					
End connection type		X					
No. Ports		X					
Travel direction to open		X					
Flow direction		X					
Trim							
Id						X	
Cage material		X					
Bushing material		X					
Seat ring material		X					
Valve plug							
Id						X	
Material		X					
Guiding type		X					
Balance type		X					
Port size		X					
Opening characteristic		X					
Shutoff class		X					

Bonnet							
Style		X					
Boss size		X					
Packing		X					
Bolting							
Bonnet		X					
Packing Flange		X					
Actuator							
Style		X					
Size		X					
Air to Actuator		X					
Valve action on air failure		X					
Handjack position	X						
Positioner							
Type		X					
Input signal		X					
Accessories		X					
Valve action on signal increase		X					
I/P Positioner							
Certification		X	X				
Explosion-proof approval		X	X				
Intrisically safe approval		X	X				
Transducer							
Input signal		X					
Output signal		X					
Action		X					
Mounting		X					
Airset		X					
Certification		X	X				
Explosion-proof approval		X	X				
Intrinsically safe approval		X	X				

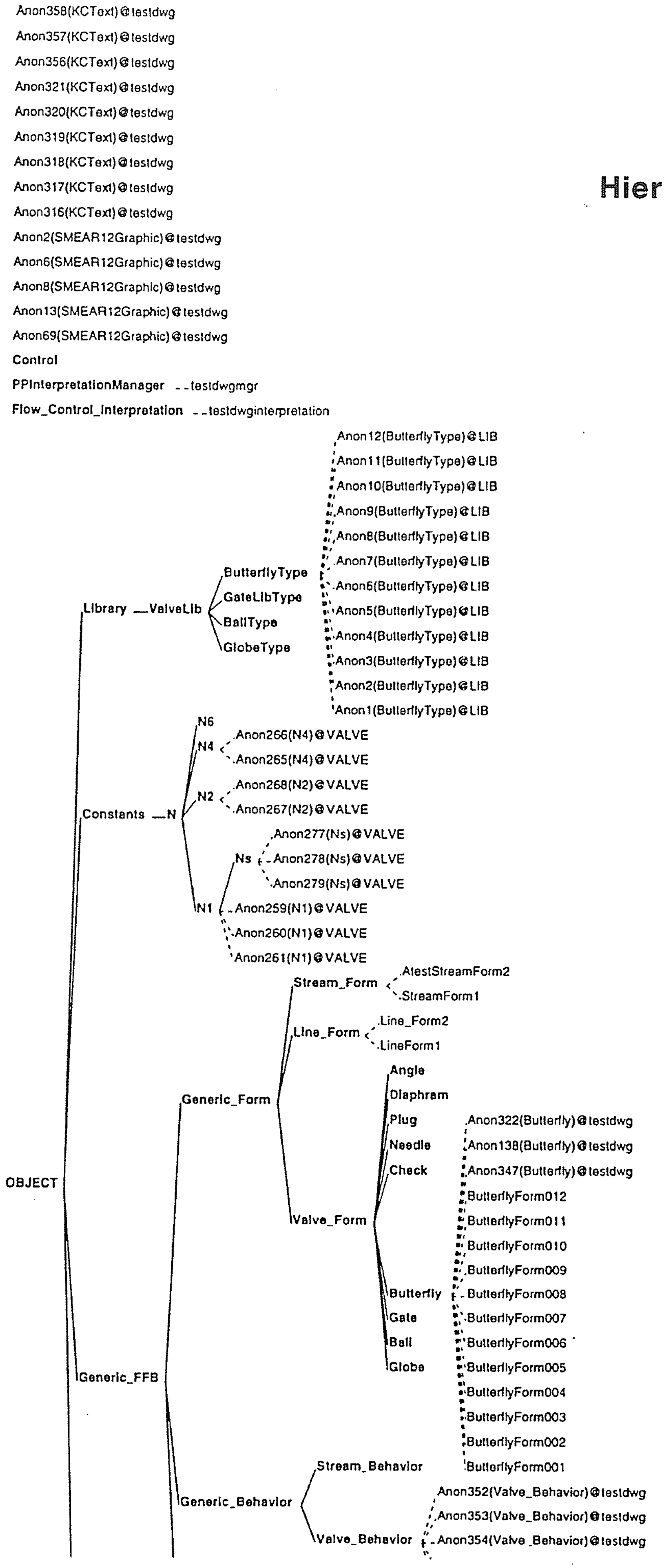
		SelectBodyMaterial		X			X		
		Evaluate trim given service reqs and business rules					X		
		Eval. trim type per performance degradation (see maintenance)					X		
		Evaluate packing given service reqs and air quality regs					X		
Procurement	**Maintain Vendor List**								
		Preferred Vendors						X	
		Pre-qualifications							
		Product List and Spec sheets.						X	
		Product Prices						X	
		Product Reps.						X	
	RFB Package								
		Functional requirements	X	X	X	X	X	X	
		Contractual requirements						X	
	Vendor Review of RFB and Issuance of Tender Documents								
		Vendor Valve Spec Recommendations (see valve sizing & material selection above)	X	X	X	X	X	X	
	Evaluate Bids								
		Review Vendor Tender Documents (see valve sizing & material selection above)	X	X	X	X	X	X	
	Purchase Order								
		PO Id						X	
		Item list w/product IDs						X	
		Project tag nos for each item						X	
		Prices						X	
		Final contract conditions							

