ABSTRACT

Title of Document: **MODEL BASED SYSTEMS ENGINEERING APPROACH FOR COLLABORATIVE REQUIREMENTS IN COOLING WATER SYSTEM DESIGN**

Binyam Abeye, Master of Science, 2013

Directed By: Professor John Baras
Department of Electrical Engineering and ISR

Evaluation of the manufacturing process industry confirms that there is still manual exchange of product data between design and procurement engineers and equipment suppliers. Manual data exchange incurs human error, increases the cost, and takes more time. Also manual data exchange prevents designers from automatically evaluating a larger pool of suppliers and verifying supplier requirements. This thesis proposes to develop a collaborative requirements framework using a Model Based System Engineering approach to representing, communicating, and verifying requirements. Collaborative requirements entail that equipment data and process system requirements are shared in a common way to encourage automated of equipment tradeoff and requirement traceability. The collaborative requirement framework includes SysML to represent the multiple views of requirements, Multilevel Flow Model functional diagrams to depict the high level qualitative functionality, and lastly an optimization tool to verify requirements. Overall, this thesis shows the benefits of using the collaborative requirements framework automating data exchange between design engineers and equipment suppliers.

MODEL-BASED SYSTEMS ENGINEERING APPROACH FOR COLLABORATIVE REQUIREMENTS IN COOLING WATER SYSTEM DESIGN

By

Binyam Girma Abeye

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Masters of Science
2014

Advisory Committee:
Professor John Baras, Chair
Professor Mark Austin
Professor Linda Schmidt

Acknowledgements

At the beginning of this all was my dear Professor Baras. I am thankful for risk he took in giving me this opportunity and his patience with me through the ups and down. Though the time was short, he has taught life lessons that greatly appreciate. Next I would like to extend a sincere word of gratitude to the very knowledgeable researchers I work alongside with at the National Institute of Standards and Technology (NIST). Mark Palmer was a tremendous help in getting me up to speed with my project work, both on this thesis and NIST work. Additionally, the information he was able to attain through teleconferences and meetings with industry gave me the opportunity to even write this thesis. Without his persistence and reminders I don't know what I would have done. Peter Denno was a highly great aide in guiding my technical research and the approaches I should take for my thesis. The many one-on-one discussions helped me gain clarity and direction with what I wanted to do for my research. Edward Barkmeyer was the one that brought everything all together. His wisdom was by far one of the most valuable aspects of working at NIST that I will take with. Over the time I have worked at NIST I have probably talked with him the most and he is never bashful to let me know the truth about anything. His candor was priceless and impacted me in many ways. Also I would like to acknowledge my system engineering professor, Professor Mark Austin. He has aided me through most of my systems engineering course and has taught me many lessons. His openness and ability to drop whatever he is doing to listen to my concerns was priceless. I don't know if this thesis would be as it is without his guidance and multiple inquisitions about "how is it going?" Also I would like to show

great appreciation for the guidance and leniency shown to me by Professor Linda Schmidt. The independent study I worked with her has enlighten me about much of the topics that my thesis is involved with. I thank her for her continued support and willingness to sit on my committee. Last, but most definitely not least, I would like to thank my family and friends. My family has bear with me much and this very well may be their thesis, which is the reason I am dedicating this thesis to them. Their unconditional love was a strong foundation that would be impossible for me to fathom what I would do without it. My friends both inside and outside the office were great in keeping me sane and giving me advice in all aspects of life. I am blessed to have these people in my life that have supported me in a vast amount of ways. I thank you all from the bottom of my heart. Finally, this research was supported by the NIST research grant 70NANB11H148 under the Collaborative Requirements Engineering (CRE) project.

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Chapter 1: Introduction

Problem Statement

The aspiration for the future in manufacturing is automatic access of supplier data for manufacturing design engineers easily evaluate and determine the best suppliers for their system components. Additionally the designer's manufacturing requirements will trace to the specific attributes of the supplier equipment in an easy automated way. Overall this automated process of building manufacturing systems will lead faster, cheaper, and with less probability of errors manufactured systems.

Today the exchange of manufacturing equipment data and system requirements is a manual process where both the design engineers and equipment suppliers must manually input system requirements and equipment data into their own data management systems to evaluate information. This type of data exchange is costly not only in time and money of the design engineers and suppliers, but also in quality and performance of manufacturing systems, which affects all users of the manufacturing system.

Therefore this thesis will propose a method for the representation, communication, and verification of requirements to aid the data exchange process between the design engineers and equipment suppliers. The method will include system engineering principles and optimization techniques. Specifically system engineering principles deal with integrating all the disciplines in the development process from the concept to operation and it considers both the business and technical needs of all customers and their goals [1].

Current Trends

In the manufacturing industry there is a big push for smart manufacturing. Smart manufacturing is the application of information technology into all aspects of the manufacturing process and products, which can fundamentally change how products are invented, manufactured, shipped and sold [2]. Introduced in the late 1990s, smart manufacturing is now reemerging as the solution to data management and enhancing manufacturing operations because of the new technological innovations with software management tools. Companies such as IBM [3] and Siemens [4] are using smart manufacturing principles in software to increase productivity and efficiency. One of the major software solutions for smart manufacturing is Product Lifecycle Management (PLM).

PLM software evaluates the business processes that govern a product from the beginning to the final stages of a product's life cycle to produce the best possible value for the business of the enterprise, customer, and other involved partners [5]. Some examples of successful use of PLM software (e.g. Siemens PLM NX) include the collaboration between NASA and JPL to design and simulate the latest Mars rover Curiosity [6]. Such cases show that PLM can be beneficial to the design of products, but there are also some caveats to their usage.

First, PLM software conflicts with the processes set in place by manufacturing companies. Usually, one-off software solutions are created by manufacturing company engineers to support their version control, partner collaboration, change approval management, and other applications. With PLM all those custom functions become obsolete [7]. As a result, PLM limits the business and engineering capabilities of the manufacturing company. Secondly, PLM struggles with dealing with domain-specific knowledge (information specifically important to the manufacturing company). Differing perspectives on the product domain lead to poor verification of data. As a consequence information flow is poorly linked between the design engineers and equipment suppliers. This problem is embodied by companies like Bis-sell Homecare, who have a tremendous amount of domain-specific knowledge and struggles to represent that information in PLM software. Instead companies like Bis-sell have resorted to knowledge-based engineering (techniques that capture decision-making knowledge and also offer a medium for exploiting efficient strategies used by experts [8]). Currently Bis-sell has expressed interest into system engineering techniques to strengthen their knowledge-based engineering [9].

Proposed Methodology

This thesis shows how Model Based System Engineering (MBSE), functional modeling, and optimization tools can aid in traceability, communication, and verification analysis of system and component requirements. By using MBSE, functional modeling, and optimization tool requirements (both qualitative and quantitative) can be verified in a way that the current PLM systems are unable to do (mainly in the information flow and tracing of that flow). Additionally this method will allow for requirement and equipment data exchange between different suppliers and customers in the business enterprise by the use of data models (represented using MBSE). As a result, product data and their associated constraints are communicated automatically between multiple participants, spanning across the lifecycle of a project and allowing for better reasoning on requirements.

The first part of the framework is the system models, created by MBSE principles. MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [10]. This modeling formalism is used because it allows for the representation of system structure and behavior, as well as allow for the representation of textual and quantitative requirements in an integrated manner. As a result, MBSE allows for requirement management, ensuring the organization of requirements documents. Specifically within requirement management MBSE allows for tracing, prioritizing, change management, and communicating requirements. The MBSE language used is Systems Modeling language (SysML) because it is an industry-standard, providing good visual modeling to support system engineering [10].

Functional modeling is used because of its ability to represent a products or subsystem's overall function with respect to a formal function representation [11]. This allows for a higher abstraction for representing how functions are related. One type of functional modeling language is Multilevel Flow Modeling (MFM). MFM was designed for industrial process functional modeling and allows for the representation of how functions satisfy high level requirements (labeled as goals within MFM). Therefore, MFM is highly useful because of its ability to represent qualitative requirements and how they relate to requirements in a formal way (that fosters to reasoning). This thesis will focus on using MFM to perform functional modeling.

Lastly, an optimization tool is used because of its ability to verify requirements and determine the best system designs. Along with verification, such tools also allow for greater understanding as to how requirements are effect certain low level behavior and structure. These attributes are highly desirable in this framework because they quantify the impact of requirements and how they relate to all parts of the system. Also, this functionality allows for deeper understanding into how the system can be improved by altering equipment specifications (low level structure), which enable negotiation. The optimization tool used in this thesis is IBM ILOG CPLEX Optimization Solution because of its strong mathematical programming solver, which is capable of high order mixed integer programming.

Figure 1 shows the steps this thesis will follow to trace from system requirements to conceptual design of a water cooling system. The process begins by collecting requirements for the water cooling system from various design and procurement engineers. Then the equipment specifications, process specifications (qualitative requirements), and operational specifications are derived. Finally the equipment requirements are represented in SysML, process requirements are represented in MFM diagrams, and the operational requirements are represented in the optimization tool. Once modeled the requirements from each part of the framework are linked with respect to their shared requirements. This thesis will apply this step by step approach for a water cooling system.

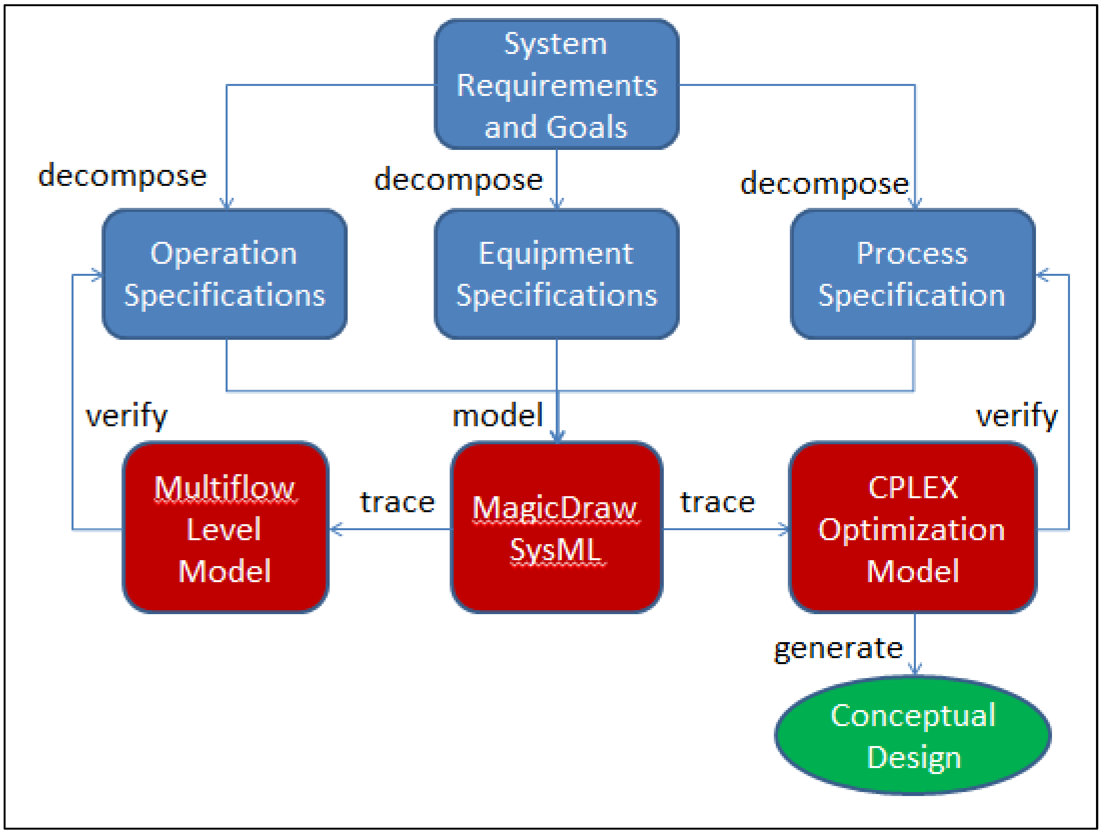


Figure 1 MBSE Approach for Process Plant Design

Thesis Overview

This thesis will demonstrate the collaborative requirements framework on a small process plant subsystem known as the Closed Loop, Heat Transfer, Liquid Circulating (CHL) system. Specifically, this framework will examine the process of representing, communicating, and verifying requirement during the final design and procurement phases of the CHL system lifecycle.

In Chapter 2, prior related research is compared to the concepts in the thesis. Chapter 3 describes the CHL system requirements (equipment, process, and operation) and the relationship of requirements. Chapter 4 summarizes SysML and how the CHL system was modeled in SysML. Chapter 5 introduces functional modeling with the MFM language and the software implementation to support the language. Chapter 6 defines how the optimization problem is formulated with respect to the operational requirements (represented as constraints) using CPLEX. Chapter 7 describes the results of using this framework for collaborative requirements. The results include the optimization results and the methods used for integrating the models. Discussion, evaluation and conclusion are in Chapter 8.

Chapter 2: Prior Related Work

Resource Description Framework (RDF) for Component Selection

RDF is a model for data exchange on the Web, but can be extended to show directed and labeled graph models. At the core of the models are triples, which are the linking structure of RDF. Triples represent the relation between two entities as "<Subject, Predicate, Object>" where the "Subject" and "Object" represent the entities and the "Predicate" represents the relation [12]. The two entities represent nodes in the graph and the relation is the edge between the entities. Previous work focused on RDF-based component selection. The project used RDF because it allowed for automated component and system requirement checking. Using RDF triples, plant equipment (pumps, heat exchanger, valves, and surge tank) were related to their attributes (pressure, flow rate, cost, etc.). This type of triple represented the product model for equipment. Next, triples were generated using inferences, which were based on component interface requirements. Inferences would check whether two equipment could be connected (e.g. If node is a pump and another node is a valve the inference generates a connection relation between the two nodes) and compatible (whether they could operate together based on engineering specifications). Figure 2 and Figure 3 show the results from the inferences. Lastly, a tradeoff analysis was conducted to determine the best configurations based on cost, reliability, and functionality.

For the thesis, the inference requirements of this work were used in the development of requirements used in the thesis. Also the idea of RDF was tested for requirement checking. Still RDF for the system component selection is still limited to evaluating component to component requirements and not system to component requirements (e.g. the power required for the pump based on all the components selected in the system). For this reason, RDF will only be explored for simple requirement checking. Also, the graphs would grow exponentially large if the attributes and component connections were managed in this way, making this method difficult to scale up.

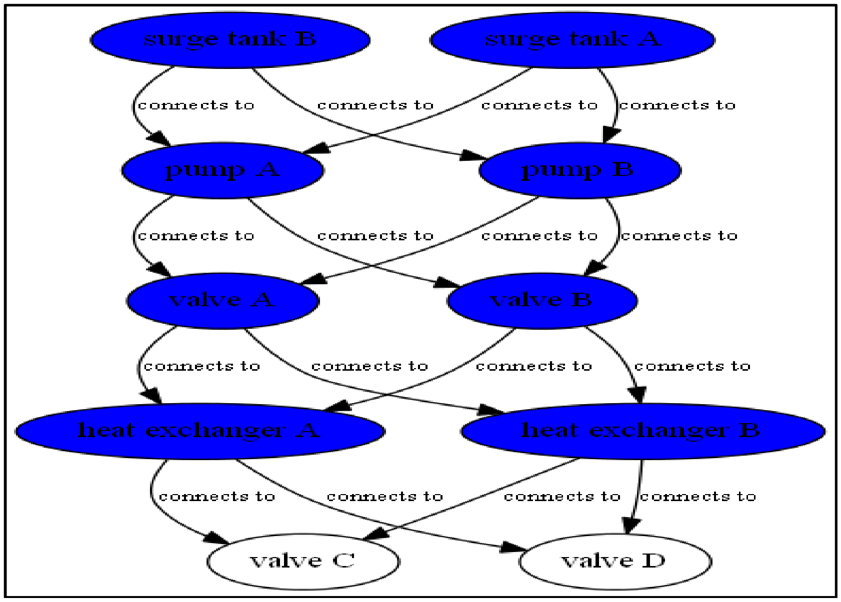


Figure 2 Connection Relation created by Inferences

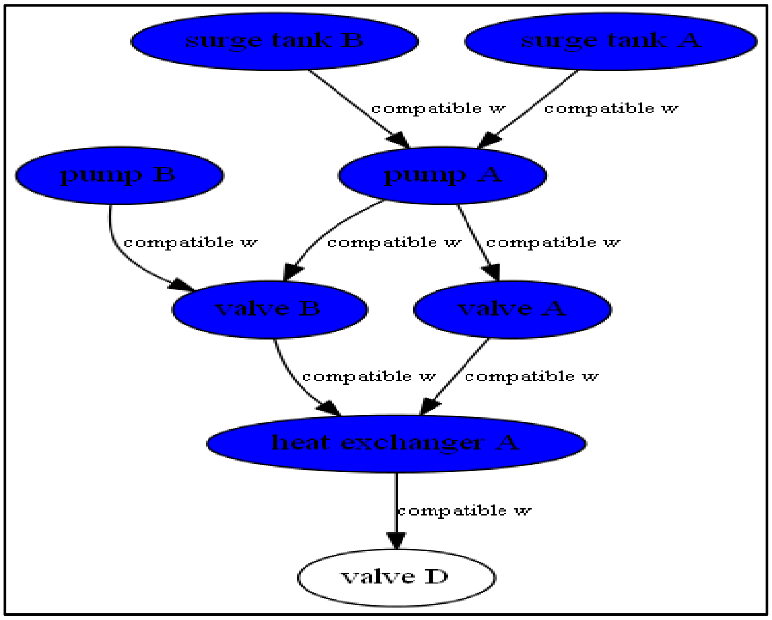


Figure 3 Compatibility Relation created by Inference

Product Data Sheet Ontology

Work conducted at the National Institute of Standards and Technology (NIST) focused on developing a Product Data Sheet Ontology (PDSO) for collaborative requirements. The reason for a PDSO was to push for automated data exchange. Currently, data in product data sheets are not computer interpretable, which prevents automated exchange. Ontologies provide meaning to the data sheet elements so that a computer can interpret and use the data for exchange. In order to develop a good ontology, a common dictionary of terms must be shared among all users of the ontology. Therefore, the PDSO mapped common data sheet terminology to standard-based terminology (ISO15926 part 4) and definitions. This ensured a common definition of data sheet terminology. PDSO ontologies were generated from the Unified Modeling Language (UML) models of a general data sheet and three common process components (centrifugal pump, valve, and pressure transmitter). This research uses the concept of modeling component data in a similar way to map terminology to standards, but modeling is in SysML.

Integrated Product and Process Design

Another motivation for using MBSE for collaborative requirements was the University of Maryland project on Integrated product and process design (IPPD). The IPPD is a decision making tool that aides the process for selecting components for the construction of a microwave modules. The tool optimized the component selection by reducing the cost, improving quality, and gaining leverage in time to market the product. To optimize the component selection, the tool used a multi-objective optimization model that selected the components and processes for a conceptual design that were Pareto optimal according to the previous metrics described. Overall, the tool improved the coordination and communication of requirements between the process design and product design by using a common interface [13]. Similar to the IPPD tool, this thesis aims to use a common interface (SysML) to coordinate and communicate requirements between the engineering design and supplier specifications. The thesis also used aspects of the IPPD architecture (in Figure 4) as guidance for incorporating the optimization.

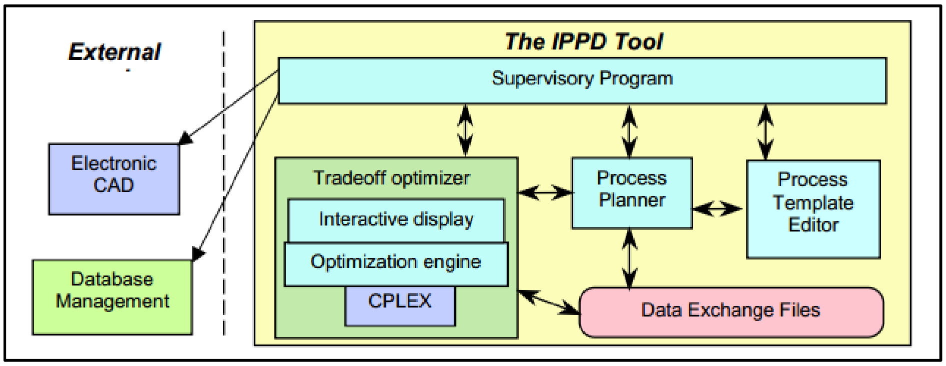


Figure 4 IPPD Architecture

Chapter 3: Closed Loop, Heat Transfer, Liquid Circulating System (CHL)

Introduction

The CHL system is a class of process cooling water system that focuses on temperature reduction of process fluid. The CHL system was develop through the Collaborative Requirements Engineering (CRE) project at the National Institute of Standards and Technology (NIST) [14]. The project involved working closely with representatives of the power and chemical process industries to identify a type of system common to many types of facilities and plants. The fruit of those discussions with industry was the CHL System. This thesis will use the CHL system because it is of the information provided by the project and the collaboration with industry. This collaboration from different industries permitted the comparing of multiple forms of information representation and determining the management challenges in requirements engineering.

CHL Description

A process flow diagram (PFD) shows the interconnection of components in the closed loop, heat transfer, and liquid circulating system (CHL) and the main equipment that will be focused on for this thesis (see Figure 5). As well as the piping, the main system component at will be examined are the surge tank (pressure vessel), centrifugal pump, control valve, and plate heat exchanger.

The goal of the CHL system is to remove heat from certain process fluids at a specific mass flowrate and heat load with recirculated cooling water within a closed-loop system. This goal is achieved by the centrifugal pump and plate heat exchanger. At start, the system is fully filled with water and a pump forces the flow of water by increasing the pressure of the fluid at the pump outlet. This pressure difference across the pump causes the water to flow through the pipes at a certain flow rate that is maintained throughout the system. The specific flowrate for the system is constant to allow for stable operation of the plate heat exchanger and other equipment. The plate heat exchanger inputs the cooling fluid at a certain temperature and flow rate to reduce the temperature of the process fluid that is also entering the heat exchanger. Entering through different ports and flowing through different chambers, the cooling fluid and process fluid exchange heat through the thin metal plates inside the plate heat exchanger. Afterward the cooling water exits the heat exchanger to be feed back to the inlet of the centrifugal pump and the process fluid is output to an external process system.

In addition to the centrifugal pump and plate heat exchanger, safety equipment is also used to support the main function. Safety equipment helps control and handles deviations in system pressure and temperature. Safety equipment include the surge tank, control valve, instruments, check valves, gate valves, and flow and temperature elements. This thesis will only focus on the surge tank and control valve in terms of safety equipment.

The surge tank provides the necessary pressure of the inlet of the centrifugal pump and also aids in temperature fluctuations in the system by changing the cooling fluid volume. The water level in the tank determines the outlet pressure of the tank. Therefore, changes in the water level result in changes to the outlet pressure. The outlet pressure serves the centrifugal pump operation. The centrifugal pump needs a certain inlet pressure to operate safely. In addition, the surge tank serves the system operation. When the system pressure surpasses certain limits of a level the surge tank will intake more cooling water, resulting in the water level in the tank increasing to accommodate for the system's over-pressurization. Similarly, when the fluid temperature in the feedback is too high the surge tank will intake the fluid, resulting in a water level rise. The reason this happens is because the temperature raises the pressure of the fluid.

Control valves are also included in the CHL system. The control valve maintains the flow rate of the cooling water in the system. In the CHL system they are located at the outlet of the plate heat exchanger and at the outlet of the refrigeration system .For this thesis we will only focus on control valves that proceed after the heat exchangers. They are used in situations when the cooling water flow rate or pressure rises or fall outside normal operation levels. The control valve reacts by either shrinking or widening its aperture to stabilize the cooling water's flow rate or pressure. Also the control valve is dependent upon instrumentation to react to system flow rate and pressure changes. Since instrumentation is not considered in this thesis, the main focus on the control valve will be on sizing it for the system minimum and maximum pressure and flow rate levels and not reaction time and other control aspects. Some of the parameters that would be focused on include the pressure drop and the maximum flow rate allowance.

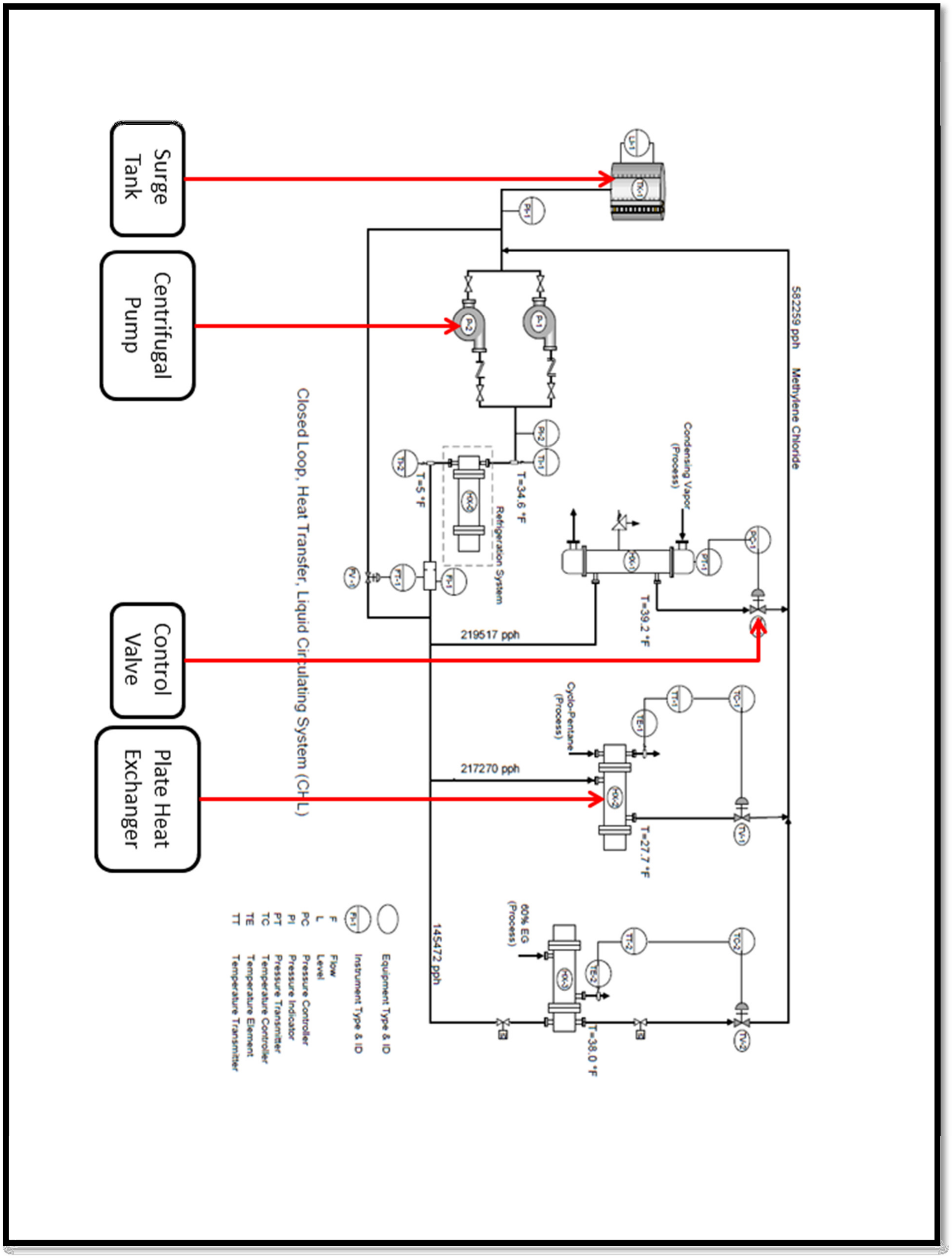


Figure 5 PFD of CHL System

CHL Requirements

The main sources of requirement information on the CHL system came from nuclear power industry, data sheet industry standards, and the chemical process plant industry. Each industry provided a different perspective on the CHL system and contributed their own requirements problems with respect to the representation, communication, and verification of requirements.