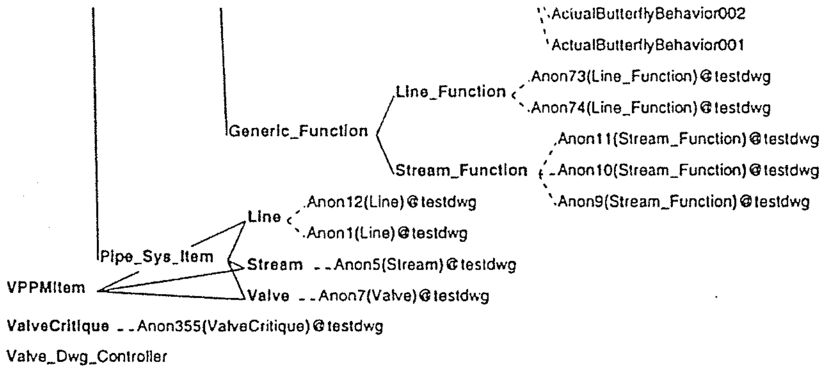
	Delivery								
		Tests			X				
		Env. Reqs			X				
		Installation procedures	X		X				
		Operation manuals			X			X	
		Delivery dates						X	
		Shipping Manifest							
		Delivery date						X	
		Valve data sheets						X	
		Test results (Hydro, seat leakage, RT, PT, MT)						X	
		Environmental. reqs.						X	
		Installation procedures	X						
		Interface procedures (special coatings, etc.)	X						
	Structural Installation								
		Support reqs.		X					
		Location		X					
	Mechanical Installation								
		Class sheets	X						
		P&ID drawings	X						
		Weights	X						
		Envelope dimensions	X						
		Installation procedures	X		X				
	Electrical Installation								
		Elect hookups		X					
		Voltages		X					
		Safety requirements		X					
	Inspsection								
		(all installation reqs. above)		X					

Commission Process									
	Tests								
		Benchmark operationg values from hot and cold commission tests and conotol systems tuning (see maintenance diagnostics, see below)							
		Trip Test values (verify safety operation of control valve for upset conditions)							
Maintenance									
		Part identification and property description							
		Vendor id						X	
		Part id (serial no.)						X	
		Part Properties		X					
		Test approvals		X					
	Overhaul evaluation diagnostics								
		Stem travel				X			
		Instrument signal				X			
		Instrument air to positioner				X			
		supply pressure				X			
		actuator pressure				X			
		Actuator spring rate and bench set					X		
		Valve stroke and friction					X		
		Stroking speed					X		
		Seat load					X		
		Stem-nut adjustment					X		
		Air supply pressure					X		
		Positioner calibration, linearity and hysteresis					X		
		I/P calibration linearity and hysteresis					X		
		Packing friction					X		
		Maintenance management information **Time-based history of;**							
						X			
		Maintenance vendor						X	

		Service provided						X	
		Material procurement		X				X	
		Material vendor						X	

Appendix D
Kappa Object Hierarchy Diagram




ActualButterflyBehavior002
ActualButterflyBehavior001
Line_Function
Anon73(Line_Function)@testdwg
Anon74(Line_Function)@testdwg
Generic_Function
Anon11(Stream_Function)@testdwg
Stream_Function
Anon10(Stream_Function)@testdwg
Anon9(Stream_Function)@testdwg
Anon12(Line)@testdwg
Line
Anon1(Line)@testdwg
Pipe_Sys_Item
Stream
Anon5(Stream)@testdwg
VPPMItem
Valve
Anon7(Valve)@testdwg
ValveCritique
Anon355(ValveCritique)@testdwg
Valve_Dwg_Controller