From the nuclear power industry, the CHL system is closely related to the component cooling water systems (CCWS), a common non-safety subsystem in a nuclear plant. Several CCWS control and requirement documentation were used for developing requirements for the CHL system. These requirements on components provided the key metrics that CHL equipment designers would need from component suppliers. Additionally, the DCDs also provided system requirements that showed how system specifications changed with respect to different scenarios of the system. From a greater standpoint, this information provided insight into what specifications were most important for communication with suppliers. An example of system and component requirements is shown below in Figure 6 [16] and Figure 7 [17].

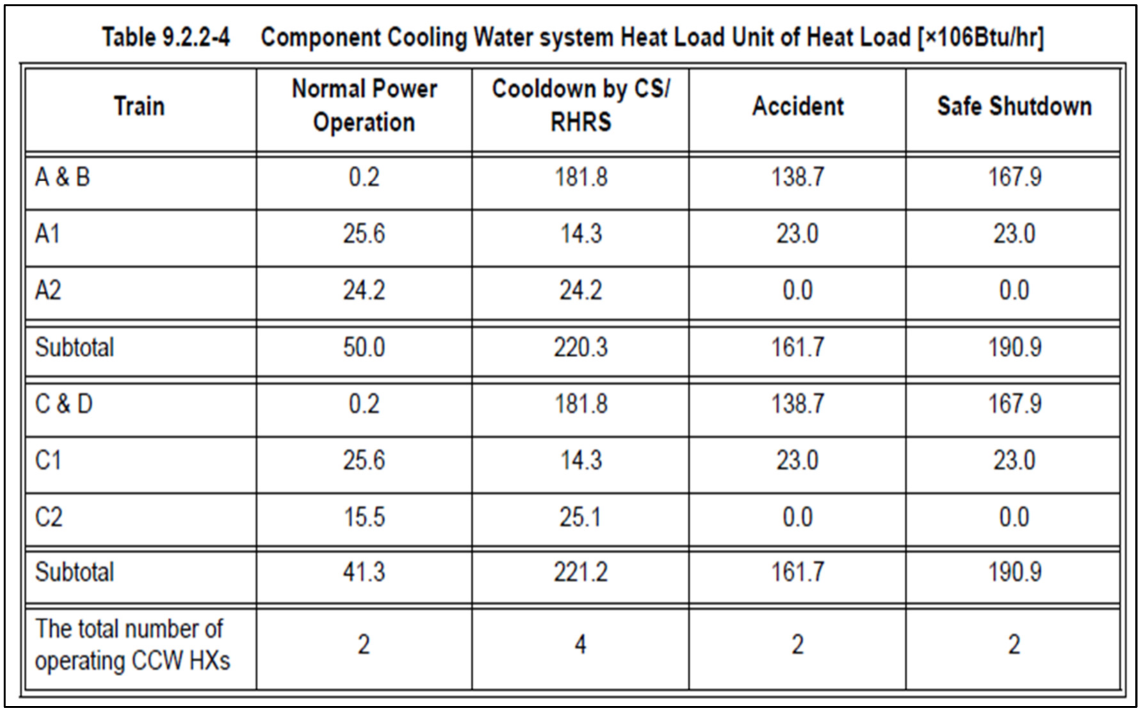


Table 9.2.2-4 Component Cooling Water system Heat Load Unit of Heat Load [×106Btu/hr]

Train	Normal Power Operation	Cooldown by CS/ RHRS	Accident	Safe Shutdown
A & B	0.2	181.8	138.7	167.9
A1	25.6	14.3	23.0	23.0
A2	24.2	24.2	0.0	0.0
Subtotal	50.0	220.3	161.7	190.9
C & D	0.2	181.8	138.7	167.9
C1	25.6	14.3	23.0	23.0
C2	15.5	25.1	0.0	0.0
Subtotal	41.3	221.2	161.7	190.9
The total number of operating CCW HXs	2	4	2	2

Figure 6 System Power and Heat Load Requirements from Mitsubishi

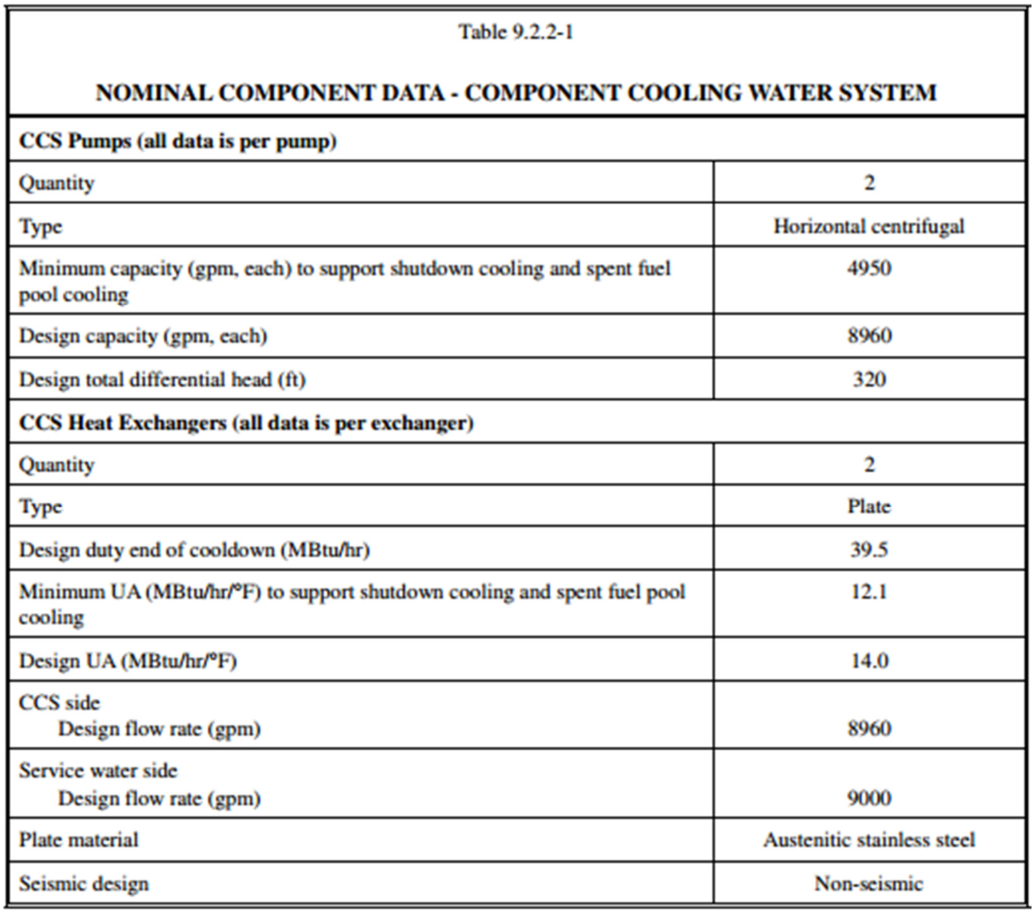


Table 9.2.2-1

NOMINAL COMPONENT DATA - COMPONENT COOLING WATER SYSTEM

CCS Pumps (all data is per pump)	
Quantity	2
Type	Horizontal centrifugal
Minimum capacity (gpm, each) to support shutdown cooling and spent fuel pool cooling	4950
Design capacity (gpm, each)	8960
Design total differential head (ft)	320
CCS Heat Exchangers (all data is per exchanger)	
Quantity	2
Type	Plate
Design duty end of cooldown (MBtu/hr)	39.5
Minimum UA (MBtu/hr/°F) to support shutdown cooling and spent fuel pool cooling	12.1
Design UA (MBtu/hr/°F)	14.0
CCS side Design flow rate (gpm)	8960
Service water side Design flow rate (gpm)	9000
Plate material	Austenitic stainless steel
Seismic design	Non-seismic

Figure 7 Component Requirements From AP1000 DCD

Industry data sheet standards also provided a variety of requirement specifications with respect to the standards domain. Specifically these requirements focused on CHL components. Of all the components, the centrifugal pump and heat exchanger were well represented in terms of standards. For the centrifugal pump ASME B73.1, ANSI/API 610, and ISO 15926 were incorporated to the component requirements. For the heat exchanger the ISO 15926 and private industry data sheets were used. For the control valve and surge tank the ISO 15926 and handbook data sheets were used. These requirements, as a whole, showed how the component requirements for the CHL were commonly represented for design and communication to suppliers.

In terms of the system requirements, the chemical plant industry provided project documentation, which gave insight into main requirements needed for specific aspects of design. Additionally, process simulation tools, such as CHEMCAD and AFT Fathom, provided clarity into how component requirements were verified. Overall collection of these system requirements provided an understanding of what CHL system requirements are most important for verification.

Another aspect that is important to the CHL system requirements is traceability. Most of the provided information involved specifications, irrespective of their development. Figure 8 shows the requirements taxonomy for the CHL system and how requirements for one component feed into the other components [17]. This is very important because it provides for traceability and requirement verification. These requirements will be reexamined in the modeling section to show how requirements are represented in this manner.

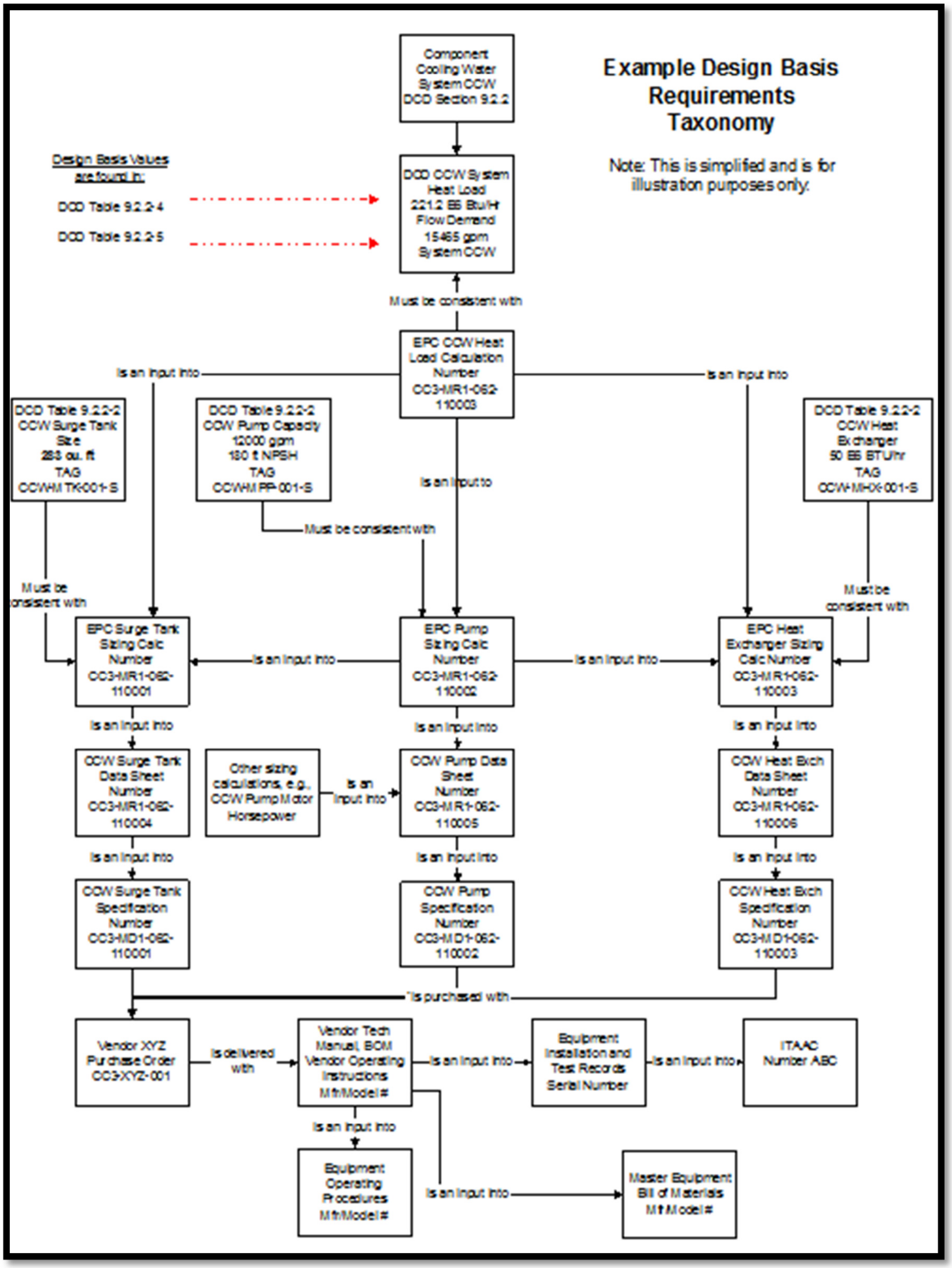


Figure 8 Design Basis Requirements

Chapter 4: Systems Modeling Language (SysML) for CHL

Introduction

To apply MBSE principles to the CHL system this thesis has proposed to use OMG Systems Modeling Language (SysML). SysML is the main language for implementing MBSE. It is a general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation of complex systems [18]. Figure 9 (below) represents the main diagrams supported by the SysML language [18]. The diagrams represent the behavior, requirements, or structure of a system. Primarily the models of most importance for the CHL are the activity, use case, block definition, internal block, parametric, and requirement diagrams for the CHL system.

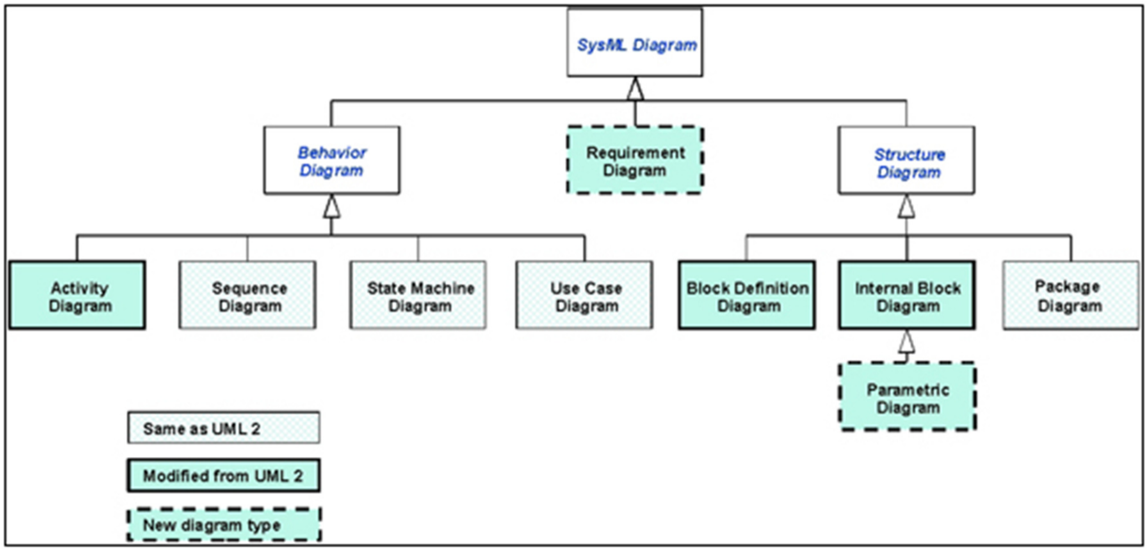


Figure 9 SysML Diagrams

While it is a visual modeling language that provides a metamodel for semantics (rules governing the creation and the structure of SysML models) and notation (representation of meaning, graphical or textual) it is not a methodology or tool [19]. Since SysML is methodology independent, there is freedom to use the SysML language as fitting for the system in design. From coursework at the University of Maryland a set methodology is proposed that is shown in and [20]. These methods are used in developing the diagrams.

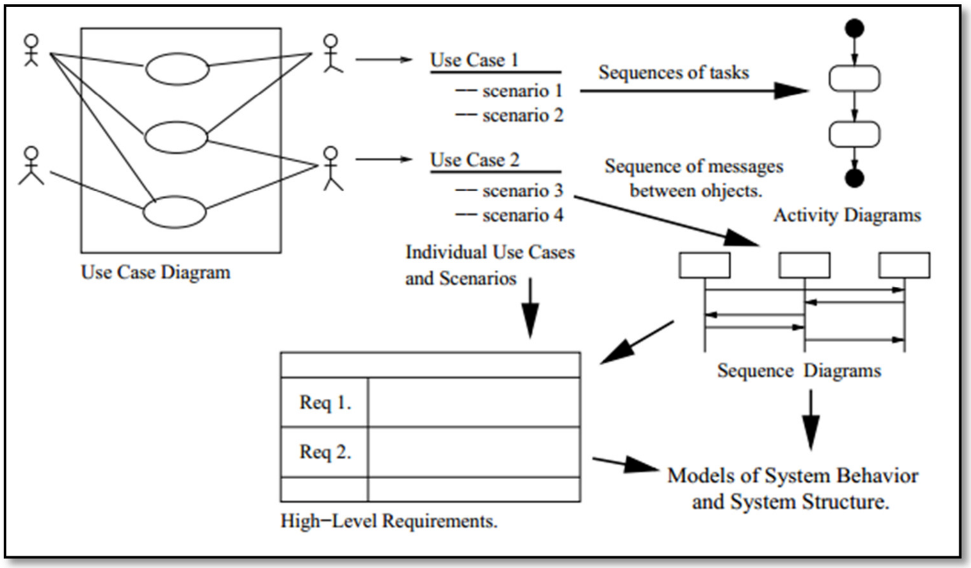


Figure 10 Pathways from Goals and Scenarios to Structure and Behavior of System

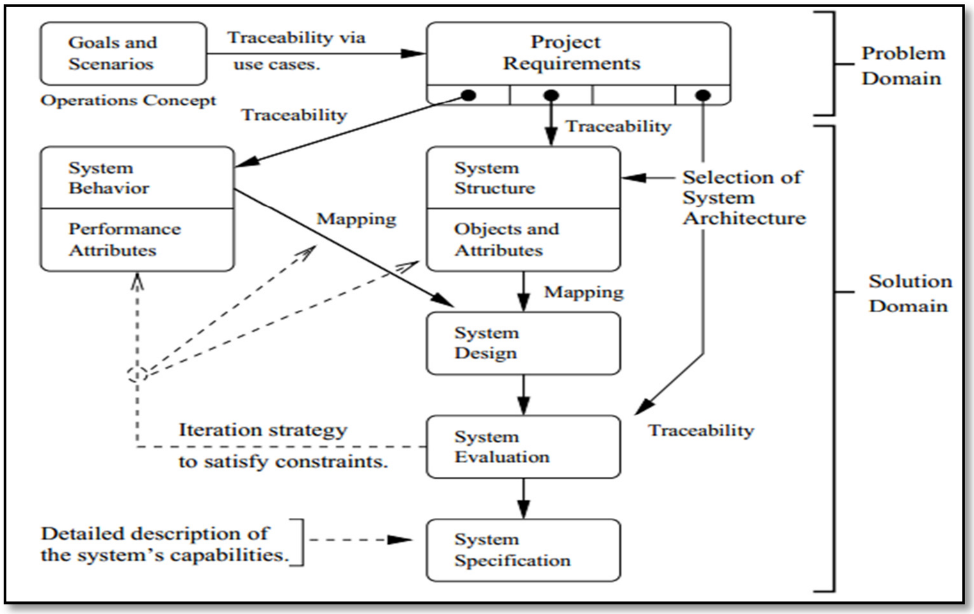


Figure 11 Development of System Specifications

Use Case Diagrams

Use cases describe the functionality of a system in terms of how it is used to achieve the goals of its various users. They are also used to capture system requirements in terms of system uses. Use cases can be further elaborated with detailed descriptions of their behavior, using activities, interactions, or state machines [21]. Use case diagram visually show the relations between use cases and actors with respect to the system boundary.

For the collaborative requirement framework use cases serve as a beneficial method to representing functional capabilities in a visual format. Additionally, this use case representation allows for building relationships between system behavior and requirements for the system (see requirement section for more). To show the benefits CHL use cases were developed.

Using the functional descriptions from the nuclear power design control documents for a component cooling water system (CCW) two use case diagrams were developed for the CHL system (see Figure 12). This first use case diagram shows how the CHL system interacts with other mechanical systems for the purpose of automated operation. As shown there are three primary use cases, which include Monitor Flowrate, Monitor Process Fluid Heat Removal, and Monitor Surge Tank Fluid Level. These use cases depict the ways that the user will use the system, which the CHL system must accommodate for. The second use case diagram (see Figure 13) focuses on the interaction the process fluid, refrigeration system, and the CHL system.

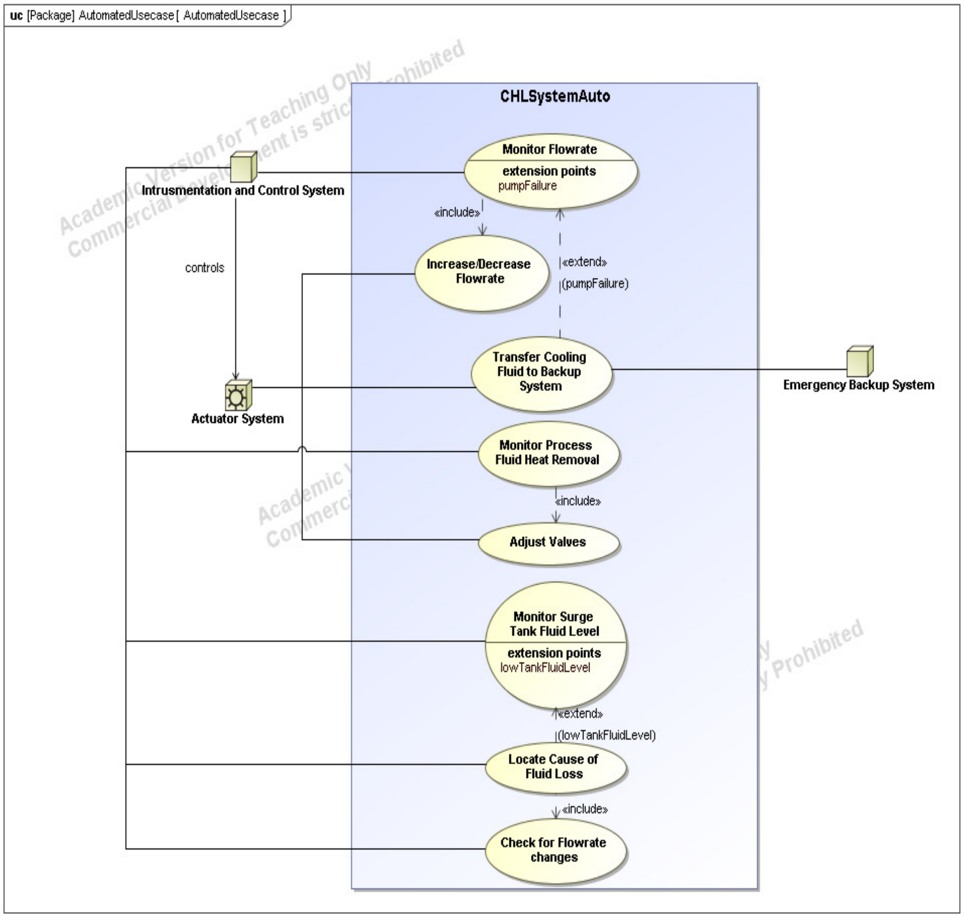


Figure 12 CHL Automation Use Case Diagram

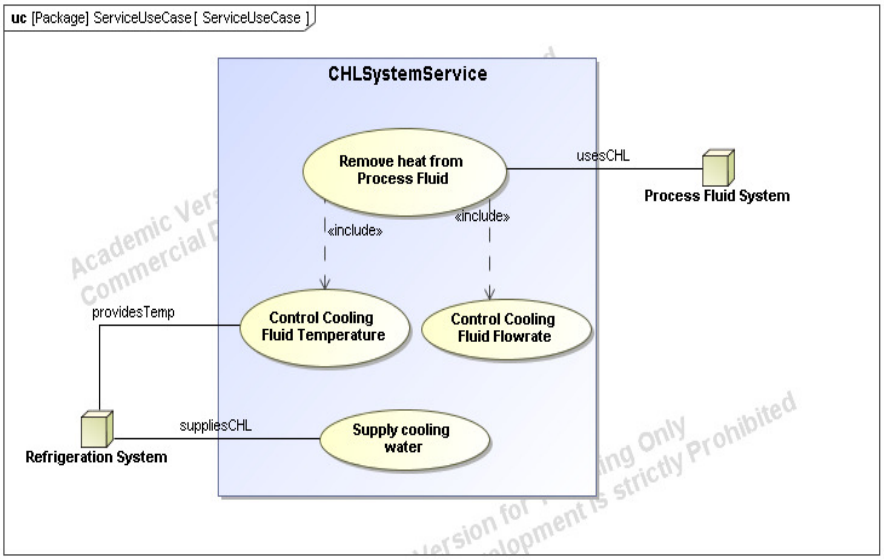


Figure 13 CHL Service Use Case Diagram

To further elaborate on the use case diagrams, each use case can be described in detail through use case scenario descriptions. Elaborating on use cases is necessary for the collaborative requirements framework to show the fine details of a process plants behavior. Below is an example of a scenario for the “Remove heat from Process Fluid” in the second use case (Figure 13).

Use Case 1: Remove heat from Process Fluid

- Actors: Process Fluid System, Refrigeration System
- Preconditions:
    1. CHL pump must be operating at steady state
    2. All equipment is working error free
- Basic Flow of events:
    1. The Refrigeration system decreases the temperature of the cooling fluid to 41 deg F.
    2. Cooling fluid enters the heat exchanger at 6500 gpm and 41 deg F.
    3. Process fluid enters the heat exchanger traveling at 3000 gpm flow rate and 90 deg F.
    4. Heat gets transferred within the heat exchanger from the process fluid to the cooling fluid.
    5. Cooling fluid exits the heat exchanger at 70 deg F and the process fluid exits the heat exchanger at 70 deg F.
- Alternative Flow 4:

4a. Process fluid exits the heat exchanger at undesirable temperature.

1. The cooling fluid flow rate is increased to increase heat transfer.
    a. Performed by increasing the power to the pump or opening the valve downstream to increase flowrate.
2. The cooling fluid temperature out of the Refrigeration is decreased to encourage more heat transfer.

- Post Condition:
    1. Cooling fluid is feedback into the CHL system.
    2. Process fluid is returned to the Process Fluid System.

Overall use case diagrams and use case descriptions serve as a first step in defining the system behavior and developing behavioral requirements. Unfortunately there is no method for currently validating or reasoning on these use cases, which would benefit in the automated aspect of the collaborative requirement framework. This is the reason another functional modeling tool is also used along with the use case diagram (describe later in MFM section). Otherwise use cases still serve an important purpose in their relationship to requirements and requirement diagrams.

Requirement Diagrams

Once finished collecting all the user requirements from the use cases, requirement diagrams can be developed to show how requirements are related. There are several requirement relationships that will be used for describing the CHL requirements. First relationship is containment. A containment relationship shows the decomposition of requirements, showing the high level requirement and all the sub requirements that are included within it. The second relationship used is the derived requirement relationship. This relationship shows how a general requirement can related with a more detailed requirement based on calculations or other forms of justification. The third relationship used is the verify relationship. The verify relationship connects a requirement with the method with which the requirement would be evaluated on the system. Most of the verify relationships used in the CHL requirements will connect requirements to constraint blocks (one way of verification). The last relationship used is the satisfy relationship. This relationship shows what block or component in the system the requirement will be associated with (what structural or behavior aspect of the system must "satisfy" this requirement). In Figure 14 the requirements diagram of the CHL system is shown. The diagram shows how from one high level requirement there were many sub requirements that were contained within it (a containment requirement used). Requirements can also be viewed in a tabular format that is in **Appendices D: Tabular Requirements**.

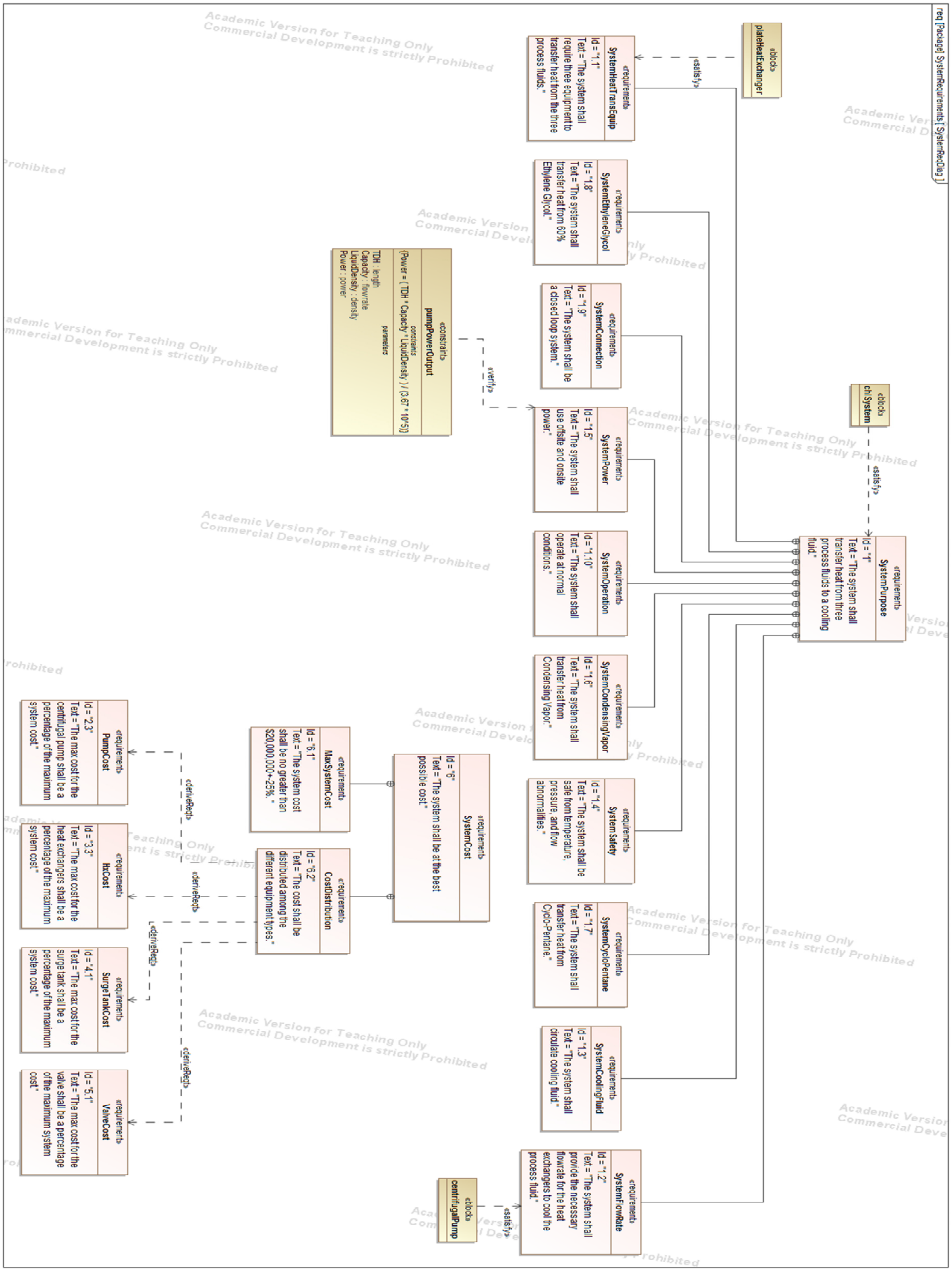


Figure 14 CHL System Requirements

As stated earlier, by using the verify relationship requirements can be linked to the verification method used. SysML can represent verification methods such as inspection, analysis, demonstration, and test. For the CHL all the components have engineering equations associated with them, so analysis used as the verification method. One form of analysis is through constraints (bounded equations). Below in Figure 15 is an example of a Surge Tank requirement and its verification method (a constraint called “SurgeTankSizing”).

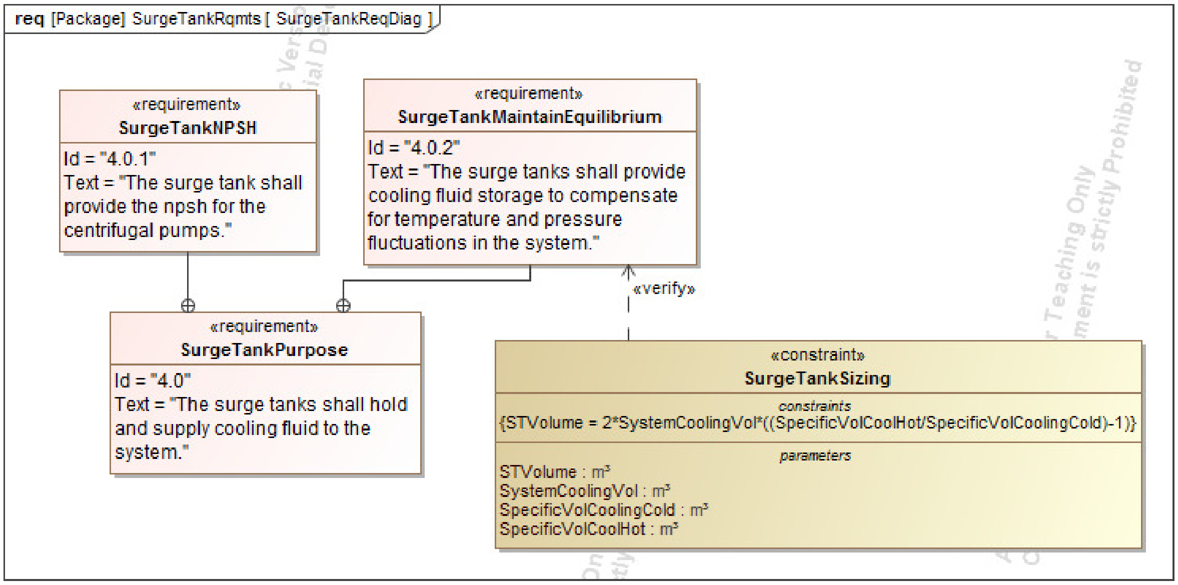


Figure 15 Surge Tank Requirements

Lastly, requirements allow for referencing to the source where the requirement was taken from. For example, in Figure 16 the requirement titled “ValveDifferentialPressure” is sourced from a software tool (AFT Fathom). This allows for requirements that were once separated to be joined together, without losing their original source. Sourcing can also be seen in “ValveFlowrate” and “ValveMassFlowrate” requirements.

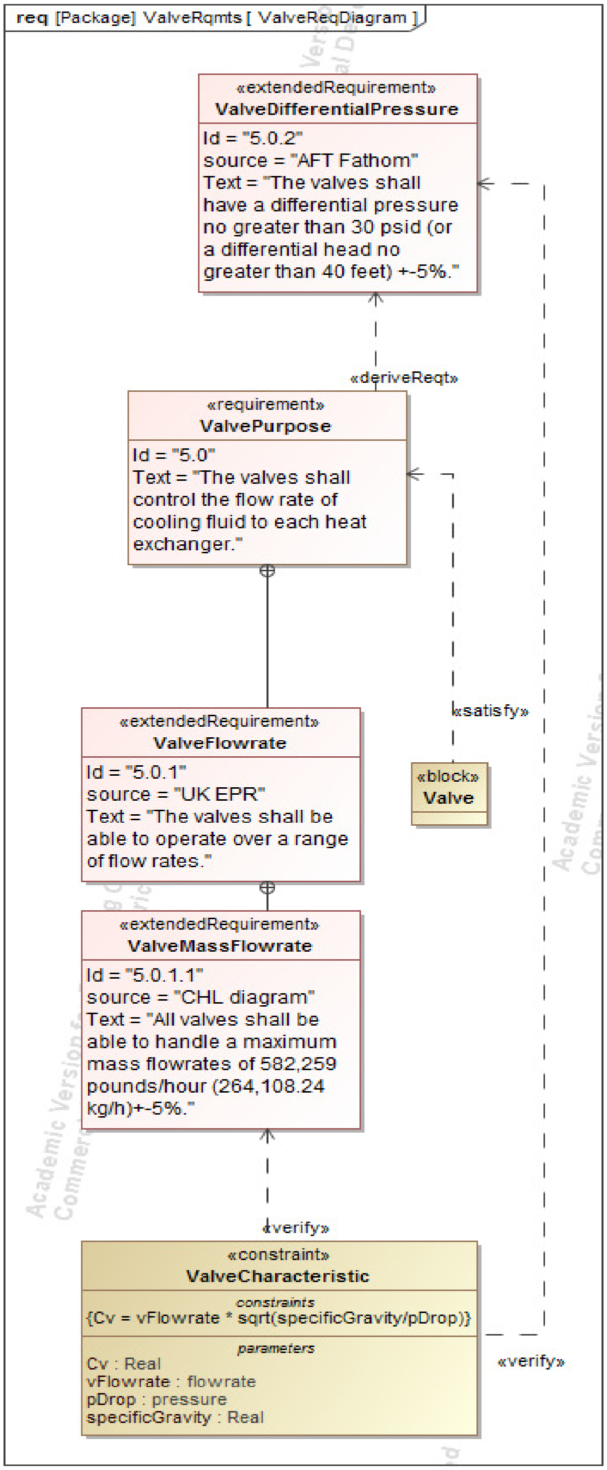


Figure 16 Control Valve Requirements

The remaining requirements for the CHL system are located at **Appendices C: SysML Diagrams** and **Appendices D: Tabular Requirements**.

Activity Diagrams

The main diagram used to describe activity in a system is the activity diagram. These diagrams define the actions in the system that are required to achieve a certain functionality (determined through use cases) along with the flow of input/output and control between the actions [21]. Describing the CHL system in this manner allows for a strictly functional view of the system without any allocation to components or structure of the system. Since the CHL system is already provided (the structure of the system) this activity diagram is not used for design, but for requirement tracing, since requirements can be satisfied by both structure and behavior. In Figure 17 an activity diagram shows how the different actions feed into one (with object flows) and the sequence of actions that are taken (the control flow of the system). Also, activity diagram mirror functional block diagrams that are used in the Product Process Design, which gives credibility to using activity diagram to represent the CHL system's behavior.

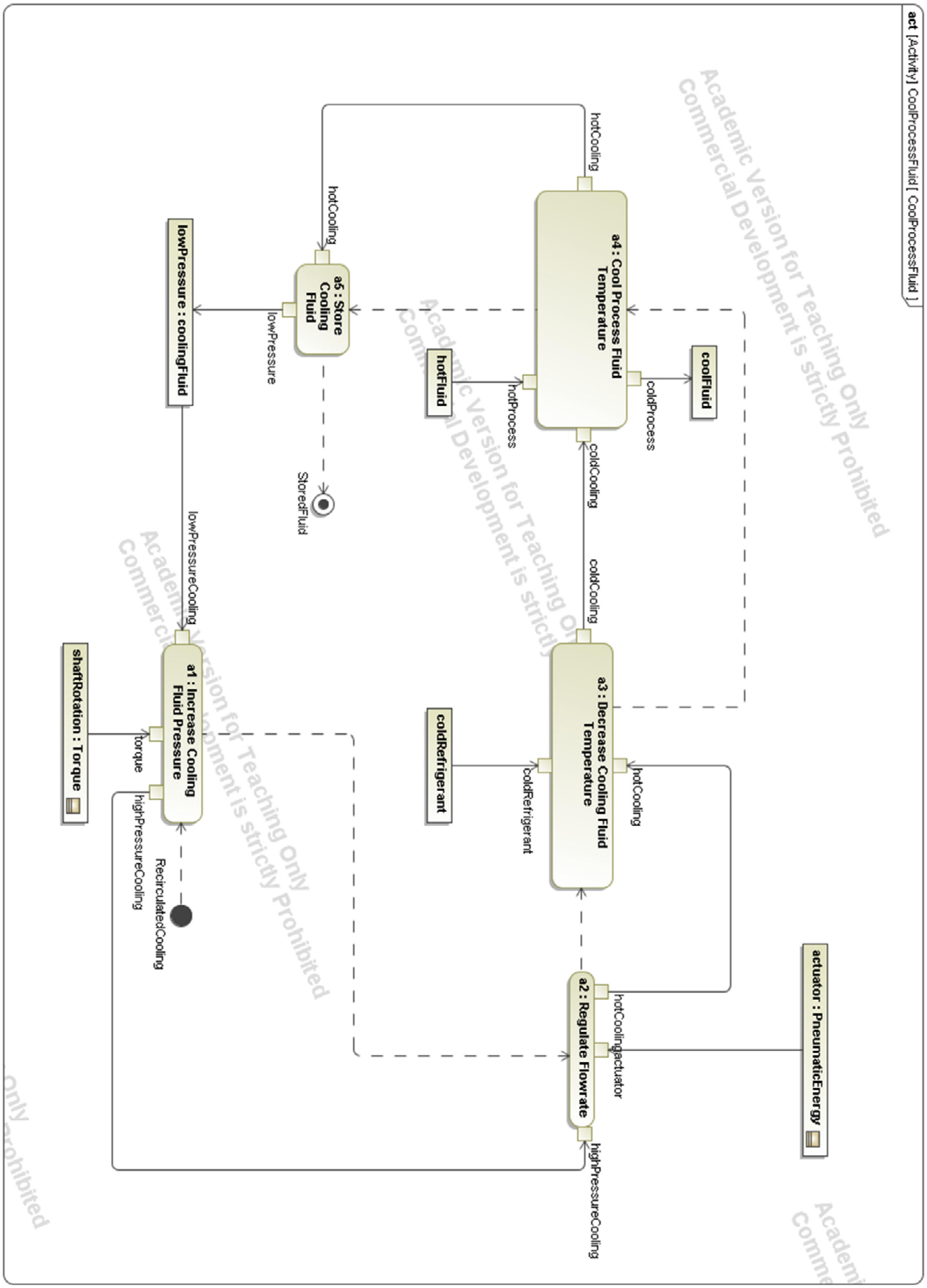


Figure 17 Activity Diagram of Heat Transfer Process

Another highly beneficial aspect of behavioral modeling with activity diagrams is the ability to allocate actions to the structure. During the design stage this allows for a better understanding of the requirements imposed on the structure. This allows for traceability from the requirements gather in the use cases to the activities that achieve the function of the use cases to the structure that embody the behavior. Below in Figure 18 shows the allocation of actions to component in the CHL system structure.

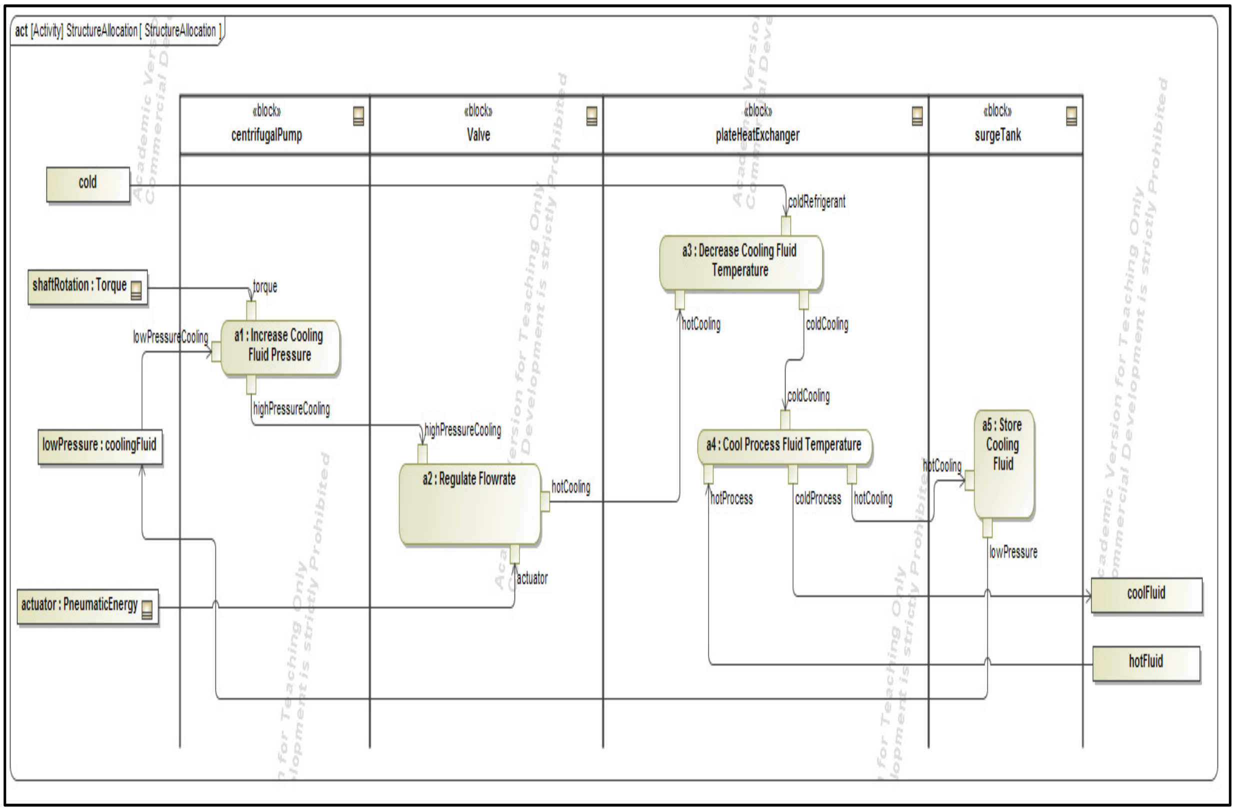


Figure 18 Activity Diagram with actions Allocated to CHL Structure

Block Diagrams

The way SysML models structure is through blocks, a modular unit of structure that can represent a system, component, item that flows through a system, conceptual entity, or other logical abstraction [21]. This flexibility allows the blocks to represent manufacturing component models. These models can represent what designers use to specify the component to satisfy the system functionality and also used to generate documents to send to vendors as RFQs. From the PDSO work, the distinction between the designed component, the product model, and actual component (physical component) is the way they are referenced (tag numbers, part number, and serial numbers), but they are required to be the same in terms of engineering parameters. Therefore a model that can relate design components to product models (from the vendor) and check for their alignment would build toward collaborative requirements. Below in Figure 19 shows the connection between these representations of the component and their attributes.

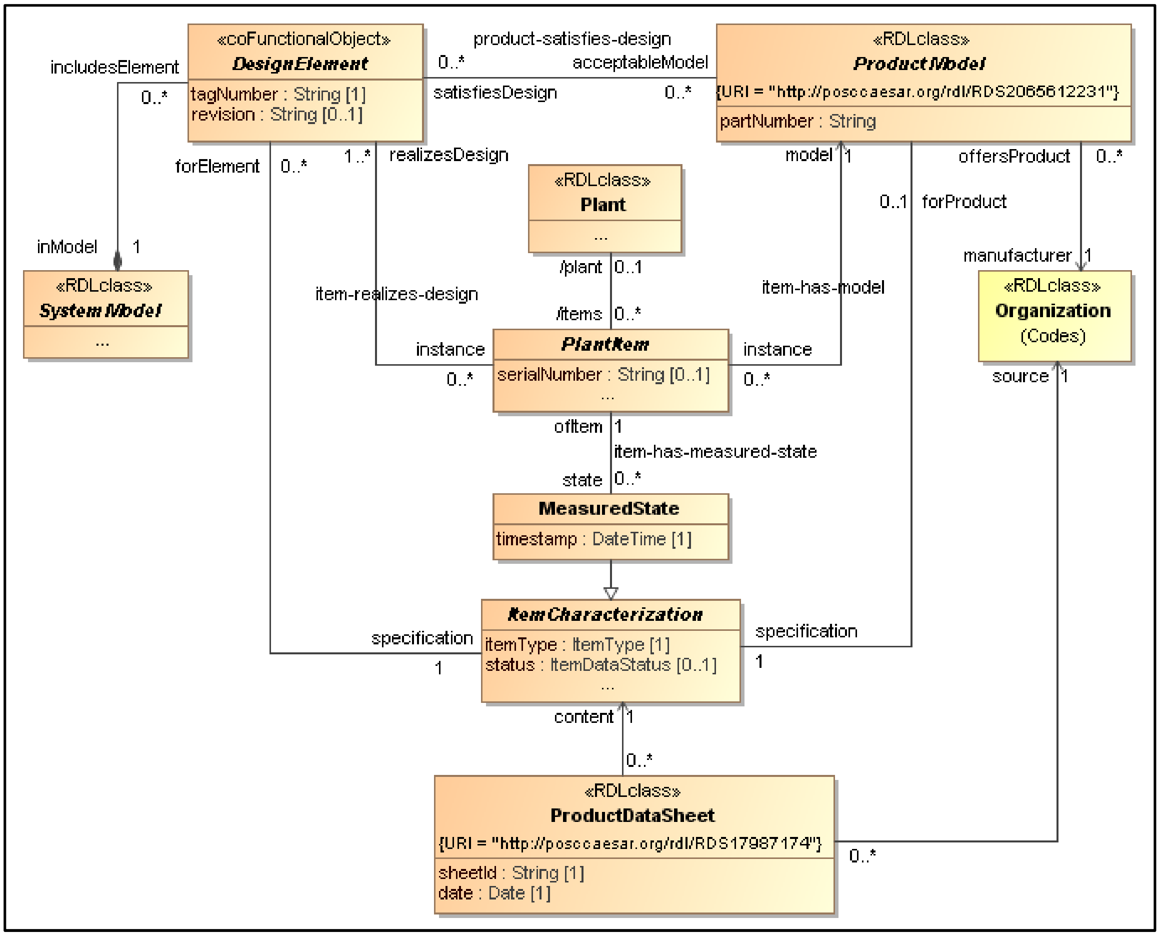


Figure 19 Product Data Sheet Ontology UML Model

The system architecture for the CHL system is show in a block definition diagram (BDD), which shows all the models of the components in the CHL system. Each block contains the attributes associated with that component as well as the components constraints, operations, and associated requirements which it satisfies. Below in Figure 20 the BDD is shown.