Appendix E
A/E/C Application Protocols

- **Electrical**
  - AP 212 Electromechanical design and installation
- **Ship Building**
  - AP 215 Ship Arrangements
  - AP 216 Ship Molded Forms
  - AP 217 Ship Piping
  - AP 218 Ship Structures
  - AP 226 Ship Mechanical Systems
- **Process Plant**
  - AP221 Functional Data and its Representation
  - AP227 Plant Spatial Configuration
  - AP231 Process Engineering Data: Process Design and Process Specification of Major Equipment
- **A/E/C**
  - AP 225 Structural Building Elements using explicit shape representation
  - AP 228 Bldg. Services HVAC
  - AP 230 Bldg. Structural Frame: Steelwork

Appendix F
ISO 13584 PLIB Documents (Parts)

The following documents are in development process or are proposed within the PLIB initiative:

Part 1	Overview and fundamental principles;
Part 10	Conceptual model of parts library;
Part 20	General resources;
Part 24	Logical model of supplier library;
Part 26	Supplier identification;
Part 31	Programming interface;
Part 42	Methodology for structuring part families;
Part 101	Geometrical view exchange protocol by parametric program;
Part 102	Geometrical view exchange protocol by ISO 10303 conforming specification.

References

[Arnold, Teicholz 1996] Arnold, J. A, Teicholz, P.: 1996, Data Exchange for Construction Components: File Transfer, Transaction Processing and Application Interoperability *in* Third Congress on Computing in Civil Engineering. ASCE, Anaheim, CA, June 17-19

[Chevron corp. 1993] Chevron Corp.: June 1993, Instrumentation and Control Manual, Section 900, Control Valves

[Clayton, Fruchter, Krawinkler, Kunz, Teicholz 1993] Clayton, M. J., Fruchter, R., Krawinkler, H., Kunz, J. and Teicholz, P.: 1993, Propose-Interpret-Critique-Explain: A communication cycle for collaborative conceptual building design, in Gero, J. S. and Maher, M. L. (eds.), *AI in Collaborative Design*, AAAI, Menlo Park, CA, pp. 287-292

[Clayton, Kunz, Fischer, Teicholz 1994] Clayton, M. J., Kunz, J. C., Fischer, M. A., Teicholz, P.: 1994 First drawings, Then Semantics. *in Reconnecting, ACADIA94.* (eds.) Anton Harfmann and Michael Fraser, Association for Computer Aided Design in Architecture, 1994. pp. 13-26 .

[Clayton, Fruchter Krawinkler, Teicholz 1994] Clayton, M. J., Fruchter, R., Krawinkler, H., and Teicholz, P.: Interpretation Objects for Multi-Disciplinary Design *in* J. S. Gero and F. Sudweeks (eds.), *Artificial Intelligence in Design* '94, 573-590. Kluwer Academic Publishers. Printed in the Netherlands

[Clayton, Fischer, Kunz, Fruchter 1995] Clayton, M. J., Fischer, M., Kunz, J., and Fruchter, R.: 1995, Behavior Follows Form Follows Function: A Theory of Design Evaluation *in* Second ASCE Congress on Computing in Civil Engineering, Atlanta GA.

[Dym & Levitt 1991] Dym, C. L., Levitt, R. E.: Knowledge-Based Systems in Engineering. © 1991 McGraw-Hill, Inc. ISBN 0-07-018563-8

[Eastman 1995] Eastman, C. M.: 1995, Managing Integrity in Design Information Flows *in Computer Aided Design*, IPC Press

[Emerson 1990] Emerson, C.: 1990, Control Valves: Predictive Techniques in addition to a regular maintenance program will improve valve performance and safety throughout your plant *in* Chemical Engineering, May, 1990

[Fisher 1993] Fisher Sizing Program, Revision 1.41. Copyright © 1989-1993. Fisher Controls, International, Marshalltown, Iowa

[Fitzgerald 1990] Fitzgerald, W. V.: 1990, Automated Control Valve Trouble-Shooting: The Key to Optimum Valve Performance *in* Instrumentation Society of America paper #90-142, by courtesy of Fisher Controls