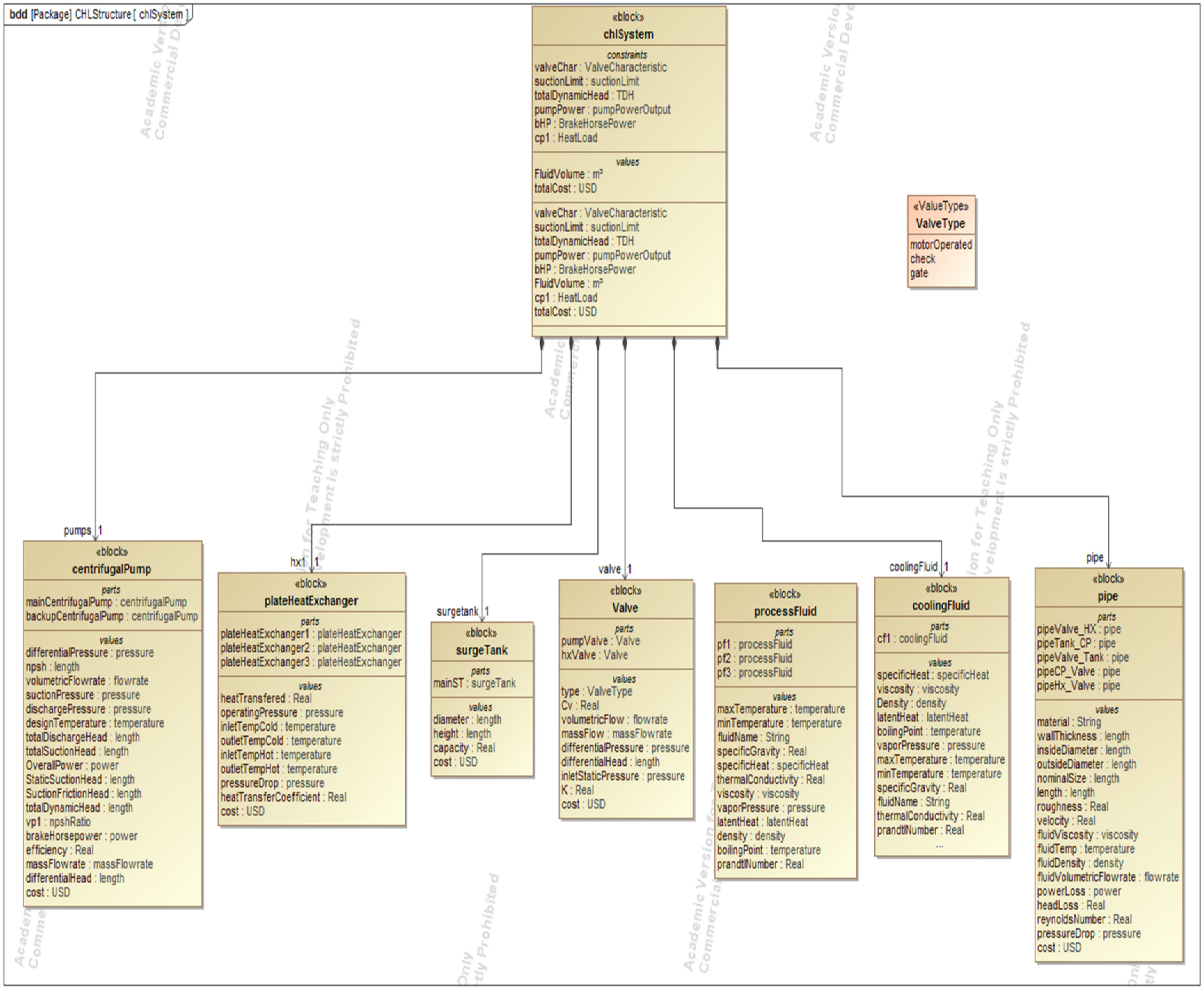
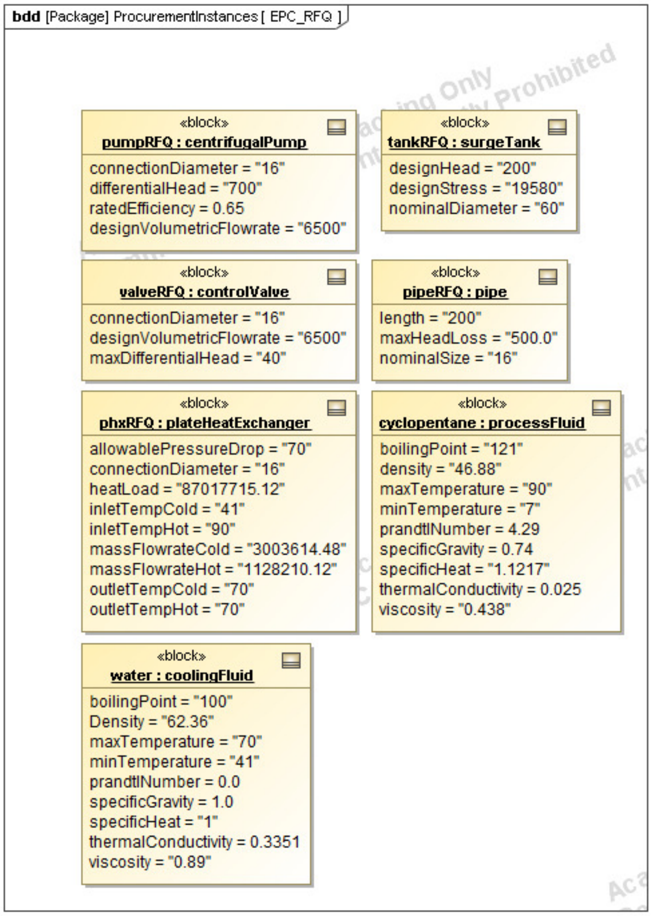


Figure 20 Block Definition Diagram of CHL

Another interesting aspect of the blocks is that instances of them can be created. Like in java with classes and objects, blocks are the template for what is contained in a component model for design and RFQ, but the instances are the actual specification with values supplied for the attributes. This allows for RFQ information to entered into the instances of the components and sent out to multiple suppliers. Below in an example of RFQ information for the components and fluids in the CHL system are shown. The MagicDraw tool used for building the SysML models also allow for the generation of excel files, so the RFQ data can be exported to excel to allow for communication of requirements. shows the output from the exported excel.


bdd [Package] ProcurementInstances [EPC_RFQ]

«block»
pumpRFQ : centrifugalPump
connectionDiameter = "16"
differentialHead = "700"
ratedEfficiency = 0.65
designVolumetricFlowrate = "6500"

«block»
tankRFQ : surgeTank
designHead = "200"
designStress = "19580"
nominalDiameter = "60"

«block»
valveRFQ : controlValve
connectionDiameter = "16"
designVolumetricFlowrate = "6500"
maxDifferentialHead = "40"

«block»
pipeRFQ : pipe
length = "200"
maxHeadLoss = "500.0"
nominalSize = "16"

«block»
phxRFQ : plateHeatExchanger
allowablePressureDrop = "70"
connectionDiameter = "16"
heatLoad = "87017715.12"
inletTempCold = "41"
inletTempHot = "90"
massFlowrateCold = "3003614.48"
massFlowrateHot = "1128210.12"
outletTempCold = "70"
outletTempHot = "70"

«block»
cyclopentane : processFluid
boilingPoint = "121"
density = "46.88"
maxTemperature = "90"
minTemperature = "7"
prandtlNumber = 4.29
specificGravity = 0.74
specificHeat = "1.1217"
thermalConductivity = 0.025
viscosity = "0.438"

«block»
water : coolingFluid
boilingPoint = "100"
Density = "62.36"
maxTemperature = "70"
minTemperature = "41"
prandtlNumber = 0.0
specificGravity = 1.0
specificHeat = "1"
thermalConductivity = 0.3351
viscosity = "0.89"

Figure 21 RFQ data as Instances in BDD

Table 1 Instances of RFQ generated in Excel

#	Name	Slot
1	ProcurementInstances	
2	cyclopentane	boilingPoint = "121" density = "46.88" maxTemperature = "90" minTemperature = "7" prandtlNumber = 4.29 specificGravity = 0.74 specificHeat = "1.1217" thermalConductivity = 0.025 viscosity = "0.438"
3	phxRFQ	inletTempCold = "41" inletTempHot = "90" outletTempCold = "70" outletTempHot = "70" connectionDiameter = "16" allowablePressureDrop = "70" heatLoad = "87017715.12" massFlowrateCold = "3003614.48" massFlowrateHot = "1128210.12"
4	pipeRFQ	length = "200" maxHeadLoss = "500.0" nominalSize = "16"
5	pumpRFQ	connectionDiameter = "16" designVolumetricFlowrate = "6500" differentialHead = "700" ratedEfficiency = 0.65
6	tankRFQ	designHead = "200" designStress = "19580" nominalDiameter = "60"
7	valveRFQ	designVolumetricFlowrate = "6500" maxDifferentialHead = "40" connectionDiameter = "16"

8	water	boilingPoint = "100" Density = "62.36" prandtlNumber = 0.0 specificGravity = 1.0 specificHeat = "1" thermalConductivity = 0.3351 minTemperature = "41" maxTemperature = "70" viscosity = "0.89"

Internal Block Diagrams

In addition to a BDD there is also a internal block diagram (IBD) that shows how the component in the CHL system are connected together. This is similar to the process flow diagram (PFD) that was first shown to describe the system. Another industry diagram also specializes in describing the connection between component and enumerating the requirements for each component (and the system) on the diagram. This diagram is known as the Piping and Instrumentation Diagram (P&ID). Since the industry has a vast amount of knowledge in these diagrams (PFDs and P&ID) the IBD should be used for small scale examination of the flow between components. Figure 22 shows the IBD of the CHL system (excluding the piping and control valve).

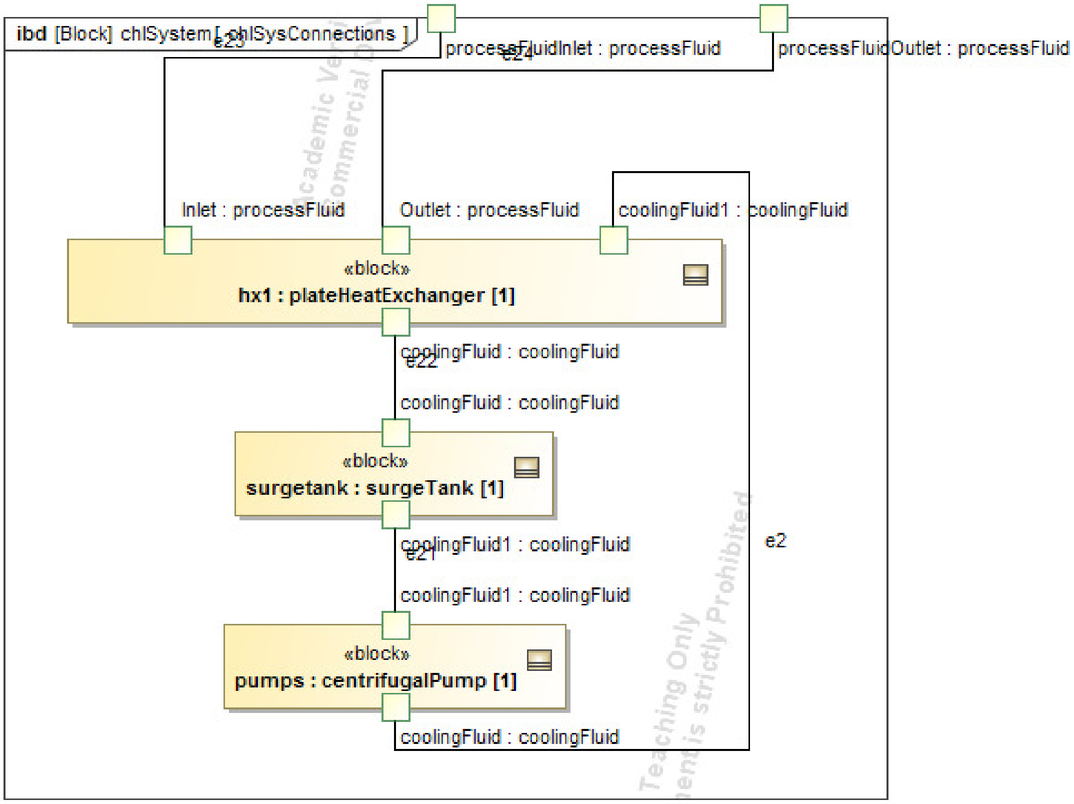


Figure 22 Internal Block Diagram of CHL

Parametric Diagrams

Apart from just showing attributes and connection of components there is also the ability to show the constraints on the attributes of the components. Constraints are added to the models by the use of constraint blocks and the parameteric diagram. Parameteric diagrams allow for specialization of blocks (parts) to be constrained by constraint blocks. The constraint blocks consist of equations and parameters. The parameters of the constraint are associated with the attributes of the component associated with the constraint. This way the actual physical and behavioral constraints the component truly has can be modeled and tied directly to the block (through the part). Below in Figure 23 a parameteric diagram is shown for plate heat exchanger and it constraint on its heat load. The parameteric diagrams for the Centrifugal Pump, Valve, Pipe, and cost analysis are shown in **Appendices C: SysML Diagrams**.

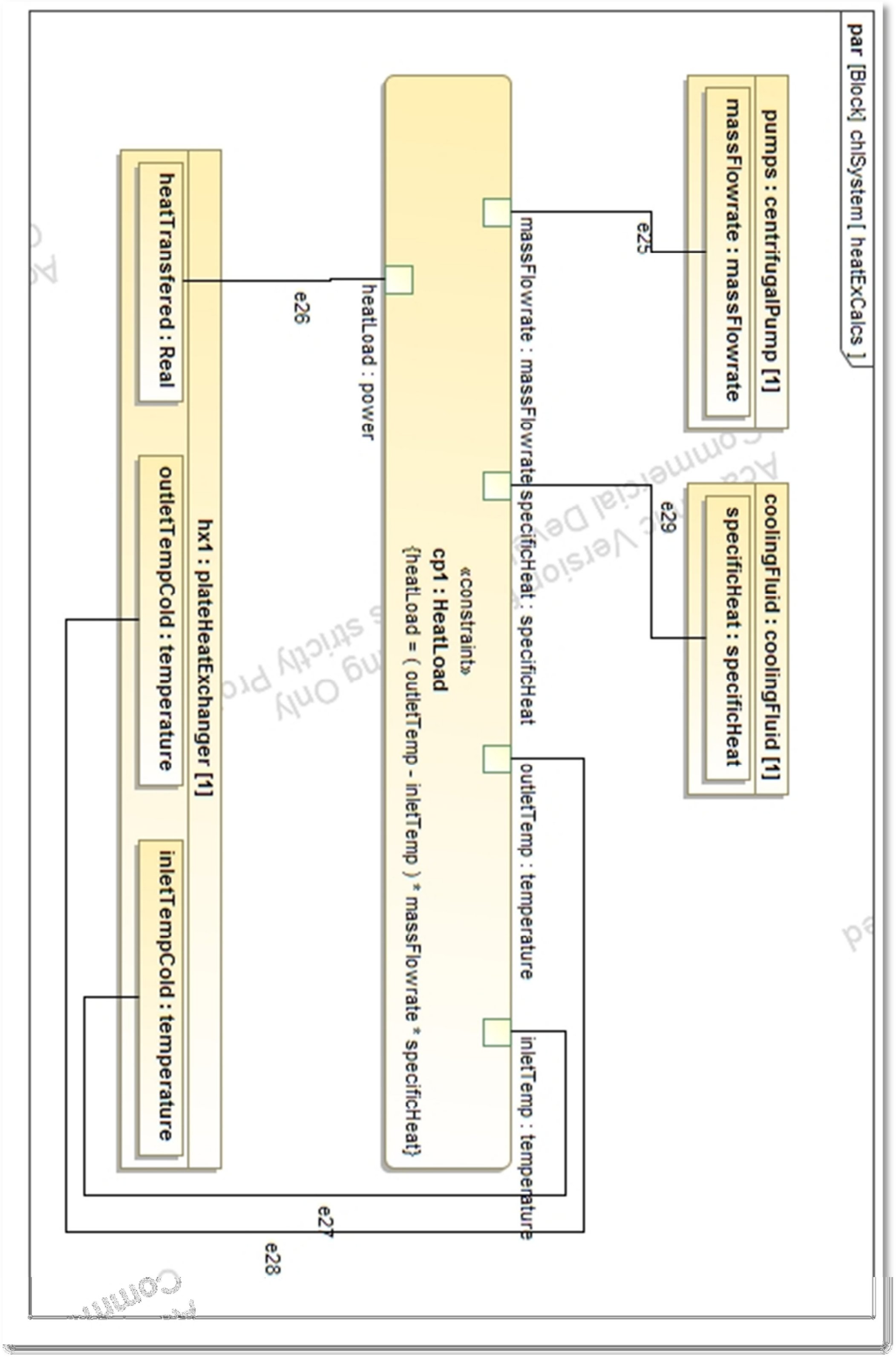


Figure 23 Parameteric Diagram of Plate Heat Exchanger Constraint

Chapter 5: Functional Modeling with MFM

Introduction

Over several decades, researchers from the Technical University of Denmark have created a modeling language for industrial process plants. The purpose of the modeling language was to represent functional behavior of the industrial process with respect to the goals of the system by using means-end and whole-part relations. This functional modeling allows for qualitative reasoning, which reasons about knowledge of physical phenomena and systems that cannot be done by quantitative methods [22]. This capability makes MFM beneficial for communicating requirements that are quantitative. Therefore, this thesis will apply MFM to connect requirements that are qualitatively based. Currently MFM has no dedicated software implementation, so this thesis will develop a software implementation of the model. Below in **Figure** 24 is a legend of symbols to represent MFM models. Also in **Figure** 25 there is an example MFM diagram [22].

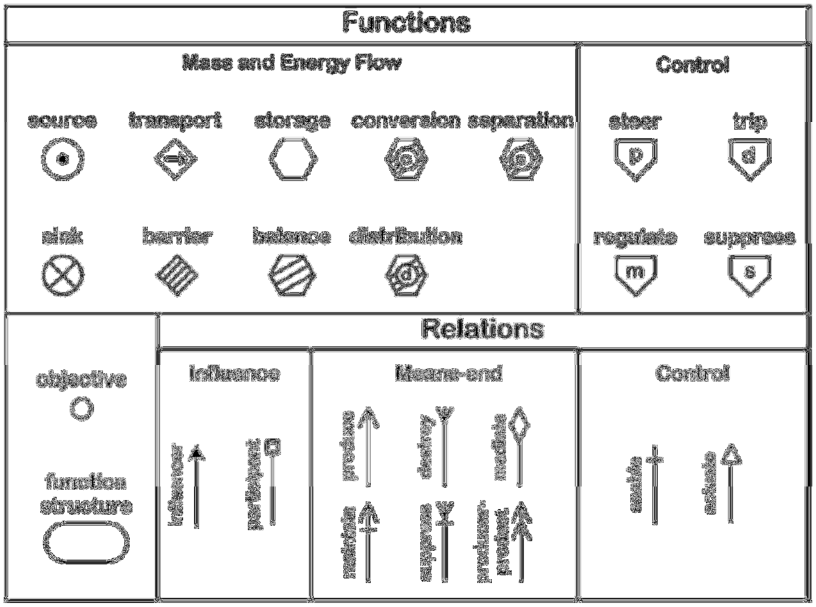


Figure 24 MFM Functional Model Symbols

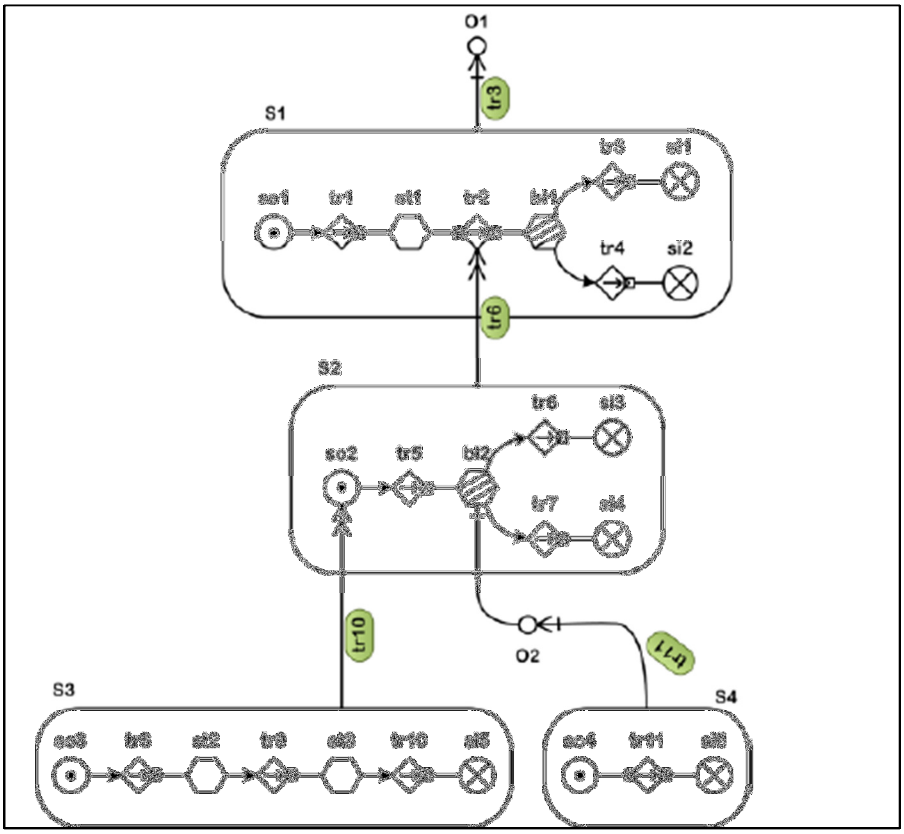


Figure 25 MFM Model Example: Water Mill

Implementation for Thesis

The MFM language is developed as a UML profile within the MagicDraw software. The profile consists of the different function types, relations, function structures, and goals. By creating this profile a domain specific language (DSL) is created. Following the creation of the profile, customizations or rules were applied to the elements (connection rules between functions). Afterward a custom diagram was created for the MFM language, where MFM diagrams can be created via the MagicDraw software interface. Figure 26 shows an example of an MFM diagram created in the MagicDraw interface.

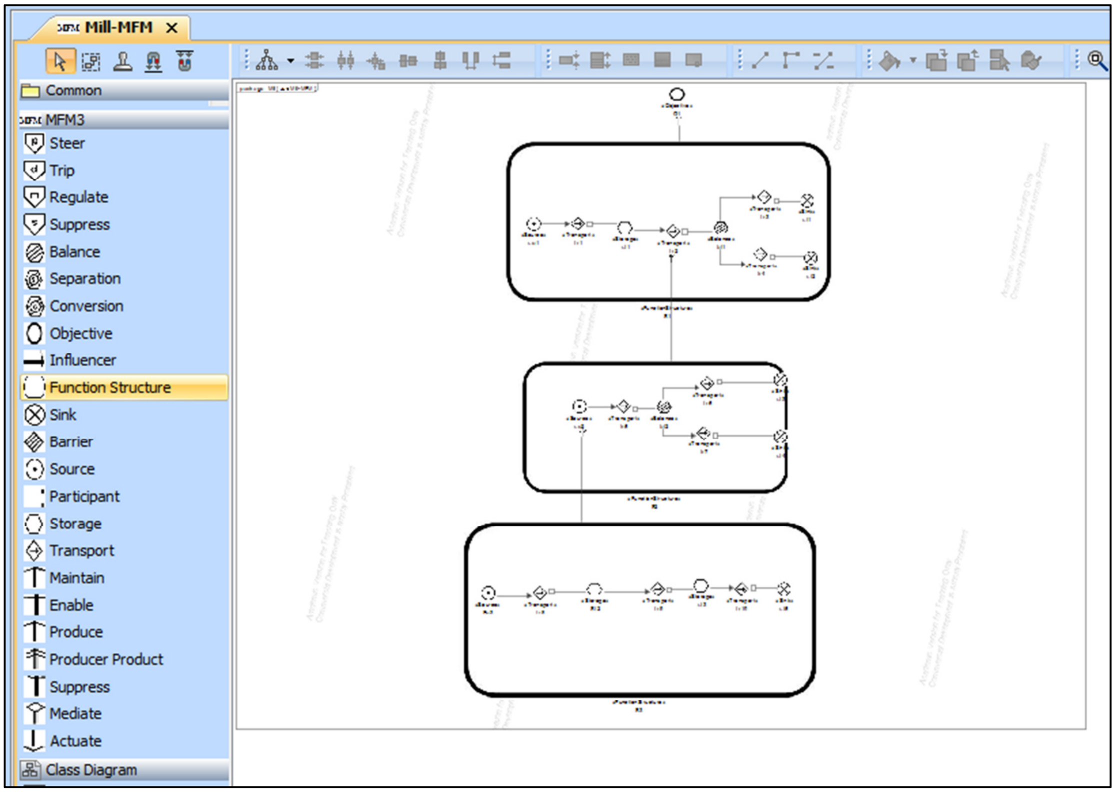


Figure 26 MFM diagram MagicDraw Implementation

<u>*CHL MFM Model*</u>

To demonstrate the value of MFM modeling, models of the CHL functionality were developed using the MFM language. As a result of developing the models a greater understanding of the means-to-end relationships were developed. These types of relationships guide in the requirement traceability, since there is an understanding on how functions are related. Above in Figure 27 a part of the MFM diagram for the CHL system (whole diagram available in Appendices E: CHL MFM Model) shows how there is a heat balance between the cold cooling fluid and hot process fluid. Another beneficial aspect of the MFM diagrams is that the model elements are linkable to the SysML components. Figure 28 (below) shows how the surge tank storage functionality relates to the structural representation of the surge tank in SysML. Also the requirements for the pump and valve are related to their functional representations in the MFM model. This capability makes these MFM models highly useful and allow for traceability between the two models.

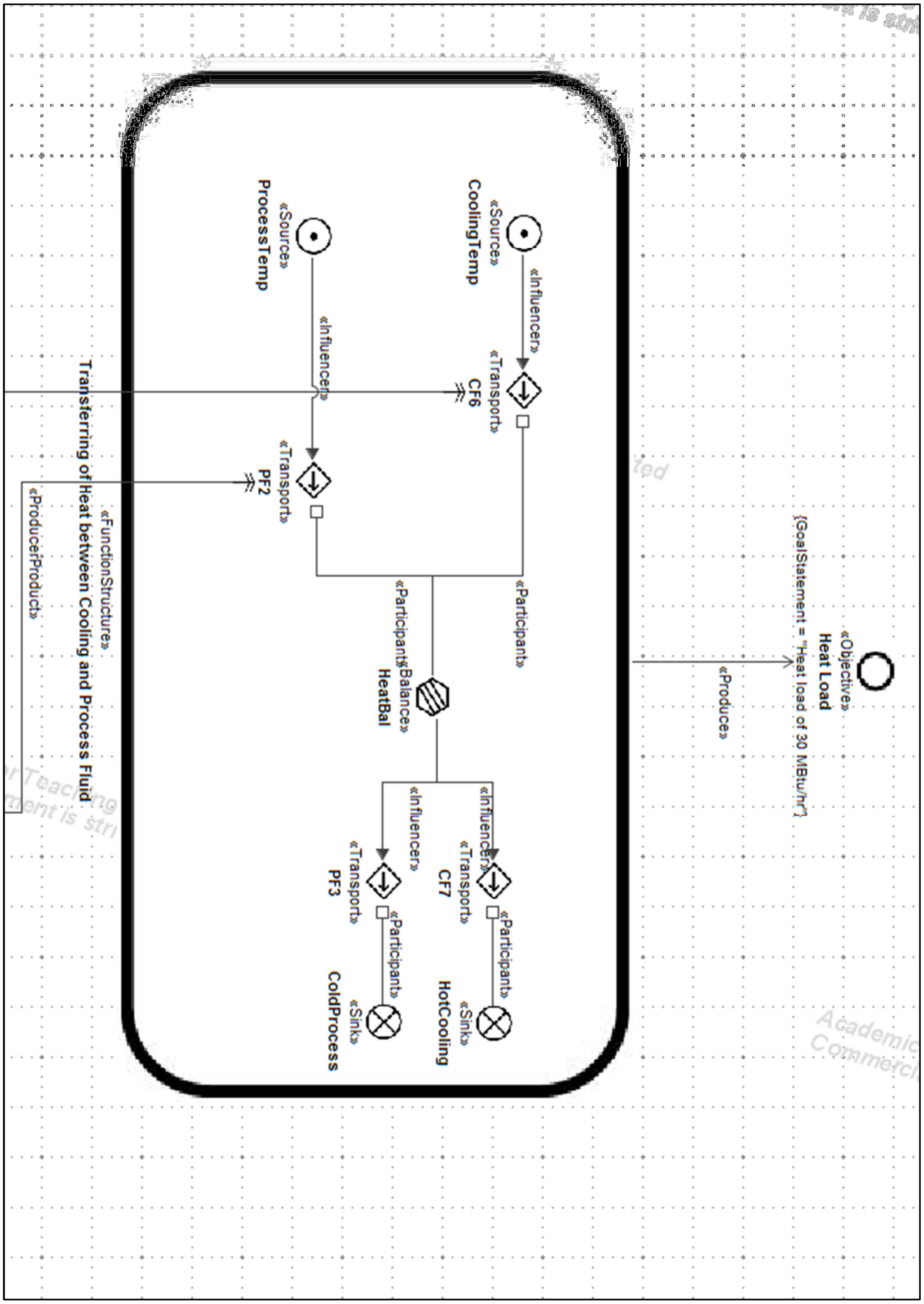


Figure 27 CHL Heat Transfer MFM Model

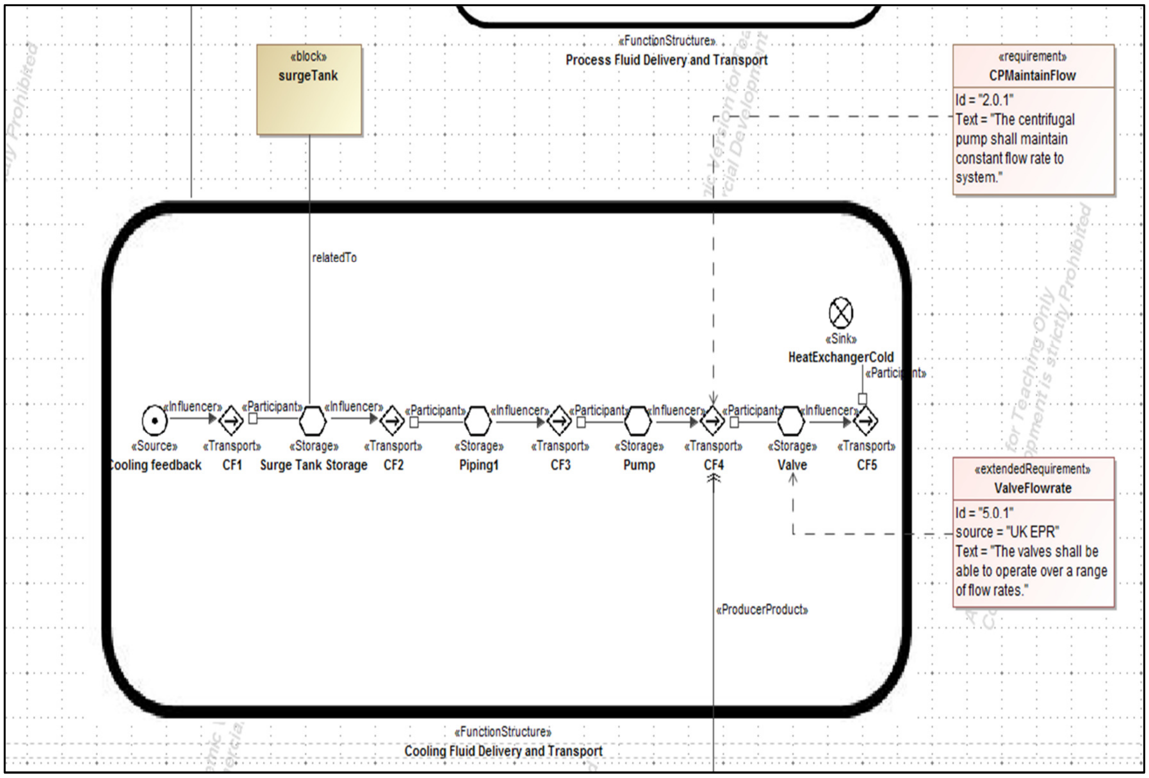


Figure 28 CHL MFM and SysML Relationships

Functional Reasoning

Another benefit to using the MFM language is the ability to perform reasoning on the models. The main type of reasoning that is performed on the model is cause-effect reasoning. For the MFM model, the focus of this reasoning is on the goal-function and function-function patterns [22]. Therefore this reason is ideal for determining how changes in one component requirements or their functionality will affect all the other system functionality downstream and the overall goal of the system. From that perspective MFM models aid in both the representation and verification of system functionality and requirements in the collaborative requirements framework.

Chapter 6: Formulating the Optimization Problem

Purpose

Within the process plant industry tremendous amount of work has been conducted in designing the best process, most suitable plant structure, and optimal parameters of the process. The only area that has not had much attention involves the best design of the plant equipment [23]. This area is difficult to address because it is highly interconnected with the other areas of design. For that reason, the optimization of this thesis will focus on the optimization on the plant equipment design based on the requirements from the process that focus on normal operation and the equipment requirements.

In addition to design, optimization can also aid in the understanding of requirements and how they affect the component selection process. This aspect is extremely important when trying to negotiate requirements between equipment designers/procurement engineers and the equipment/pipe suppliers. Therefore this thesis will also use optimization to determine the best group of equipment from a list of suppliers that will satisfy the individual equipment requirements as well as the process requirements. This is beneficial because it allows the equipment designers/procurement engineers to grasp what needs to be changed in the suppliers' equipment specifications to achieve their process requirements. Also, the requirements can be traced to the equipment specifications that have the most impact. All of these concepts aid the equipment designers/procurement ability to negotiate with the equipment suppliers and have more insight into how much more optimal the process plant can be with the available suppliers. In order to perform the design and selection optimization a software package was used name IBM ILOG CPLEX.

Optimization Tool

The optimization software package used for the project was IBM ILOG CPLEX Optimization studio. The CPLEX optimizer can solve integer programs, very large linear programming problems using either primal or dual variants of the simplex method, quadratic programs, and convex quadratically constrained problems. This thesis uses a powerful mathematical programming engine (CPLEX engine) and a constraint programming engine (CP engine). The CPLEX engine can solve linear, mixed-integer, quadratic, and quadratically constrained programs. The CP engine can solve models with complex combinatorial constraints and uses powerful constraint-propagation and branch-and-bound techniques. Additionally, the CPLEX Optimization Studio provides the Optimization Programming Language (OPL) for modeling the constraint problem. Two of the main features used from OPL were the interface to Excel that allowed for the input and output of data to Excel spreadsheets and the easy to use OPL script that can run optimization programs multiple times with changing constraint bounds and store results in text files for later analysis [24]. Below is a model of how CPLEX was generally used in the thesis work (see Figure 29).

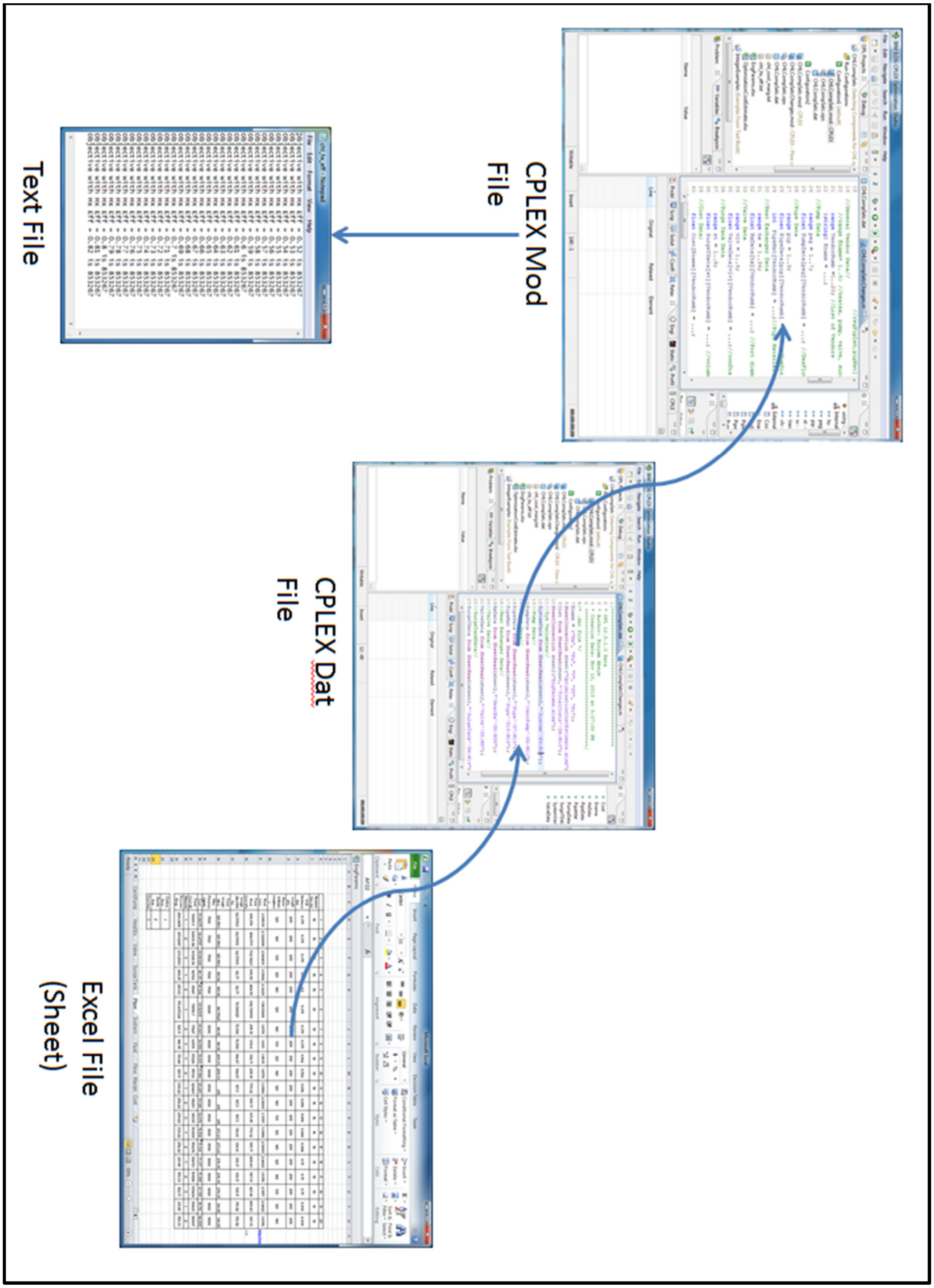


Figure 29 CPLEX Input and Output Data

Problem Formulation

In order to evaluate the components selected we have to use a constraint programming language. Each component has their own physical and functional constraints, but the main benefit of constraint programming is the ability to evaluate component selections with respect to system constraints that depend on the connection of all component (or interaction between groups of components). System constraints mirror the high level requirements. Therefore, these high level requirements can be immediately validated in the component selection using the constraint programming. Additionally, this shows if there is a viable collection of components (from supplier data) that can satisfy the system requirements. Otherwise, if there isn't a group of components that satisfy the system constraints a recommendation can be provided as to what needs to change in order to get viable system. Recommendations can range from changing one parameter of one supplier data to changing multiple parameters for multiple components. These recommendations may also give more information as to whether or not the system constraints should be loosened or can be made stricter.

To begin formulating the component selection process with constraint processing several aspects must be made clear. First the objective function (the goal constraint programming is to satisfy the maximization, minimization, or equality of a specific equation related to the constraint variables) must be determined. For this component selection problem the objective is to minimize total cost (the sum of the cost for each component). Second, component constraints that only involve a single component must be defined. Third, the constraint that involves multiple components must be described. Lastly, the system constraints must be represented in terms of some set of the components. Each of these steps involves understanding the characteristic functionality of the component. Once the functionality of each component is determined, then their interaction (how their functionality serve other components and aid in their functionality) can be described in constraints. The combination of these interactions then yields a system functionality that can be controlled with system constraints.

Objective Function

Minimize Cost:

$$\min \sum_{i=1}^{5} \sum_{j=1}^{20} C_{ij} * x_{ij}$$

i=type of components
j=number of vendors
x is Boolean to determine whether the component which component from 20 vendors is selected
C is a cost matrix that has the cost for each of the individual components

Constraints

Subject to:

$$\sum_{j=1}^{20} x_j(\mathrm{i}) = 1$$

Ensures that there is only one component picked out of the 20 vendors, i=the component type

$$\sum_{j=1}^{20} \mathrm{D}_j(\mathrm{i},\mathrm{y}) x_j(\mathrm{i}) \leq SV(y)$$

D = Component engineering data from vendor
i= the component type
y= engineering parameter index (number of parameters vary for each component vary)
SV= a vector system variable that constrain the component selection (

These types of constraints include the max flow rate for the pump and max power constraints on the pump.

$$\sum_{j=1}^{20} \mathrm{D}_j(\mathrm{i},\mathrm{y})x_j(\mathrm{i}) \geq SV(y)$$ (Same as above)

These types of constraints include surge tank supply head minimum, heat exchanger and pump efficiency.

$$\sum_{j=1}^{20} \mathrm{D}_j(\mathrm{i},\mathrm{y})x_j(\mathrm{i}) = SV(y)$$ (Same as above)

These types of constraints include the pipe, heat exchanger, valve, and pump connection constraint (has to all be the same size).

$$\sum_{j=1}^{20} \mathrm{D}_j(i_1,\mathrm{y})x_j(i_1) + \sum_{j=1}^{20} \mathrm{D}_j(i_2,\mathrm{y})x_j(i_2) \leq SV(y)$$

These constraint include more than one component (component interaction) and the SV represents a system variable margin. Constraints on the pipe, valve, and hx with respect to the allowable pump flow rate margin would fit this constraint, as well as the pump supply head margin equation (involve all components). Also the pumps supply pressure from the surge tank constraint is modeled in the same fashion.

Chapter 7: Optimization Results and Trade-off

Analysis of High Impact Parameters

After executing the optimizer a list of high impact system and component parameters were determined. The reason they are high impact is because they interconnect each component or greatly affect the functionality of another component or the overall system. The high impact system and component parameters are listed below in Table 2.

Table 2 Parameters for Analysis

High Impact System/Component Parameter	Components Involved
Pressure Margin	Centrifugal Pump, Plate Heat Exchanger, Control Valve, Surge Tank, and Pipe
Flow rate Margin	Centrifugal Pump, Plate Heat Exchanger, Control Valve, and Pipe
Centrifugal Pump Power	Centrifugal Pump

Using these high impact parameters, the design options were evaluated. This results in a range of viable system options that had to be evaluated. This range of options allow for a tradeoff of system components and component arrangements to take place. In addition to cost, component efficiencies, power, and system volumetric flow rate can be evaluated. The flow rate margin, pressure margin, and power were all compared with respect to the objective (to minimize cost).

The constraint on volumetric flow rate started with the system requirement that the flow rate must be at least up to the design parameter (6500 gpm). From there the constraint was applied on the other equipment. The valve, heat exchanger, and piping all have max flow rate tolerances that need to be consider. So in order to select a pump, there must first be a check over the design space to find if there is a heat exchanger, valve, and pipe that can withstand that specific flow rate. Margin is added to this selection process to show how close the pumps provided flow rate is to the other equipment's rated flow rate. Ideally the margin should be minimized to only compensate for variations in the system operation, such as switches in operation mode or to allow for extra time to react to system safety problems (such as a leak or broken equipment). The optimal selection of components for their specific flow rate margin is shown below in Table 3, Table 4, Figure 30, and Figure 30.

Table 3 Flow rate Margin analysis (16 in)

16 inch connection						
Hx	Pu	V	St	Pi	Obj	cMarg
1	1	1	1	3	794000	1000
1	2	1	1	3	797185	990
1	2	1	1	3	797185	980
1	2	1	1	3	797185	970
1	2	1	1	3	797185	960
1	2	1	1	3	797185	950
1	2	1	1	3	797185	940
1	2	1	1	3	797185	930
1	2	1	1	3	797185	920
1	2	1	1	3	797185	910
1	2	1	1	3	797185	900
1	3	1	1	3	799308	890
1	3	1	1	3	799308	880
1	3	1	1	3	799308	870
1	3	1	1	3	799308	860
1	3	1	1	3	799308	850

1	3	1	1	3	799308	840
1	3	1	1	3	799308	830
1	3	1	1	3	799308	820
1	3	1	1	3	799308	810
1	3	1	1	3	799308	800
2	4	1	1	3	805748	790
2	4	1	1	3	805748	780
2	4	1	1	3	805748	770
2	4	1	1	3	805748	760
2	4	1	1	3	805748	750
3	4	1	1	3	810772	740
3	4	1	1	3	810772	730
3	4	1	1	3	810772	720
3	4	1	1	3	810772	710
3	4	1	1	3	810772	700
6	5	1	1	3	827084	690
6	5	1	1	3	827084	680
6	5	1	1	3	827084	670
6	5	1	1	3	827084	660
6	5	1	1	3	827084	650
7	5	1	1	3	832108	640
7	5	1	1	3	832108	630
7	5	1	1	3	832108	620
7	5	1	1	3	832108	610
7	5	1	1	3	832108	600
10	6	1	1	3	848243	590
10	6	1	1	3	848243	580
10	6	1	1	3	848243	570
10	6	1	1	3	848243	560
10	6	1	1	3	848243	550

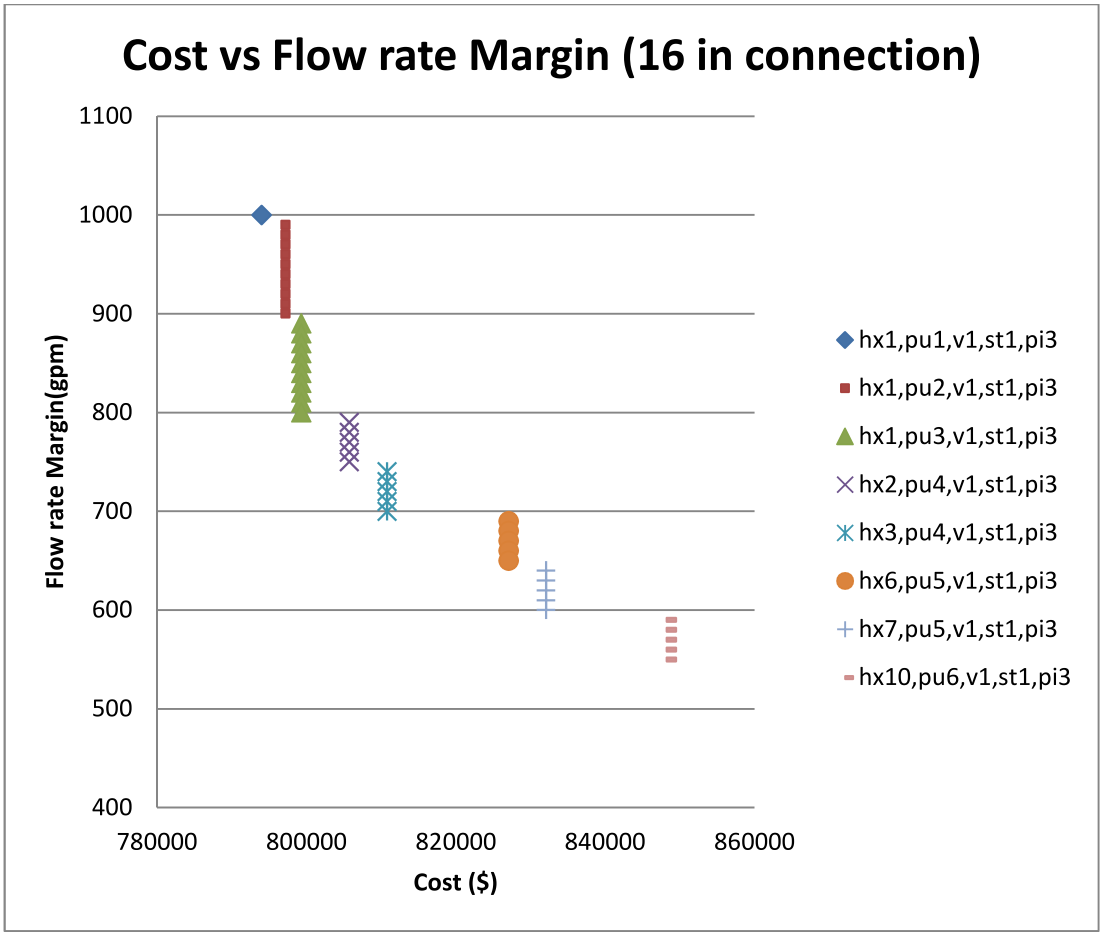


Figure 30 Cost vs Flow rate Margin (16 in)

Results for the component with 16 inch connections show that as the volumetric flow rate margin increases, the cost of the system decreases. This is not a surprise, since over sizing the components allows for the selecting of cheaper components. The flow rate margin decreases all the way to 550 gpm. It is also interesting to point out that the valve, surge tank, and pipe remain constant for all the system configurations.

Table 4 Flow rate margin analysis (18 in)

18 inch connection						
Hx	Pu	V	St	Pi	Obj	cMarg
11	11	11	1	8	874995	1000
12	11	11	1	8	880020	990
12	11	11	1	8	880020	980
12	11	11	1	8	880020	970
12	11	11	1	8	880020	960
12	11	11	1	8	880020	950
13	11	11	1	8	885044	940
13	11	11	1	8	885044	930
13	11	11	1	8	885044	920
13	11	11	1	8	885044	910
13	11	11	1	8	885044	900
14	11	11	1	8	890068	890
14	11	11	1	8	890068	880
14	11	11	1	8	890068	870
14	11	11	1	8	890068	860
14	11	11	1	8	890068	850
15	11	11	1	8	895092	840
15	11	11	1	8	895092	830
15	11	11	1	8	895092	820
15	11	11	1	8	895092	810
15	11	11	1	8	895092	800
16	11	11	1	8	900117	790
16	11	11	1	8	900117	780
16	11	11	1	8	900117	770
16	11	11	1	8	900117	760
16	11	11	1	8	900117	750
17	11	11	1	8	905141	740
17	11	11	1	8	905141	730
17	11	11	1	8	905141	720
17	11	11	1	8	905141	710
17	11	11	1	8	905141	700
18	11	11	1	8	910165	690
18	11	11	1	8	910165	680
18	11	11	1	8	910165	670
18	11	11	1	8	910165	660
18	11	11	1	8	910165	650
19	11	11	1	8	915190	640
19	11	11	1	8	915190	630
19	11	11	1	8	915190	620

19	11	11	1	8	915190	610
19	11	11	1	8	915190	600
20	11	11	1	8	920214	590
20	11	11	1	8	920214	580
20	11	11	1	8	920214	570
20	11	11	1	8	920214	560
20	11	11	1	8	920214	550

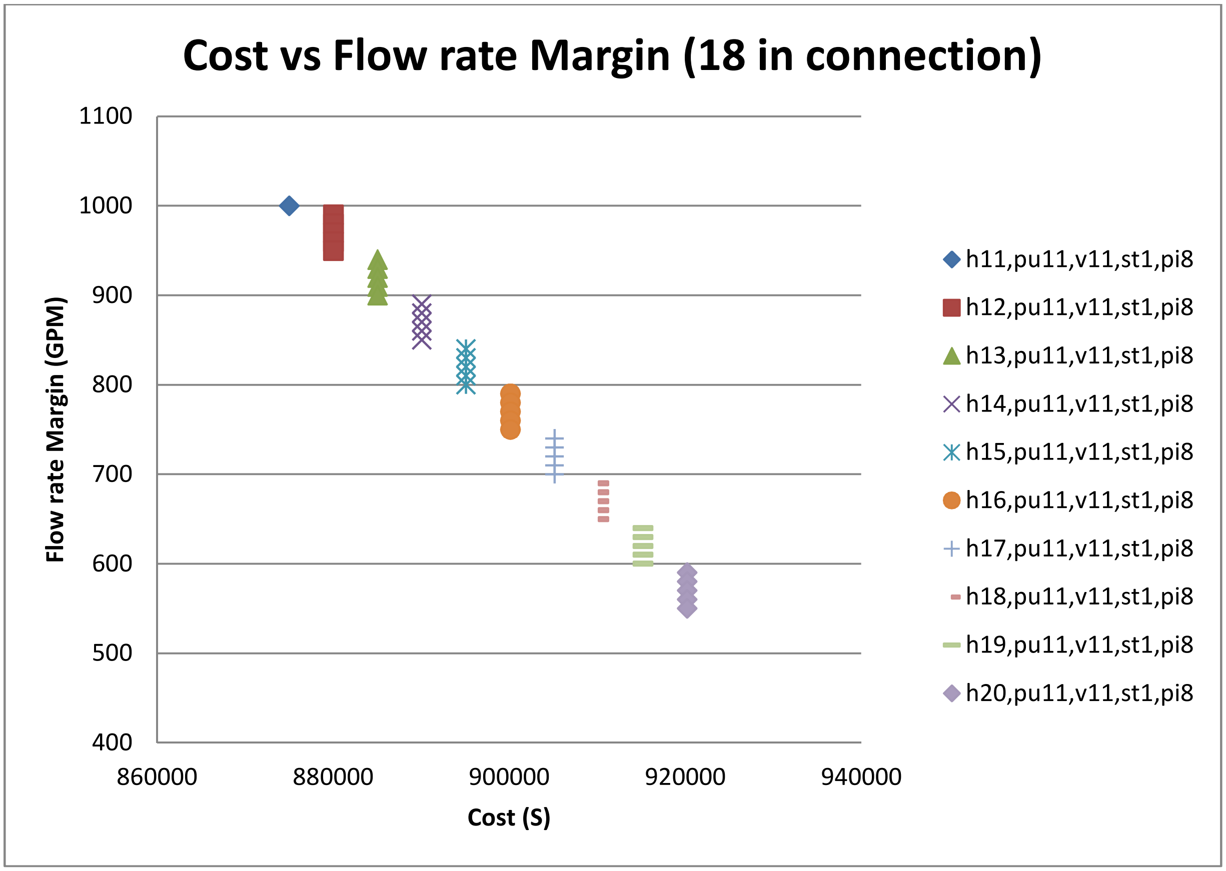


Figure 31 Cost vs Flow rate Margin (18 in)

The 18 inch connection system also depicts this trend. One distinction between the two connection sizes is that the 18 inch system cost more than the 16 inch system (as expected since there is more material used in the pipe). Otherwise, the flow rate margin also goes as low as 550 gpm. Lastly, the only component in these component selection is the heat exchangers (the pump, valve, surge tank, and pipe remain constant).