[Galbraith 1977] Galbraith, J.: 1997, Organization design. Reading, Mass.: Addison-Wesley Pub. Co., © 1977. ISBN 0-201-02558-2

[Gero 1995] Gero, J.: 1995, The Role of Function-Behavior-Structure Models *in* ASCE 2nd Congress on Computing in Civil Engineering, June 5-7, 1995

[Howie, Kunz, Binford, Chen, Law 1995] Howie, C., Kunz, J. C., Binford, T., Chen, T., Law, K. H.: 1995, Computer Interpretation of Process and Instrumentation Drawings *under review for* The Fourth International Conference on the Application of AI Techniques to Civil and Structural Engineering, (CIVIL-COMP 95) Developments in Computer Aided Design and Modeling for Civil Engineering, Ed. by B.H.V. Topping, Civil-Comp Press, pp. 13-20, 1995.

[ICAM 1981] ICAM, Integrated Computer-Aided Manufacturing Function Modeling Manual IDEF0, report UM 110231100, June 1981

[IFC 1995] Industry Foundation Classes: 1995, Industry Foundation Classes Management Overview. Industry Alliance for Interoperability

[ISA 1976] ISA Handbook of Control Valves, 2nd Edition © 1976, Instrument Society of America, Pittsburgh Pennsylvania

[ISA-S75.01 1991] ISA-S75.01, Standards and Recommended Practices for Instrumentation and Control, 11th edition ©1991. Instrument Society of America, 67 Alexander Dr. P.O. Box 12277, Research Triangle Park, North Carolina 27709

[ISO IS 10303-11 1994] ISO IS 10303-11: 1994, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 10303 Product data representation and exchange - Part 11: Description methods: the EXPRESS language reference manual

[ISO WD 10303-221 1995] ISO WD 10303-221: 1995, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 10303 Product data representation and exchange - Part 221: Functional data and their schematic representation for process plant

[ISO CD 10303-227 1995]. ISO CD 10303-227: 1994, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 10303 Product data representation and exchange - Part 227: Plant Spatial Configuration

[ISO CD 13584-10 1995]	ISO CD 13584-10: 1995, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 13584, Parts Library - Part 10: Conceptual Descriptions: Conceptual Model of Parts Library
[ISO CDC 13584-20 1994]	ISO CDC 13584-20: 1994, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 13584, Parts Library - Part 20: General Resources
[ISO CD 13584-24 1995]	ISO CD 13584-24: 1995, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 13584, Parts Library - Part 24: Logical Model of Supplier Library
[ISO DRAFT 13584-31 1994]	ISO DRAFT 13584-31: 1994, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 13584, Parts Library - Part 31: Programming Interface
[ISO CD 13584-42 1995]	ISO CD 13584-42: 1995, International Standards Organization, Technical Committee ISO 184, Industrial automation systems and integration, Subcommittee SC 4, Industrial data and global manufacturing programming languages - ISO 13584, Parts Library - Part 42: Methodology for Structuring Part Families
[Khedro, Genesereth, Teicholz 1993]	Khedro, T., Genesereth, M. R., Teicholz, P.: 1993, FCDA: A Framework for Collaborative Distributed Multidiciplinary Design Workshop on AI *in* Collaborative Design, 11th National Conference on AI, July 1993, Washington, DC
[Koskela 1995].	Koskela, L.: 1995, On Foundations of Construction Process Modeling. *in* Modeling of Buildings through Their Life-Cycle. CIB Workshop on Computers and Information in Construction, August 1995, Stanford University, Stanford. CIB proceedings, Publication 180. Pp. 503 - 514
[Kunz 1988]	Kunz, J. C.: 1988, Model Based Reasoning in CIM. Intellicorp 1988, Mountain View, California 94040
[Kunz 1996]	Kunz, J. C.: 1996, Rapid Conceptual Design Evaluation Using a Virtual Product Model. Center for Integrated Facilities Engineering Technical Report No. 105, 1992