The power required by the centrifugal pump directly affects its flow rate capacity and amount of pressure it can overcome in the system. Since power is a limited resource, it is best to reduce its usage while also examining the affect it will have on the cost of the overall system.

Table 5 Max Power analysis (18 inch)

18 in Connection						
Hx	Pu	V	St	Pi	Obj	mPow
11	11	11	1	8	874995	2000
11	11	11	1	8	874995	1990
11	11	11	1	8	874995	1980
11	11	11	1	8	874995	1970
11	11	11	1	8	874995	1960
11	11	11	1	8	874995	1950
11	11	11	1	8	874995	1940
11	11	11	1	8	874995	1930
11	11	11	1	8	874995	1920
11	11	11	1	8	874995	1910
11	11	11	1	8	874995	1900
11	11	11	1	8	874995	1890
11	11	11	1	8	874995	1880
11	11	11	1	8	874995	1870
13	12	11	1	8	886293	1860

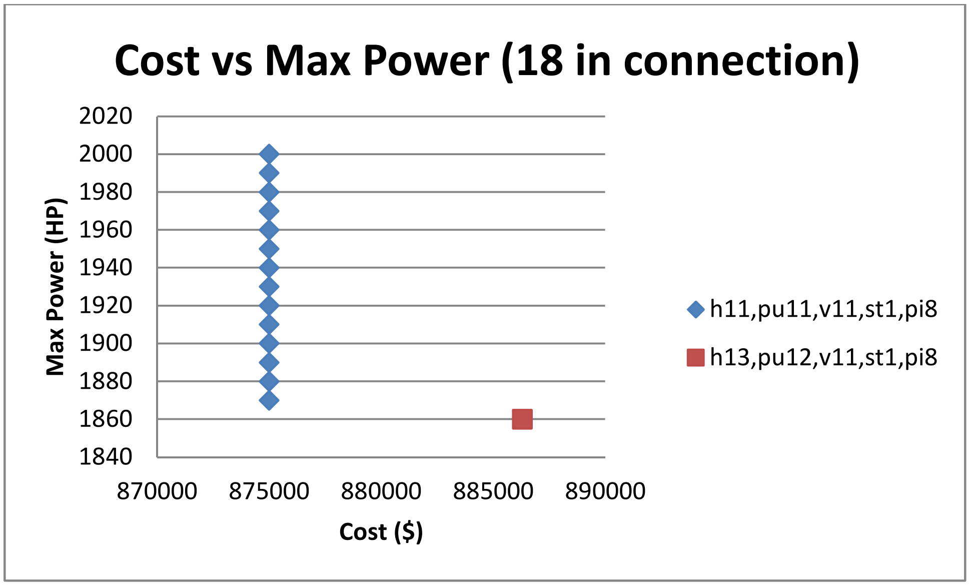


Figure 32 Cost vs Max power (18 in)

The results for the 18 inch connections result in a surprising discovery. One system configuration tends to dominate in terms of the lowest cost yet still meeting the power constraint. One other observation is the additional cost that would be added if the system had to be less than or equal to 1860 HP.

Table 6 Max Power analysis (16 in)

16 inch connection						
Hx	Pu	V	St	Pi	Obj	mPow
1	1	1	1	3	794000	2000
1	1	1	1	3	794000	1990
1	1	1	1	3	794000	1980
1	2	1	1	3	797185	1970
1	2	1	1	3	797185	1960
1	2	1	1	3	797185	1950
1	2	1	1	3	797185	1940
1	3	1	1	3	799308	1930
1	4	1	1	3	800724	1920
1	5	1	1	3	801962	1910
3	7	1	1	3	813958	1900
5	8	1	1	3	824891	1890
7	9	1	1	3	835647	1880

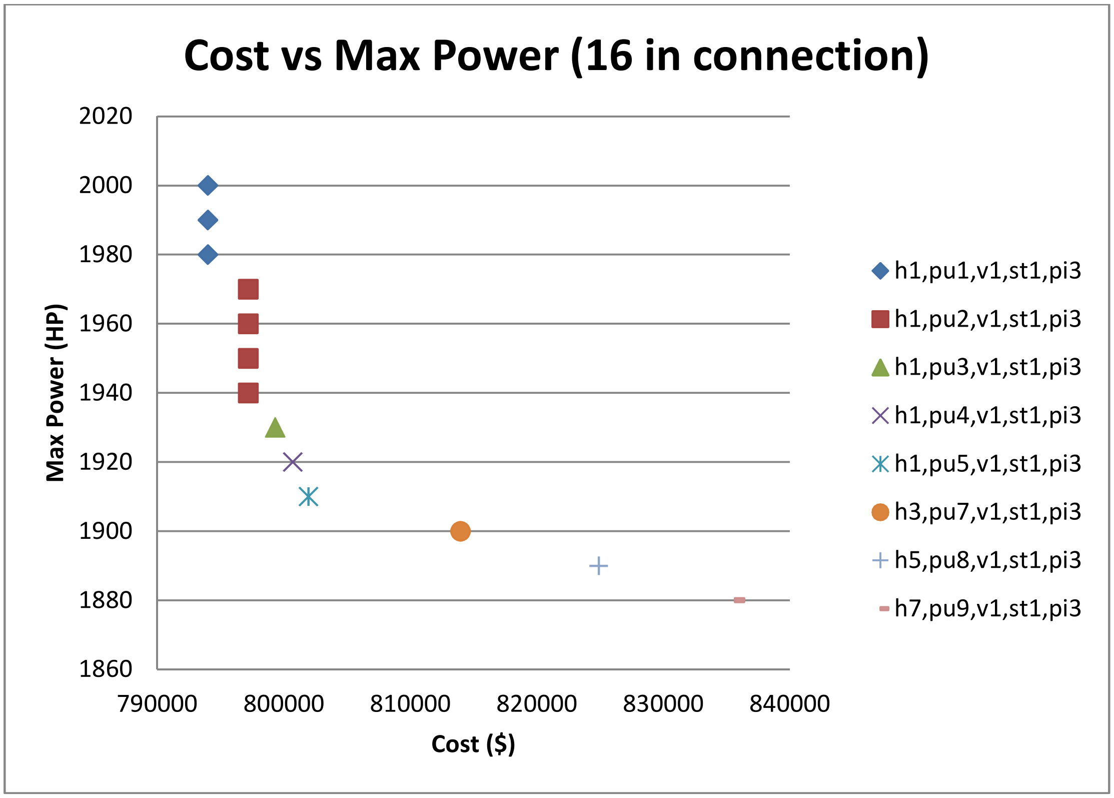


Figure 33 Cost vs Max power (16 in)

The results for the 16 inch connection also show the same trend that shows if the power is decrease the cost of the system will increase because the pump will be required to work at a higher efficiency (which costs more money). Another observation is that the main changes in system configuration involve the heat exchanger and pump, whereas the valve, surge tank, and pipe remain constant.

One of the main constraints applied to the system was the max amount of pressure drop that each component can have with respect to the discharge pressure the centrifugal pump can supply. Even though it would be ideal to have the pump working at its Best Efficiency Point (dependent on flow rate and pressure) throughout normal operation, there are always variations in system pressure and flow rate due to change in operation mode or system problems that require that the pump be sized higher than what it needs to be. This over sizing of the pump is defined as a "margin". The goal of the margin is to have it large enough to compensate for system variable, but not so much that the pump is operate at a very low efficiency (which reduces the pumps life span). The results on the pressure margin for the system are included in Figure 34 and Figure 35.

Table 7 Pressure Margin Analysis (16 in)

16 inch Connection						
Hx	Pu	V	St	Pi	Cost ($)	Pressure Marg (ft)
1	6	1	1	3	803024	0
1	6	1	1	3	803024	-10
1	6	1	1	3	803024	-20
1	6	1	1	3	803024	-30
1	6	1	1	3	803024	-40
1	6	1	1	3	803024	-50
1	6	1	1	3	803024	-60
1	6	1	1	3	803024	-70
1	6	1	1	3	803024	-80
1	6	1	1	3	803024	-90
1	6	1	1	3	803024	-100
1	6	1	1	3	803024	-110
1	6	1	1	3	803024	-120
1	6	1	1	3	803024	-130
1	6	1	1	3	803024	-140
1	6	1	1	3	803024	-150

1	6	1	1	3	803024	-160
1	6	1	3	3	805114	-170
1	6	1	5	3	807204	-180
2	6	1	5	3	812228	-190
2	6	7	6	3	816365	-200
2	6	7	8	3	838455	-210
2	6	7	10	3	860545	-220
2	6	7	12	3	882635	-230
1	6	1	17	3	889744	-240
1	6	1	19	3	891834	-250
2	6	1	19	3	896858	-260
2	6	7	20	3	900995	-270

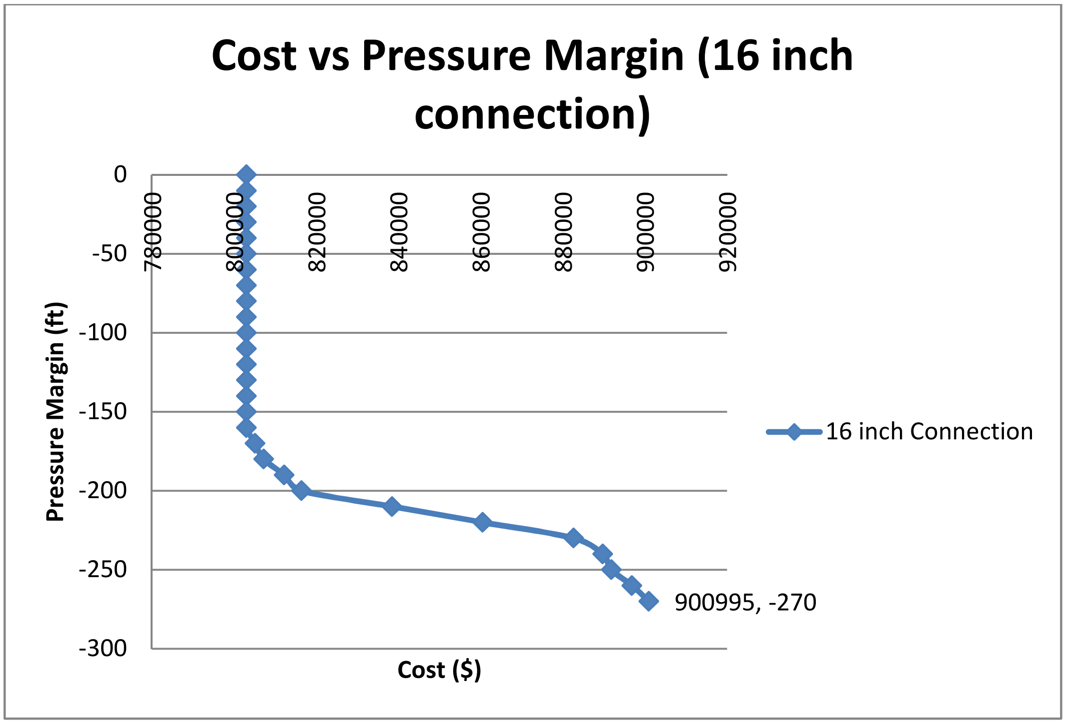


Figure 34 Cost vs Pressure Margin (16 in)

The results show that a system configuration with a pressure margin of -160 ft is the optimal value in terms of cost for lower ranges of pressure margin, but as the pressure margin increases, so does the cost because the pump has to be sized to with stand higher pressures. All components were varied, except for the pipe.

Table 8 Pressure Margin Analysis (18 in)

18 inch Connection						
Hx	Pu	V	St	Pi	Obj	pMarg
11	11	11	1	8	874995	0
11	11	11	1	8	874995	-10
11	11	11	1	8	874995	-20
11	11	11	1	8	874995	-30
11	11	11	1	8	874995	-40
11	11	11	1	8	874995	-50
11	11	11	1	8	874995	-60
11	11	11	1	8	874995	-70
11	11	11	1	8	874995	-80
11	11	11	1	8	874995	-90
11	11	11	1	8	874995	-100
11	11	11	1	8	874995	-110
11	11	11	1	8	874995	-120
11	11	11	1	8	874995	-130
11	11	11	1	8	874995	-140
11	11	11	1	8	874995	-150
11	11	11	1	8	874995	-160
11	11	11	1	8	874995	-170
11	11	11	1	8	874995	-180
11	11	11	1	8	874995	-190
11	11	11	1	8	874995	-200
11	11	11	1	8	874995	-210
11	11	11	1	8	874995	-220
11	11	11	1	8	874995	-230
11	11	11	1	8	874995	-240
11	11	11	1	8	874995	-250
11	11	11	1	8	874995	-260
11	11	11	1	8	874995	-270
11	11	11	1	8	874995	-280
11	11	11	1	8	874995	-290
11	11	11	1	8	874995	-300
11	11	11	1	8	874995	-310
11	11	11	1	8	874995	-320
11	11	11	1	8	874995	-330
11	11	11	1	8	874995	-340
11	11	11	1	8	874995	-350
11	11	11	2	8	876040	-360
11	11	11	4	8	878130	-370

11	11	11	6	8	880220	-380
11	11	12	7	8	893917	-390
11	11	12	9	8	916007	-400
11	11	12	11	8	938097	-410
11	11	11	14	8	958580	-420
11	11	11	16	8	960670	-430
11	11	11	18	8	962760	-440
11	11	11	20	8	964850	-450

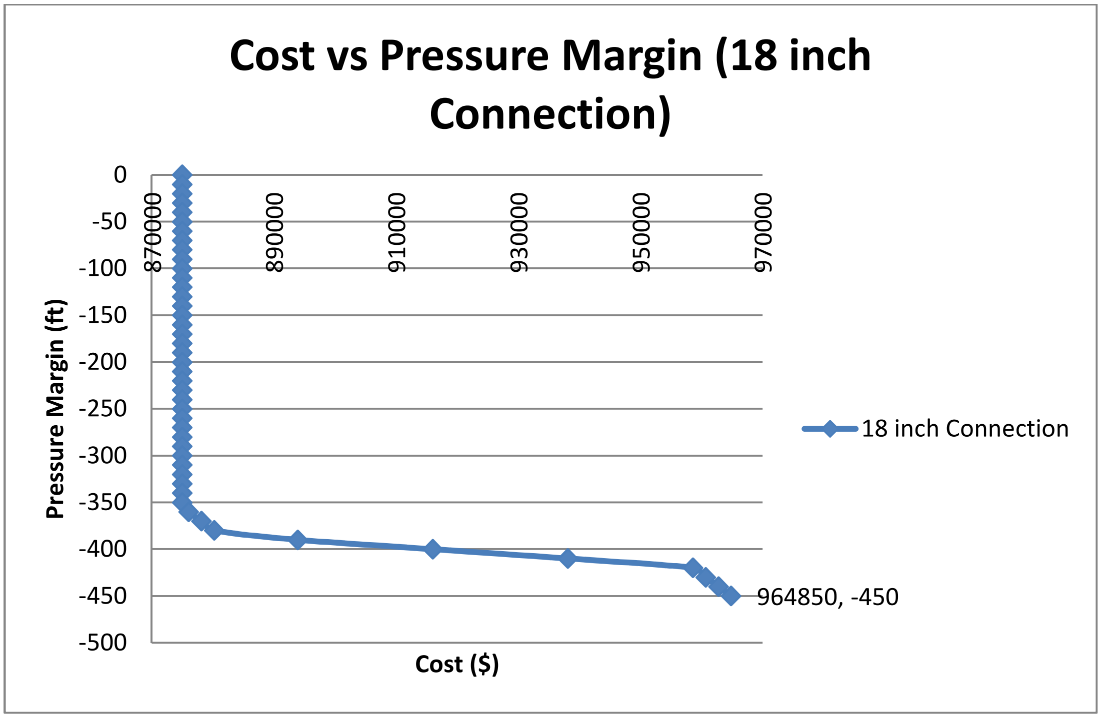


Figure 35 Cost vs Pressure Margin (18 in)

For the 18 inch connection the pressure margin is much higher than the 16 inch configurations (almost by 200 ft), but also cost more. A pressure margin of -350 is the lowest possible pressure margin for the cost. The same trend still exists for the 18 inch as the 16 inch connection, which shows that as the pressure margin increases, so does the cost.

Sensitivity Analysis with Pump Efficiencies

For testing pump efficiencies effect on the system variables we examined different pressure margin trends for changing efficiencies. The results are shown for the 16 and 18 inch connection configurations.

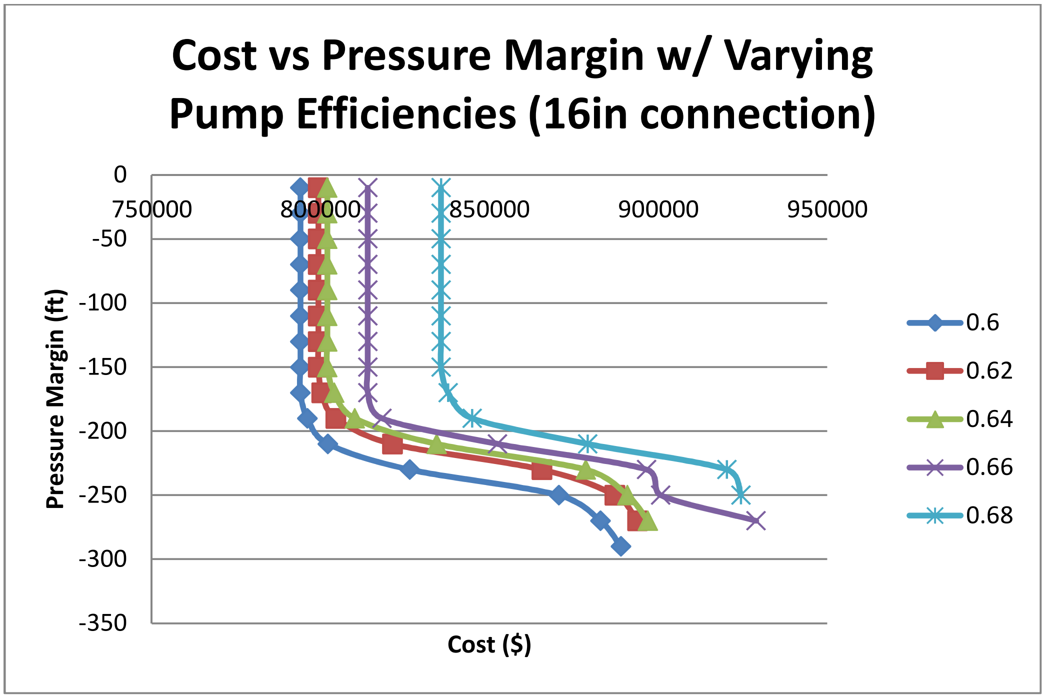


Figure 36 Pressure Margin Sensitivity Analysis (16 in)

The results shown in Figure 36 show that the efficiency have an effect on the cost of the system, but not as strong a relation to pressure margin. Another observation is that the highest pressure margin is achieved by the least efficiency. Overall this shows the dependency between efficiency and cost.

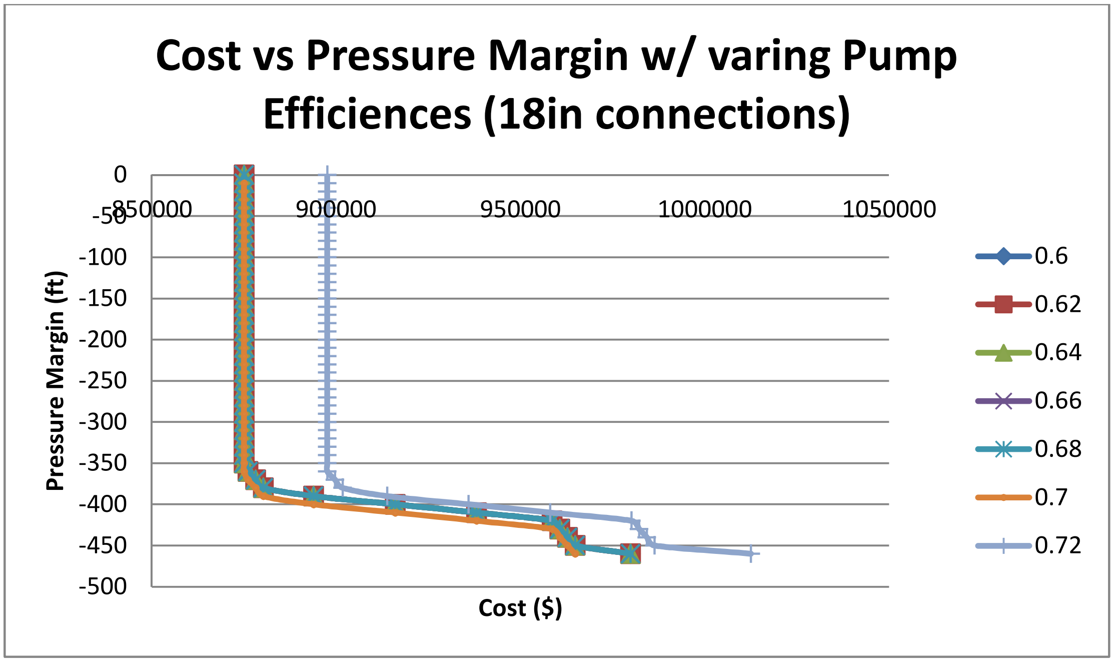


Figure 37 Pressure Margin Sensitivity Analysis (18 in)

For the 18 inch connection the results are different from those observed in the 16 inch connection. With the 18 inch configuration the pump efficiency does not have as big of an impact on cost or pressure margin until the max efficiency at 0.72. Each efficiency offer the same max pressure margin (-460 ft).

Along with pressure margin, flow rate margin is something to analysis from the perspective of pump efficiencies. Pump efficiency and flow rate affect the pump required horsepower, so even though flow rate is not directly related to the pump efficiency, there will be some effect because of the power constraint. Below the sensitivity analysis for 16 inch and 18 inch configuration options are shown in Figure 38 and Figure 39.

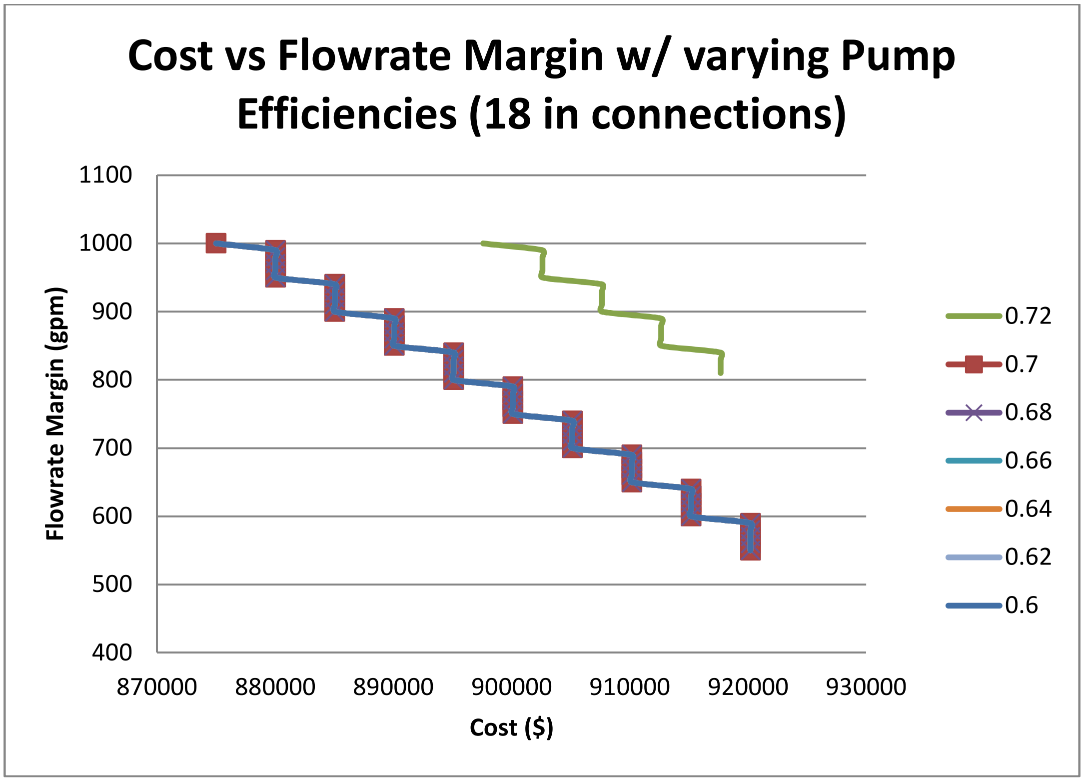


Figure 38 Flow rate Sensitivity Analysis (18 in)

The results for the 18 inch configuration show that there is very little influence the efficiency has of the flow rate margin, and only at the highest efficiency (0.72) does the cost of the configuration rise, but still not deliver a flow rate margin as low as pumps of a lesser efficiency. This result is similar to the pressure margin sensitivity as well.

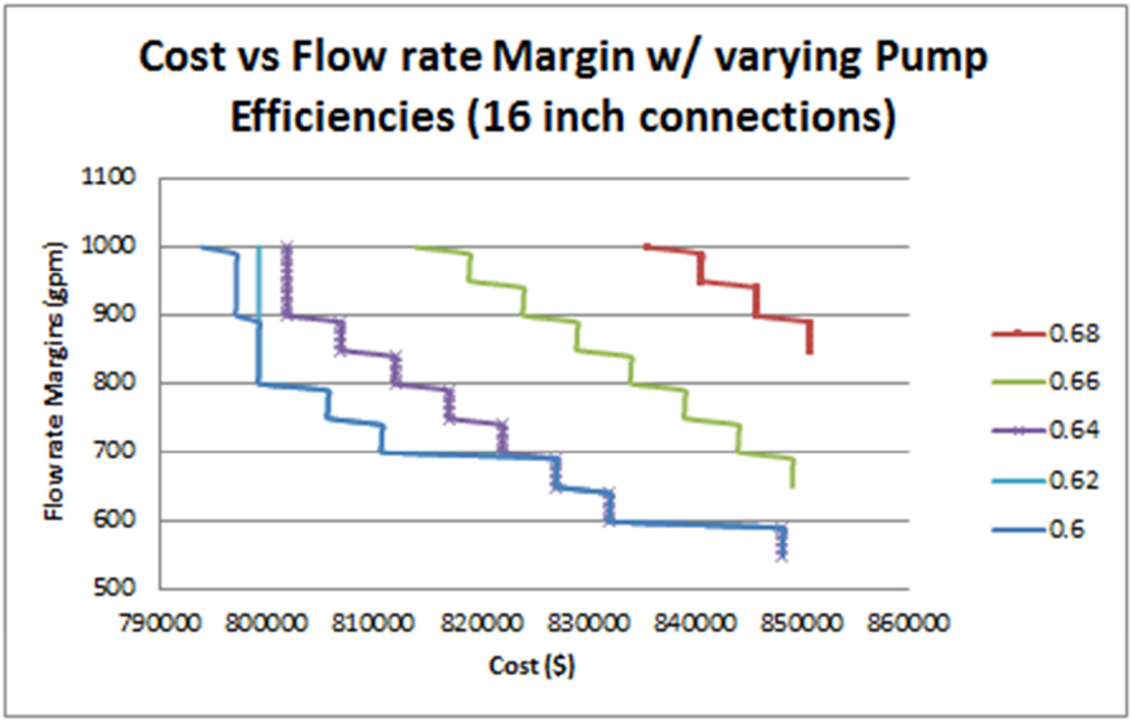


Figure 39 Flow rate Sensitivity Analysis (16 in)

Unlike the results of the 18 inch configuration, the 16 inch system configurations are highly impacted by changes in pump efficiency. The trend is such that as the pump efficiency increases, so does the cost of the system. Also at higher efficiencies the flow rate margin cannot reach lower margins, whereas lower efficiency pumps can.

CHL Trade Off and Traceability

After reviewing the results from the flow margin, pressure margin, power, and efficiency curves, several options were found that satisfy minimizing the margins and increasing efficiency.

Table 9 System Configuration Choices (16 and 18 inch)

16 inch					18 inch				
hcvstp	pressure marg	flow marg	power	efficiency	hcvstp	pressure marg	flow marg	power	Efficiency
1,1,1,1,3	-170	1000	-	0.6	11,11,11,1,8	-350	1000	1870	0.6
10,6,1,1,3	-	550	-	0.64	12,11,11,1,8	-	950	-	0.6
7,9,1,1,3	-150	1000	1880	0.68	15,13,11,1,8	-360	1000	-	0.72
1,3,1,1,3	-150	800	-	0.62	12,11,11,1,8	-	950	-	0.68
1,5,1,1,3	-150	900	-	0.64	20,11,11,1,8	-	550	-	0.7
3,7,1,1,3	-170	1000	1900	0.66	13,12,11,1,8	-	-	1860	-

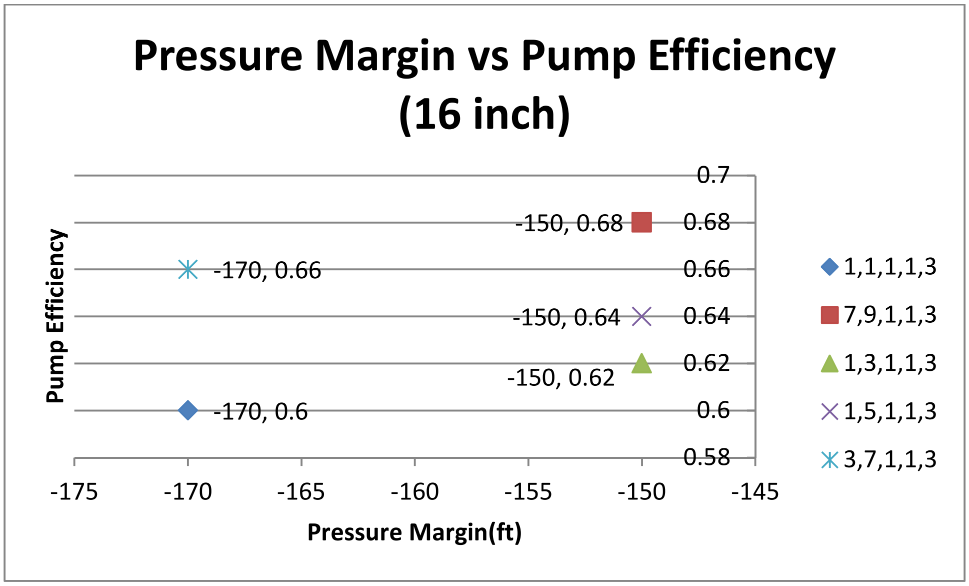


Figure 40 Pressure Margin vs Pump Efficiency (16 inch)

Analysis of the tradeoff shows that there is one pareto optimal point that satisfies minimizing pressure margin and maximizing efficiency. That point is

(7,9,1,1,3). This system configuration for 16 inch connection is considered a possible solution to the design requirements.

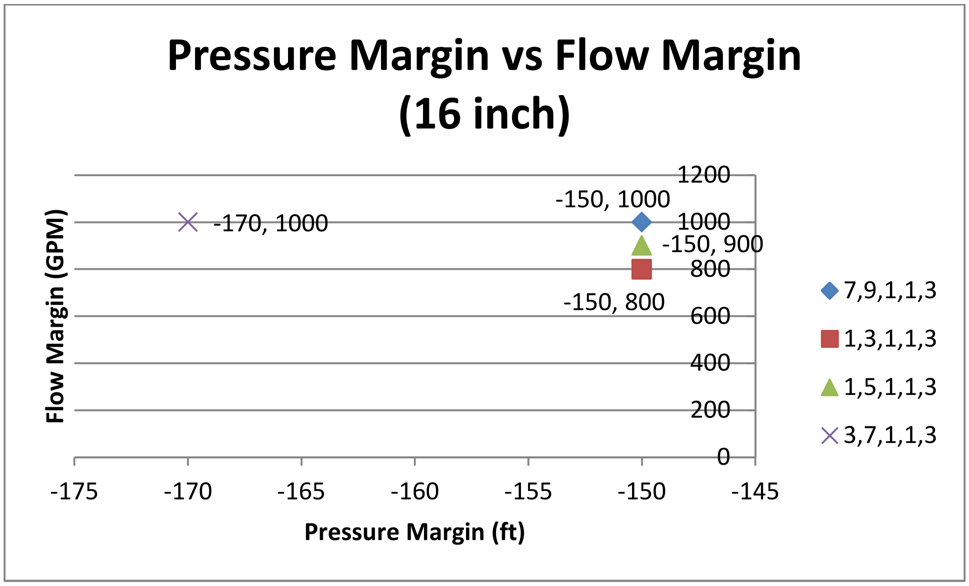


Figure 41 Pressure Margin vs Flow Margin (16 inch)

Analysis of the tradeoff for pressure and flow margin show that for minimizing both axes result in a pareto optimal point at system configuration (1,3,1,1,3). This system configuration for the 16 inch connection is a potential solution for the system. Also, it is interesting to see that the original solution proposed from the previous tradeoff graph is dominated in this tradeoff, so that shows the solution is not globally optimal.

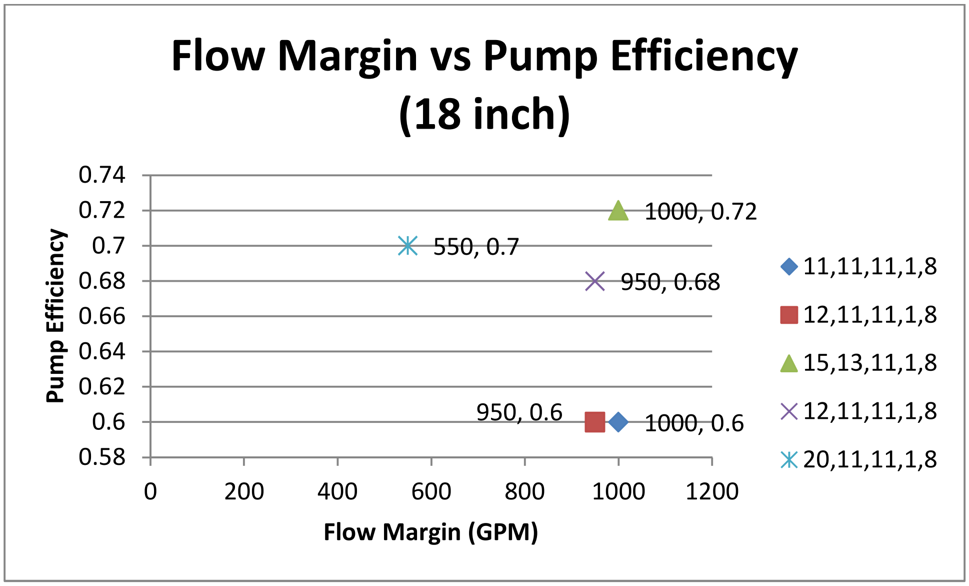


Figure 42 Flow Margin vs Pump Efficiency (18 inch)

For this tradeoff for flow margin and pump efficiency, that optimal point would minimize flow margin and maximize pump efficiency. From the tradeoff there are two non-dominated solutions (20,11,11,1,8) and (15,13,11,1,8). The first configuration is optimal because it provides the lowest margin, whereas the second configuration is optimal because it offers the best pump efficiency.

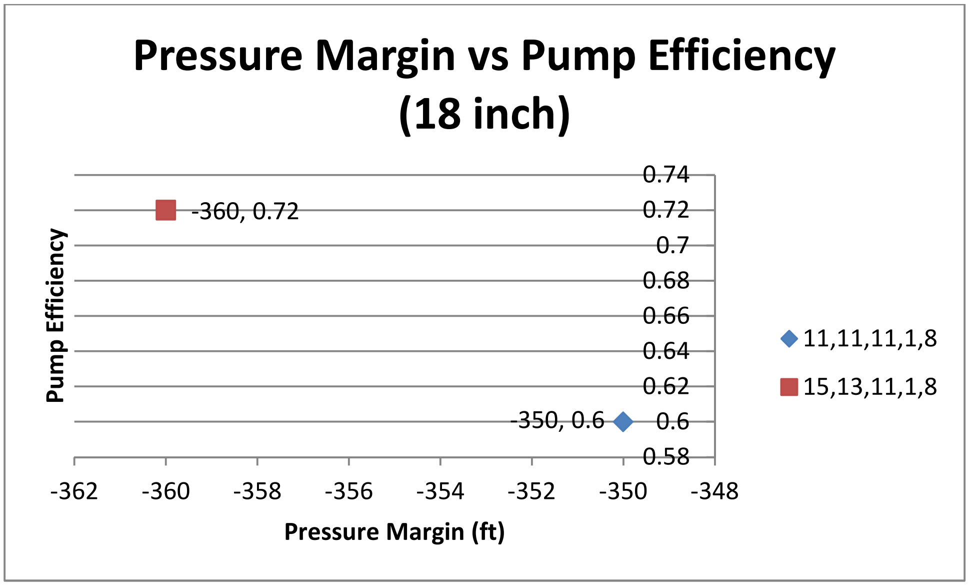


Figure 43 Pressure Margin vs Pump Efficiency (18 inch)

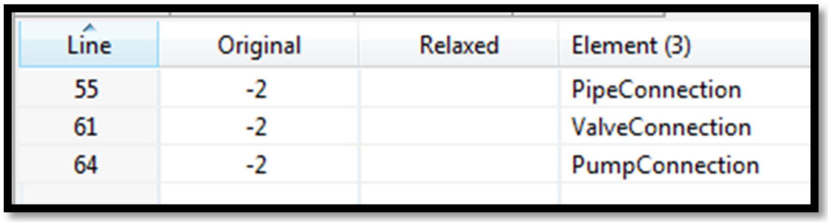
This last tradeoff graph for the 18 inch configuration relates pressure margin to pump efficiency. The selection from the last tradeoff (15,13,11,1,8) is again a non-dominating solution because it has the highest pump efficiency. The other point (11,11,11,1,8) is also non-dominating because it has the lowest pressure margin.

The resulting potential configuration options for the 16 inch and 18 inch systems are:

16 Inch Options	Cost ($)
h7,pu9,v1,st1,pi3	835647
h1,pu3,v1,st1,pi3	799308

18 Inch Options	Cost ($)
h20,pu11,v11,st1,pi8	920214
h15,pu13,v11,st1,pi8	897591
h11,pu11,v11,st1,pi8	874995

The optimization tool also aides in making changes to specifications to satisfy changes in the high level requirements (tracing system requirement to component specification changes). Take for example; that the engineer makes a change to the amount of flow rate margin they want (reduce it from 550 gpm to 500 gpm). Previously there would have to be many recalculations of components to resize them in order to simulate the process and the resubmit new RFQ to all the involve suppliers in the procurement process. With the optimization tool, the high level constraint is traced to the parameter in a specific component that needs to be changed. In this case, the main change required that the connection size of a certain pump, valve, and pipe must be increased (it is minus because it subtracts from the right hand side of the constraint on the connection size) (see). Vendor 8 for the pump, vendor 1 for the valve, and vendor 3 for the pipes was suggested to increase their connection size in order to find a solution that met the new flow margin requirement. After making the changes the new result cost for the system is $875,133.77.



Line	Original	Relaxed	Element (3)
55	-2		PipeConnection
61	-2		ValveConnection
64	-2		PumpConnection

Figure 44 CPLEX Relaxation Suggestion

Negotiation aided by Optimization

Another benefit to optimization is the information provided for negotiation between design engineer and supplier. The importance of using optimization for negotiation is because the optimization provides modifications to the system requirements and equipment parameters to meet negotiation criteria. Additionally, the optimization results show the positive and negatives of implementing the change. Negotiation is usually done with respect to cost, services, and transportation, but with optimization can be expanded to include engineering categories such as performance and reliability. This is because of the understanding of how equipment parameters are related to high level requirements. Therefore negotiation is another application of the collaborative requirement framework for verification.

The method for implementing negotiation via optimization will include defining negotiation objectives, determining the key parameter and equipment for each objective, and evaluating the negotiation objectives with respect to the equipment and the system requirements. Defining negotiation objectives is critical to negotiation because it prevents purchases from conceding and accepting equipment and system designs that could be improved. In the collaborative requirement framework negotiation objectives will be implemented as constraints in the optimization problem. Afterward, optimization results should be used to determine the key equipment parameters that affect the negotiation objective the most. This will help focus on what suppliers and equipment need to be negotiated with to improve upon the negotiation objectives. Lastly the negotiation objectives are evaluated to determine their effect on one another and to determine what the next step in negotiation should occur (if needed). An example of this negotiation method is shown below with the CHL system, evaluating several negotiation objectives.

Using the CHL system, the negotiation method will show how cost, performance, and reliability can be improved. In particular, the centrifugal pump will be the main focus because of its main contribution to the performance, reliability, and cost of the system. For evaluation, the negotiated results are compared with the previous selections using optimization. In **Table** 10 the negotiation objectives are shown for the centrifugal pump.

Table 10 CHL Negotiation Objectives

Negotiation Objectives			
Criteria	**Parameter**	**Baseline**	**Desired**
Performance	Efficiency	0.77	0.9
Reliability	Specific Speed (rpm)	2100	1900
Cost	Capacity Factor (gpm*psi)	60,000 ($15,000)	55,000 ($12,000)

The performance of the centrifugal pump (and the rest of the system) is highly related to the pump’s efficiency, best efficiency point (BEP) flowrate, and BEP differential pressure head. To represent pump performance the pump industry uses a pump characteristic curve similar to the one shown in **Figure** 45 [25]. These curves show the amount of discharge pressure head (y-axis) a pump can provide for a given volumetric flow rate (x-axis) and also show how the other components in the system increase in pressure head with the rise in volumetric flow rate (the red line). The pump curves and system curves play a role in selecting the best performing pump.

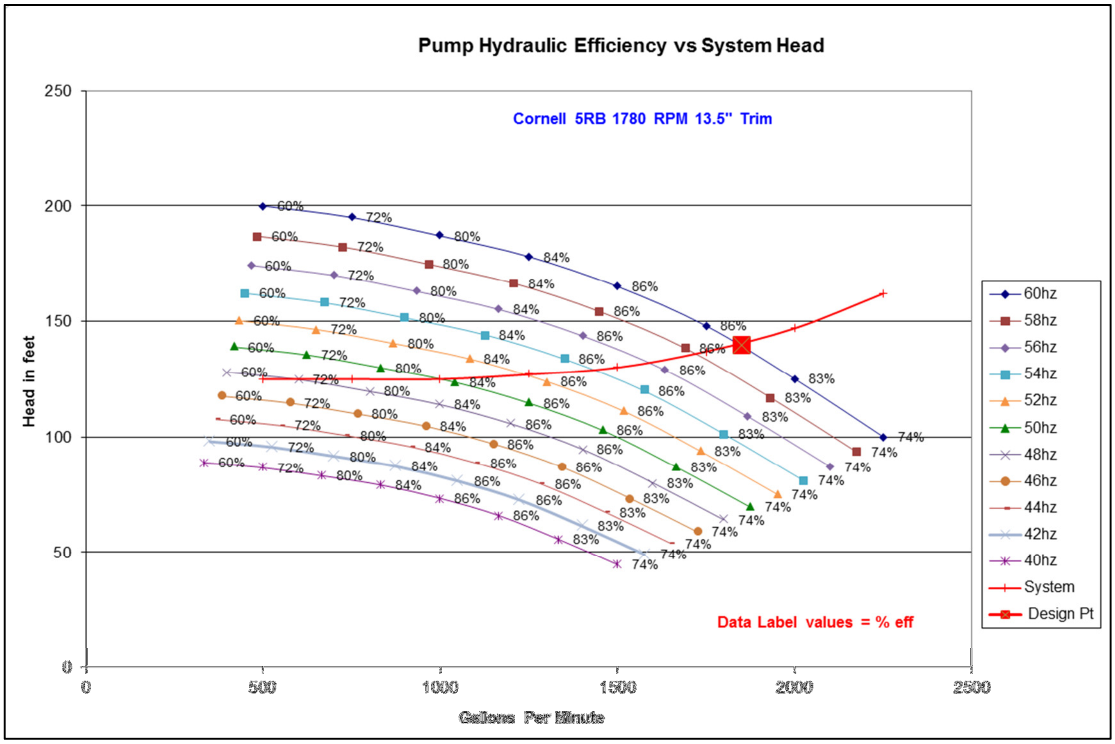


Figure 45 Sample Pump Characteristic Curve

Additionally there is a strong relationship between the efficiency, power, flowrate, and differential head (shown in equation 7.1). Therefore when negotiating with respect to efficiency (η_p) there is an effect on the pump flowrate (Q), discharge head (H), and shaft power ($P_{S(HP)}$) ($P_{H(HP)}$ is the hydraulic power).

$$P_{H(HP)} = \frac{Q*\delta*g*H}{3.6*10^6} \quad (7.1)$$

$$P_{S(HP)} = \frac{P_H}{\eta_p} \quad (7.2)$$

Another negotiation objective is equipment reliability. Equipment reliability can be defined for each component by efficiencies and material properties and from a system viewpoint. From a system viewpoint certain equipment have more priority than others equipment because of their functionality. In this case, equipment reliability also entails preventing critical equipment failure and improving the operation of critical equipment failures [26]. Equipment such as the centrifugal pump and heat exchanger are considered as critical equipment for the CHL system. To demonstrate reliability analysis for negotiation will be conducted on the centrifugal pump. The main reliability parameter for the centrifugal pump is the pump suction-specific speed. In the pump industry it is an empirically established stance that pump models with a specific speed less than 11,000 rpm has a more stable operation and are more reliable. So for pumps with a specific speed in the range of 8,000-11,000 operation should be safe. Otherwise pumps may experience impeller and casing erosion, shaft deflection and many other problems [27]. Therefore with respect to reliability, the lower the pump specific speed the better reliability of the pump. Equation 7.2 shows the relationship the specific speed (N_s) has to the pump speed (N), flow rate (Q), and discharge head (H).

$$N_s = \frac{N * \sqrt{Q}}{H^{3/4}} \quad (7.3)$$

The last negotiation objective is cost. For the centrifugal pump the main contributors to cost are the flowrate and discharge pressure. One parameter, the capacity factor [28] (the product of the flowrate and discharge pressure), is a good gauge of the cost of the pump. By negotiating the flowrate or discharge pressure down, the resulting cost of the pump will go down. Therefore the way that the pump cost will be negotiated is by reducing the capacity factor.

After analysis of the different pump suppliers (with respect to the three negotiation objectives) three options arose for the 16 inch connection size and two potential options were determined for the 18 inch connection size. **Table** 11, **Table** 12, and **Table** 13 show the suppliers selected and their objective values. Also in **Table** 14 and **Table** 15 the objective values for each supplier is shown with respect to their connection size. Lastly, the results from the tables (for the 16 inch connections) are represented in Figure 46, Figure 47, and Figure 48. All this information will be used to guide negotiation. Specifically, the 16 inch connection options will be negotiated in this example.

Table 11 Reliability (Specific speed) Objective Results

Connection Size	Centrifugal Pump Supplier	Lowest Specific Speed
16	8	2040
18	11	2090

Table 12 Cost (Capacity Factor) Objective Results

Connection Size	Pump Supplier	Lowest Pump Capacity
16	1	53200
18	11	68180

Table 13 Performance (Efficiency) Objective Results

Connection Size	Pump Supplier	Maximum Efficiency
16	10	0.76
18	14	0.8

Table 14 Objective Values for 16 inch Connection

	16 inch				
Pump Supplier	Specific Speed	Efficiency	Capacity Factor	Pump Cost	System Cost
8	2040	0.74	63471.46	15,091	539037
10	2146.665	0.76	66587.93	15,828.50	539280
1	2590.02	0.67	53200	12,869.82	538215

Table 15 Objective Values for 18 inch Connection

	18 inch				
Pump Supplier	Specific Speed	Efficiency	Capacity Factor	Pump Cost	System Cost
11	2090	0.77	68180	16,220.70	505108
14	2237.027	0.8	72533.12	17,430.50	505398

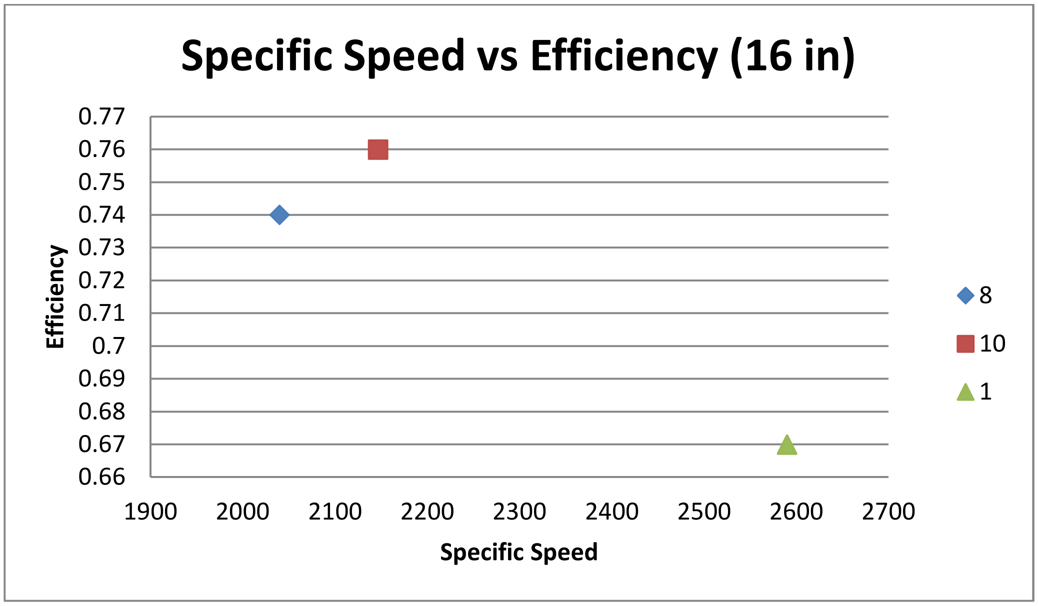


Figure 46 Specific Speed vs Efficiency for 16 inch Connection

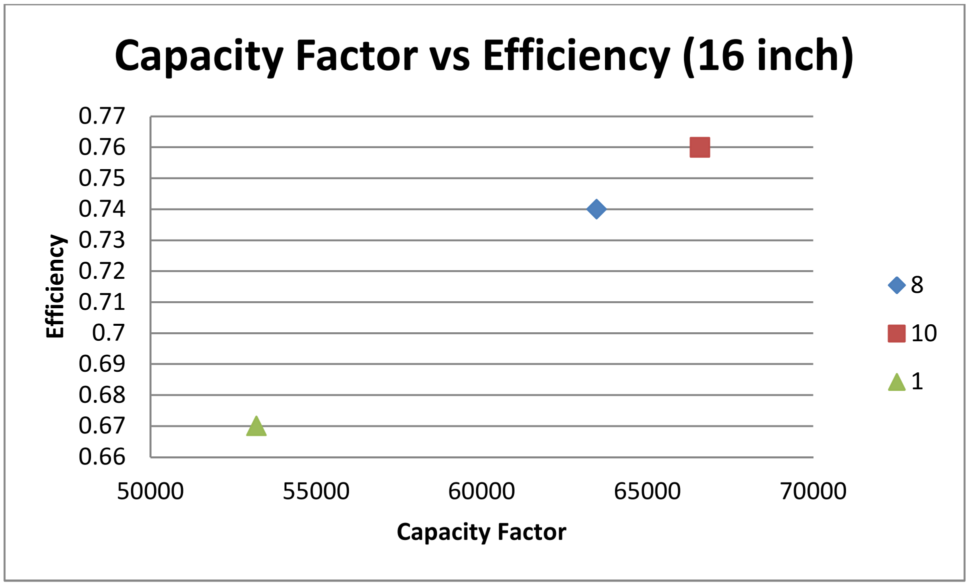


Figure 47 Capacity Factor vs Efficiency for 16 inch Connection

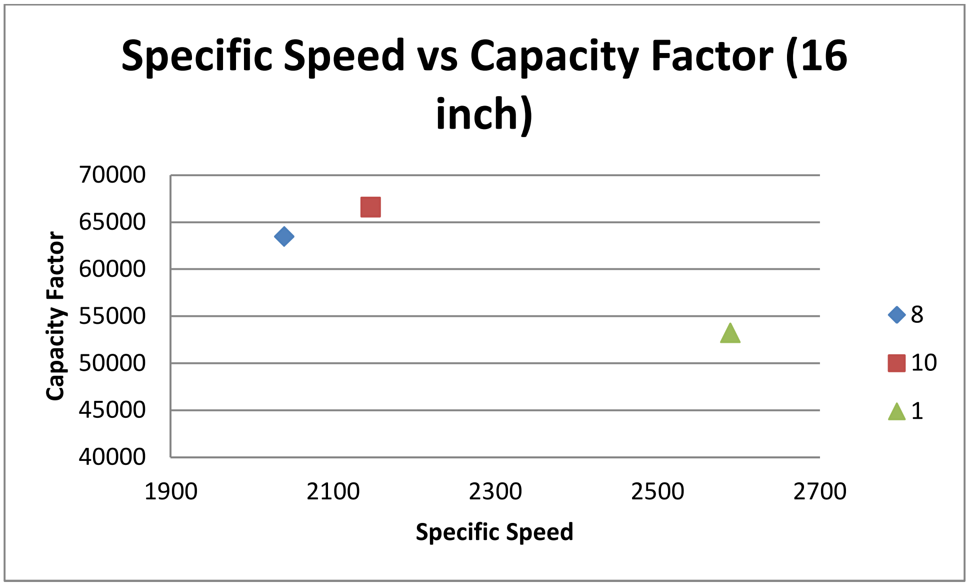


Figure 48 Specific Speed vs Capacity Factor for 16 inch Connection

When negotiating all the objective must be taken into consideration. This example shows that there is one supplier that satisfies the specific speed (reliability) criteria (supplier 8), one supplier that satisfies the capacity factor (cost) criteria (supplier 1), and no supplier that satisfies the efficiency criteria. Therefore focusing on efficiency, the design engineers want to know high the efficiency can be negotiated without affecting the other negotiation criteria. For instance, if the efficiency of supplier 8 needed to be negotiated, the design engineers need to understand how much the efficiency is allowed to increase before it affects the cost and reliability of the pump. From the optimization results it is determined that the maximum efficiency the pump can be negotiated to is 0.81 before it effects the reliability (specific speed) criteria. **Figure** 49 and **Figure** 50 show the results.