[Kunz, Law, Howie 1996]	Kunz, J. C., Law, K. H., Howie, C.: 1996, A Model-Based Approach to Software and Data Interoperability for Process Plant Applications, CIFE Seed Proposal, INT9601. Center for Integrated Facilities Engineering, Stanford University, Stanford, CA 94305-4020
[Law 1992]	Law, K. H.: 1992, Managing Design Information in a Shareable Relational Framework. CIFE Technical Report No. 60, 1992. Stanford University, Stanford, CA 94305-4020
[Lee, Yost, and PIF Working Group 1994]	Lee, J., Yost, G., and the PIF Working Group: 1994, The PIF Process Interchange Format and Framework, Version 1.0, December 22, 1994. MIT Center for Coordination Science Working Paper 180
[Levitt, Hayes-Roth 1989]	Levitt, R. E., Hayes-Roth, B.: 1989, OARPLAN: Generating Project Plans in a Blackboard System by Reasoning about Object, Action and Resources, CIFE Technical Report No. 2, 1989. Stanford University, Stanford, CA 94305-4020
[Liset, Moen, Myklebust 1994]	Liset, H., Moen, H., Myklebust, O.: 1994, Standard Parts Requirements Specifications, External Edition (unpublished). CAESAR Offshore Standard Parts Project. Document DC 2320, December, 1944.
[Luth, Krawinkler, Law 1991]	Luth, G. P., Krawinkler, H., Law, K., H.: 1991, Representation and Reasoning for Integrated Structural Design. CIFE Technical Report No. 55, June, 1991. Stanford University, Stanford, CA 94305-4020
[Maintenance Technology 1992]	1992: Predictive Maintenance for Control Valves *in* Maintenance Technology Magazine, an Applied Technology Publication/December 1992
[Malone, Crowston, Lee, Pentland 1993]	Malone, T., Crowston, K., Lee, J., Pentland, B.: 1993, Tools for inventing organizations: Toward a handbook of organizational processes. Working Paper #141 Center for Coordination Science, Massachusetts Institute of Technology, May 1993. In Proceedings of the 2nd IEEE Workshop on Enabling Technologies Infrastructure for Collaborative Enterprises, Morgantown, WV, April 20-22, 1993.
[NIJ 1989]	Nijssen, G. M., Halpin, T. A.,: 1989, Conceptual schema and relational database design, A fact oriented approach, Department of Computer Science University of Queensland, Prentice Hall, ISBN 7248-0151-0
[Nolan, Norton & Co. 1987]	Nolan, Norton & Co.: 1987, Managing Personal Computers in the Large Organization, Capital Investment, Business Strategies, Human Resources. Prepared for Lotus Development Corporation

[P.D.I.T. 1992] Product Data Integration Technologies (P.D.I.T.): 1992, Standard for the Exchange of Product Model data (STEP),

An Overview. P.D.I.T. 3780 Kilroy Airport Way, Ste. 430 Long Beach, CA 90806

[Petrie 1993] Petrie, C.: 1993, The Redux Server *in* Proceedings of the International Conf. on Intelligent and Cooperative Information Systems (ICICIS), Rotterdam, May, 1993.

[Phan, Howard 1993] Phan, D. H., Howard, C. H.: 1993, The Primitive-Composite (P-C) Approach - A Methodology for Developing Sharable Object-Oriented Data Representations For Facility Engineering Integration. CIFE Technical Report 85A, August 1993. Stanford University.

[Phelps, Wilensky 1995] Phelps, T. A., Wilensky, R.: 1995 Multivalent Digital Documents in UC Berkeley's Digital Library Project, *in* SIGLINK, Vol. 4, No. 2, September 1995.

[PISTEP 1994] Process Industries STEP Consortium: Issue 1 July 1994, Process Plant Engineering Activity Model

[Rumbaugh, Blaha, Premerlani, Eddy, Lorensen 1991] Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., Lorensen, W.: 1991, Object-Oriented Modeling and Design. © 1991, Prentice-Hall, Inc. ISBN 0-13-629841-9

[Sanvido et al 1994] Sanvido, V. et al: January 1990, An Integrated Building Process Model *in* Report of Research Sponsored by the National Science Foundation, Grant No. DMC-8717485, Technical Report No. 1, Copyright January 1990, Computer Integrated Construction (CIC)

[Schenck, Wilson 1994] Schenck, D. A., Wilson, P. R.: 1994, Information Modeling: The EXPRESS Way. © 1994 Oxford University Press. ISBN 0-19-508714-3

[SIPM ICG/2 1995] Shell International Petroleum Company, Limited, London, Information and Computing Division (IC): September 1995, The Future of Engineering Information, Report No. IC94-063, (ed.) Matthew West, SIPC-ICT/47,