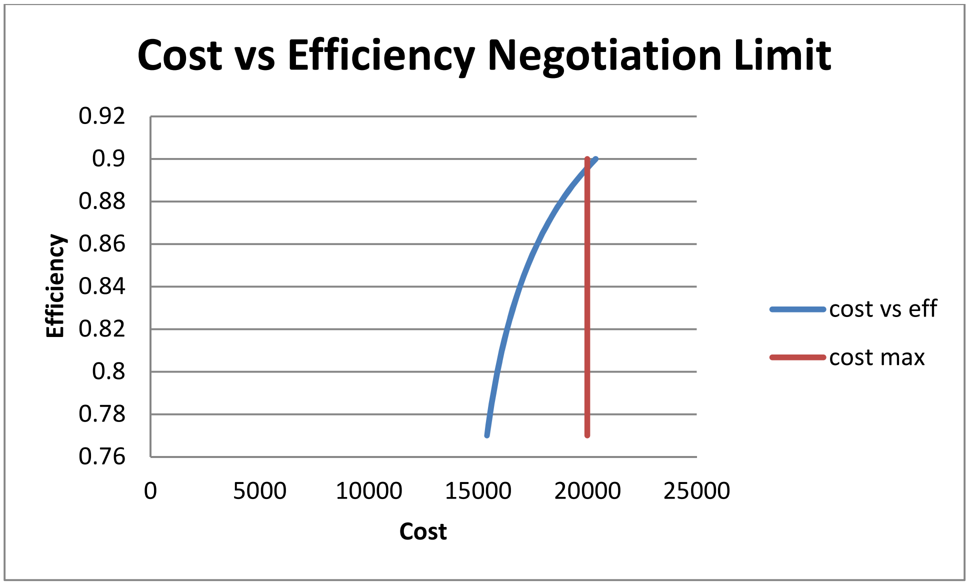


Figure 49 Cost vs Efficiency Negotiation Limit

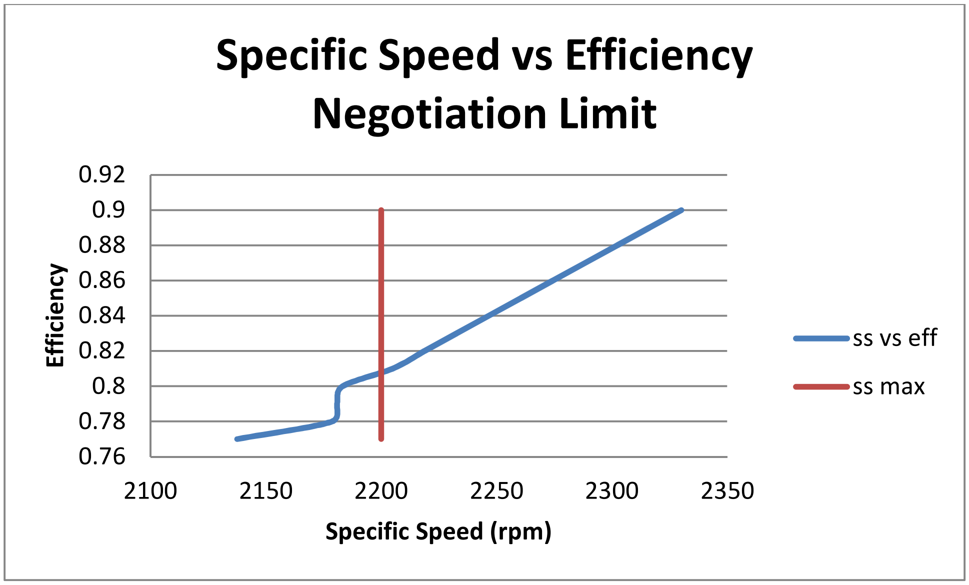


Figure 50 Specific Speed vs Efficiency Negotiation Limit

Chapter 8: Conclusion and Future Work

Conclusion

By the advent of SysML, MFM models, and CPLEX, this thesis shows there is a way of performing collaborative requirements engineering by using constraints that can be traced to high level requirements through MBSE. The CHL system served as a good baseline system to examine how CRE would work in component selection aspect of procurement. Through optimization best system could be configured base on the objective. In this case, there were tradeoffs that were identified that helped in selecting the right group of components to meet the system requirements. Overall the work will help in clarifying the related parameters and give designers more understanding on how changes in requirement will affect the configuration of components.

Future Work

Potential ways I can extend this research include applying this work to other areas of the system lifecycle instead of the procurement phase. From an engineering standpoint, further research could be applied to gather different mathematical models of the components and allow for more components to be connected. Additionally this research can look at how different simulation tools generate specifications from RFQ and the variation in the software tools supplier data (can be used to compare optimization results) To apply optimization techniques to not only the product selection, but process selection (how the component are connected and material used in construction), similar to the IPPD.

Appendices A: CPLEX Code

```
//Data
      //System Data//
            range sv = 1..26; //Number of system variables
            float SystemVars[sv] = ...;
      //General Vendor Data//
            //range  Ename=  1..5;  //heatex,  pump,  valve,  surgeTank,
pipe
            range VendorNumb =1..20; //List of Vendors
            {string} Ename = ...;
      //Pump Data
            range peg = 1..7;
            float       PumpData[peg][VendorNumb]       =       ...;
//DesFlow,Pwer,Eff,DesDiffHead,DesPress,MaxDiffHead,MaxDiffPress,NPS
Hr[8],connDia[9]
      //Pipe Data
            range pip = 1..9;
            float       PipeData[pip][VendorNumb]       =       ...;
//NomSiz,WallThick,Len,RoughCon,HLoss,TotHLoss,Wght,TWght,MaxFlow
            int    PipeMat[VendorNumb] = ...;//Pipe Material
      //Heat Exchanger Data
            range hx = 1..34;
            float  HxData[hx][VendorNumb]  =  ...;  //Port  diameter[8],
Cooling Vol Flow[9], DiffHead[11], Efficiency[34]
      //Valve Data
            range vlv = 1..4;
            float           ValveData[vlv][VendorNumb]            =
...;//conDia[1],Cv[2],VolFlow[3],diffHead[4]
      //Surge Tank Data
            range st = 1..9;
            float       SurgeTData[st][VendorNumb]       =       ...;
//volume[1],fluidHght[2],wallThick[3],diameter[4],height[5],desHead[
8]
      //Cost Data;
            float Cost[Ename][VendorNumb] = ...;
//Variables
dvar boolean x[Ename][VendorNumb];

//Objective
minimize
   sum(e in Ename, v in VendorNumb)
     x[e][v]*Cost[e][v];


//Constraints
subject to {
  OneVendor:
      forall(q in Ename)
    sum(z in VendorNumb)
      x[q][z] == 1;

  PipeConnection:
```

```
    sum(y in VendorNumb)
      PipeData[1][y]*x["Pi"][y]  ==  SystemVars[16];//Set  requirement
of pipe connection size
  HxConnection:
    sum(f in VendorNumb)
      HxData[8][f]*x["Hx"][f] == SystemVars[16];
  ValveConnection:
    sum(t in VendorNumb)
      ValveData[1][t]*x["V"][t] == SystemVars[16];
   PumpConnection:
     sum(w in VendorNumb)
       PumpData[7][w]*x["Pu"][w] == SystemVars[16];
  PipeLength:
    sum(e in VendorNumb)
      PipeData[3][e]*x["Pi"][e] == SystemVars[21];
  PipeMaterial:
    sum(e in VendorNumb)
      PipeMat[e]*x["Pi"][e] == SystemVars[22];
  TankSupplyPumpHead:
    sum(h   in   VendorNumb)SurgeTData[8][h]*x["ST"][h]+SystemVars[25]
>= sum(h in VendorNumb)PumpData[5][h]*x["Pu"][h];
    forall(i in 23..23)
  HxReqEfficiency:
    sum(d in VendorNumb)
      HxData[34][d]*x["Hx"][d] >= SystemVars[i];
  PumpPressLoss:
    sum(e     in     VendorNumb)HxData[11][e]*x["Hx"][e]+sum(e     in
VendorNumb)ValveData[4][e]*x["V"][e]+sum(e                          in
VendorNumb)PipeData[6][e]*x["Pi"][e]-sum(e                          in
VendorNumb)SurgeTData[8][e]*x["ST"][e]       <=        sum(e       in
VendorNumb)PumpData[4][e]*x["Pu"][e];
  forall(i in 25..25)
  HxVolFlowrateTop:
    sum(c      in      VendorNumb)HxData[9][c]*x["Hx"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] >=-SystemVars[25];
  forall(i in 25..25)
  HxVolFlowrateBot:
    sum(c      in      VendorNumb)HxData[9][c]*x["Hx"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] <=SystemVars[25];
  forall(i in 25..25)
  ValveVolFlowrateTop:
    sum(c     in     VendorNumb)ValveData[3][c]*x["V"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] >=-SystemVars[25];
  forall(i in 25..25)
  ValveVolFlowrateBot:
    sum(c     in     VendorNumb)ValveData[3][c]*x["V"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] <=SystemVars[25];
  forall(i in 25..25)
  PipeVolFlowrateTop:
    sum(c     in     VendorNumb)PipeData[9][c]*x["Pi"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] >=-SystemVars[25];
  forall(i in 25..25)
  PipeVolFlowrateBot:
    sum(c     in     VendorNumb)PipeData[9][c]*x["Pi"][c]-sum(c     in
VendorNumb)PumpData[1][c]*x["Pu"][c] <=SystemVars[25];
  PumpEfficiency:
    sum(g in VendorNumb)PumpData[3][g]*x["Pu"][g]>=SystemVars[26];
```

```
}
main
{
 thisOplModel.generate();

  var chl = thisOplModel;
  var cMarg = chl.SystemVars[25];

  //var best;
  var curr = Infinity;
  var ofile = new IloOplOutputFile("chl_cool_marg.txt");
  while ( 1 ) {
    //best = curr;

    if ( cplex.solve() ) {
      curr = cplex.getObjValue();
      writeln();
      writeln("OBJECTIVE: ",curr);
      ofile.writeln(cMarg," ", curr);
    }
    else {
      writeln("No solution!");
      break;
    }
    //if ( best==curr ) break;

      cMarg-=10;
      thisOplModel.HxVolFlowrateTop[25].LB = -cMarg;
      thisOplModel.HxVolFlowrateBot[25].UB = cMarg;
      thisOplModel.ValveVolFlowrateTop[25].LB = -cMarg;
      thisOplModel.ValveVolFlowrateBot[25].UB = cMarg;
      thisOplModel.PipeVolFlowrateTop[25].LB = -cMarg;
      thisOplModel.PipeVolFlowrateBot[25].UB = cMarg;
  }
 /* if (best != Infinity) {
    writeln("plan = ",produce.Plan);
  }*/

  ofile.close();

  0;
}
```

Appendices B: Component Engineering Data

Pipe:

Vendor #	Nominal Size (in)	Wall thickness (in)	Length (ft)	Hazen-Williams roughness constant	Head Loss (ft/100ft)	Total Head Loss (ft)	Weight (lbs/100 ft)	Total Weight (lbs)	Max Flowrate (gpm)	Cost ($/ft)	Total Cost ($)	Material	Pressure Drop (psi)
1	16	0.375	200	120	3.09039	618.078	62.57813	125.1563	7500	35.04375	70087.5	1	268.2458
2	16	0.375	200	140	2.322886	464.5771	62.57813	125.1563	7500	34.41797	68835.94	2	201.6265
3	16	0.375	200	130	2.664611	532.9223	62.57813	125.1563	7500	30.66328	61326.56	3	231.2883
4	16	0.5	200	120	3.09039	618.078	82.77	165.54	7500	46.3512	92702.4	1	268.2458
5	16	0.5	200	140	2.322886	464.5771	82.77	165.54	7500	45.5235	91047	2	201.6265
6	18	0.375	200	120	1.963541	392.7081	70.58813	141.1763	8000	39.52935	79058.7	1	170.4353
7	18	0.375	200	140	1.475891	295.1783	70.58813	141.1763	8000	38.82347	77646.94	2	128.1074
8	18	0.375	200	130	1.693014	338.6027	70.58813	141.1763	8000	34.58818	69176.36	3	146.9536

9	18	0.562	200	120	1.963541	392.7081	104.6657	209.3313	8000	58.61277	117225.5	1	170.4353
10	18	0.562	200	140	1.475891	295.1783	104.6657	209.3313	8000	57.56612	115132.2	2	128.1074
11	16	0.656	200	120	3.896581	779.3161	107.5013	215.0026	8500	60.20072	120401.4	1	338.2232
12	16	0.656	200	140	2.928857	585.7715	107.5013	215.0026	8500	59.12571	118251.4	2	254.2248
13	16	0.656	200	130	3.359729	671.9458	107.5013	215.0026	8500	52.67563	105351.3	3	291.6245
14	16	0.844	200	120	3.896581	779.3161	136.615	273.2299	8500	76.50438	153008.8	1	338.2232
15	16	0.844	200	140	2.928857	585.7715	136.615	273.2299	8500	75.13823	150276.5	2	254.2248
16	18	0.75	200	120	2.442161	488.4323	138.1725	276.345	9000	77.3766	154753.2	1	211.9796
17	18	0.75	200	140	1.835646	367.1292	138.1725	276.345	9000	75.99488	151989.8	2	159.3341
18	18	0.75	200	130	2.105692	421.1385	138.1725	276.345	9000	67.70453	135409.1	3	182.7741
19	18	0.938	200	120	2.442161	488.4323	170.9244	341.8488	9000	95.71766	191435.3	1	211.9796
20	18	0.938	200	140	1.835646	367.1292	170.9244	341.8488	9000	94.00841	188016.8	2	159.3341

Valve:

	Connection Diameter (in)	Cv	Max Allowable Flowrate (gpm)	Differential Head (ft)	Pressure Drop (psi)	Cost ($)
1	16	2000	7500	32.40207	14.0625	2915.11
2	16	2020	7550	32.18855	13.96983	3599.69
3	16	2040	7600	31.9799	13.87928	4284.27
4	16	2060	7650	31.77596	13.79077	4968.85
5	16	2080	7700	31.57658	13.70423	5314.9
6	16	2100	7750	31.3816	13.61961	5660.95
7	16	2120	7800	31.19089	13.53685	6007
8	16	2140	7850	31.00431	13.45587	6353.05
9	16	2160	7900	30.82173	13.37663	6699.1
10	16	2180	7950	30.64302	13.29907	8910.1
11	18	2200	8000	30.46807	13.22314	11284.43
12	18	2220	8050	30.29675	13.14879	13935.89
13	18	2240	8100	30.12897	13.07597	16587.35
14	18	2260	8150	29.96461	13.00464	19238.81
15	18	2280	8200	29.80357	12.93475	21890.27
16	18	2300	8250	29.64575	12.86626	24541.73
17	18	2320	8300	29.49107	12.79912	27193.19
18	18	2340	8350	29.33942	12.73331	29844.65
19	18	2360	8400	29.19072	12.66877	32496.11
20	18	2380	8450	29.04489	12.60548	35147.57

Surge Tank/Compression Expansion Tank:

Vendor	Volumeteric Capacity (gal)	Height of fluid (in)	Wall Thickness (in)	Nominal Diameter (in)	Nominal Height (in)	Corrosion allowance (in)	Design Pressure (psi)	Design Head (ft)	Critical Pressure (psi)(buckling)	Cost ($)
1	4385.711	360.7274	0.196609	60	370.727446	0.07	82.46	190	2.223446	100300
2	4583.648	364.7483	0.202114	61	374.74828	0.07	84.63	195	2.298378	101345
3	4788.252	368.8377	0.207731	62	378.837712	0.07	86.8	200	2.376289	102390
4	4999.649	372.9925	0.213459	63	382.992508	0.07	88.97	205	2.457224	103435
5	5217.964	377.2096	0.219299	64	387.209636	0.07	91.14	210	2.541224	104480
6	5443.321	381.4863	0.22525	65	391.486251	0.07	93.31	215	2.628336	105525
7	5675.846	385.8197	0.231314	66	395.819679	0.07	95.48	220	2.718606	116570
8	5915.663	390.2074	0.237489	67	400.207408	0.07	97.65	225	2.812081	127615
9	6162.899	394.6471	0.243776	68	404.647072	0.07	99.82	230	2.908812	138660
10	6417.678	399.1364	0.250175	69	409.136443	0.07	101.99	235	3.008848	149705
11	6680.125	403.6734	0.256686	70	413.673419	0.07	104.16	240	3.112239	160750
12	6950.365	408.256	0.263308	71	418.256019	0.07	106.33	245	3.219039	171795
13	7228.525	412.8824	0.270043	72	422.882369	0.07	108.5	250	3.3293	182840
14	7514.728	417.5507	0.276889	73	427.5507	0.07	110.67	255	3.443076	183885
15	7809.101	422.2593	0.283847	74	432.259338	0.07	112.84	260	3.56042	184930
16	8111.769	427.0067	0.290917	75	437.006697	0.07	115.01	265	3.681387	185975
17	8422.856	431.7913	0.298099	76	441.791277	0.07	117.18	270	3.806034	187020
18	8742.489	436.6117	0.305393	77	446.611654	0.07	119.35	275	3.934415	188065
19	9070.793	441.4665	0.312799	78	451.466477	0.07	121.52	280	4.066588	189110
20	9407.894	446.3545	0.320317	79	456.354465	0.07	123.69	285	4.202609	190155

Plate Heat Exchanger:

Vendor #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Process Heat Transferred (Btu/hr)	683698423.4	683698423.4	683698423.4	683698423.4	683698423.4	683698423	683698423.4	683698423.4	683698423	683698423	683698423.4	683698423.4	6.84E+08	6.84E+08	683698423.4	683698423	6.84E+08	6.84E+08	6.84E+08	6.84E+08
Coolant Heat Transferred (Btu/hr)	87017715.12	87742862.75	88468010.37	89193158	89918305.62	90643453.3	91368600.88	92093748.5	92818896.1	93544043.8	94269191.38	94994339.01	95719487	96444634	97169781.88	97894930	98620077	99345225	1E+08	1.01E+08
Process Inlet Temp (F)	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
Process Outlet Temp (F)	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
Coolant Inlet Temperature (F)	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41
Coolant Outlet Temp (F)	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
Temperature Difference (F)	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
Port Diameter (in)	16	16	16	16	16	16	16	16	16	18	16	18	18	18	18	18	18	18	18	18
Cool Vol. Flowrate (gpm)	6000	6050	6100	6150	6200	6250	6300	6350	6400	6450	6500	6550	6600	6650	6700	6750	6800	6850	6900	6950
Process Vol. Flowrate (gpm)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Total Pressure Drop (feet)	160.8596956	148.8677789	150.3112778	151.7576003	153.2067336	154.658665	156.1133816	145.0287583	146.372778	147.719327	149.0683959	150.4199722	151.774	141.4869	142.7426023	144.00058	145.2608	146.5233	147.7881	138.2064
Cool Mass Flowrate (lb/hr)	3003614.481	3028644.601	3053674.722	3078704.843	3103734.963	3128765.08	3153795.205	3178825.325	3203855.45	3228885.57	3253915.687	3278945.808	3303976	3329006	3354036.17	3379066.3	3404096	3429127	3454157	3479187
Process Mass Flowrate (lb/hr)	1128210.122	1128210.122	1128210.122	1128210.122	1128210.122	1128210.12	1128210.122	1128210.122	1128210.12	1128210.12	1128210.122	1128210.122	1128210	1128210	1128210.122	1128210.1	1128210	1128210	1128210	1128210
Thermal Conductivity (BTU/hr ft F)	111.0098147	111.0098147	111.0098147	111.0098147	111.0098147	111.009815	111.0098147	111.0098147	111.009815	111.009815	111.0098147	111.0098147	111.0098	111.0098	111.0098147	111.00981	111.0098	111.0098	111.0098	111.0098
Heating Area (ft2)	43065.36096	43424.23897	43783.11698	44141.99499	44500.87299	44859.751	45218.62901	45577.50702	45936.385	46295.263	46654.14104	47013.01905	47371.9	47730.78	48089.65307	48448.531	48807.41	49166.29	49525.17	49884.04
Effective Plate Area (ft2)	4306.536096	4342.423897	4378.311698	4414.199499	4450.087299	4485.9751	4521.862901	4557.750702	4593.6385	4629.5263	4665.414104	4701.301905	4737.19	4773.078	4808.965307	4844.8531	4880.741	4916.629	4952.517	4988.404
Effective Plate Length (ft)	75.62420359	75.89707047	76.16881212	76.43944234	76.70897465	76.9774223	77.24479832	77.51111539	77.776386	78.0406224	78.30383667	78.56604046	78.82725	79.08746	79.34670365	79.604979	79.8623	80.11868	80.37412	80.62864
Effective Plate Width (ft)	56.94653156	57.21464438	57.48168543	57.74766748	58.01260308	58.2765045	58.53938387	58.80125294	59.0621233	59.3220064	59.5809133	59.83885502	60.09584	60.35189	60.60699545	60.861182	61.11445	61.36682	61.6183	61.86889
Number of Plates	20	21	21	21	21	21	21	22	22	22	22	22	22	23	23	23	23	23	23	24
Number of channels per pass	10	10	10	10	10	10	10	11	11	11	11	11	11	11	11	11	11	11	11	12
Fluid Area per fluid (ft2)	5.32336177	5.629921007	5.656197846	5.68237048	5.708440143	5.73440805	5.760275373	6.075345454	6.10229858	6.1291497	6.155899963	6.182550501	6.209102	6.532488	6.560101188	6.5876143	6.615029	6.642345	6.669565	7.001084
Chan cross Sectional Area (ft2)	0.560353871	0.562992101	0.565619785	0.568237048	0.570844014	0.5734408	0.576027537	0.578604329	0.58117129	0.58372854	0.586276187	0.588814333	0.591343	0.593863	0.596372835	0.598874	0.601366	0.60385	0.606324	0.60879
Cooling Fluid Mass Velocity (lbs/ft2/hr)	564232.6429	537955.0792	539881.172	541799.387	543709.8201	545612.565	547507.7146	523233.6745	525024.366	526808.077	528584.8872	530354.8766	532118.1	509607.7	511278.1151	512942.34	514600.4	516252.4	517898.4	496949.7
Cooling Reynolds Number	12476.51507	11895.45613	11938.04659	11980.46285	12022.70703	12064.7812	12106.68744	11569.93114	11609.5276	11648.9696	11688.25908	11727.39772	11766.39	11268.63	11305.56551	11342.365	11379.03	11415.56	11451.95	10988.73
Cooling Nu Number	260.4481022	252.4981904	253.0854513	253.6695819	254.2506238	254.828618	255.4036032	247.9850835	248.536404	249.084922	249.6306711	250.1736877	250.714	243.768	244.2871058	244.80367	245.3177	245.8293	246.3385	239.8151
Cooling Heat Transfer Coefficient (Btu/hr-ft2-F)	1614.621702	4299.712087	4309.712367	4319.659343	4329.553722	4339.3962	4349.187445	4222.859811	4232.24808	4241.58861	4250.882005	4260.128862	4269.33	4151.049	4159.888116	4168.6845	4177.438	4186.15	4194.821	4083.735
Process Fluid Mass Velocity (lbs/ft2/hr)	211935.6472	200395.3733	199464.4022	198545.682	197638.9511	196743.956	195860.4492	185703.0404	184882.812	184072.861	183272.9786	182482.961	181702.6	172707.6	171980.5975	171262.32	170552.6	169851.2	169158	161147.9
Process Reynolds Number	9522.587985	9004.06609	8962.236155	8920.95667	8880.215884	8840.00239	8800.305115	8343.917432	8307.06334	8270.67103	8234.731094	8199.234414	8164.172	7760.011	7727.347396	7695.0742	7663.184	7631.669	7600.523	7240.619
Process Nu Number	179.5341257	173.1176719	172.5944849	172.0773441	171.5661301	171.060727	170.5610218	164.7580956	164.284713	163.81654	163.3534793	162.8954343	162.4423	157.169	156.7386309	156.31282	155.8914	155.4744	155.0617	150.2486
Process Heat Transfer Coefficient (Btu/hr-ft2-F)	108.1009909	104.2375192	103.9224981	103.6111176	103.3033057	102.998993	102.6981105	99.20405564	98.9190229	98.637127	98.35830882	98.08251099	97.80968	94.63449	94.37537989	94.118989	93.86527	93.61418	93.36566	90.46761
Overall Heat Transfer Coefficient(Btu /hr-ft2-F)	86.40428168	86.73327945	86.51910452	86.30715371	86.09738645	85.8897632	85.6842455	83.19058664	82.9936718	82.7987123	82.60567405	82.41452381	82.22523	79.92694	79.74528513	79.565359	79.38713	79.21058	79.03566	76.91063
Overal Heat Transferred (MBtu/hr)	87.42678103	88.49100272	89.00201205	89.51171625	90.02012916	90.5272644	91.03313521	89.08526702	89.5741977	90.0619345	90.54848949	91.03387458	91.5181	89.63401	90.10269724	90.570293	91.0368	91.50224	91.96661	90.1424
Cost ($)	602915.0535	607939.3456	612963.6377	617987.9298	623012.2219	628036.514	633060.8061	638085.0982	643109.39	648133.682	653157.9746	658182.2667	663206.6	668230.9	673255.143	678279.44	683303.7	688328	693352.3	698376.6
Efficiency(Heat Trans Coef/Optimal)	0.864042817	0.867332794	0.865191045	0.863071537	0.860973864	0.85889763	0.856842455	0.831905866	0.82993672	0.82798712	0.82605674	0.824145238	0.822252	0.799269	0.797452851	0.7956536	0.793871	0.792106	0.790357	0.769106
Pressure Drop (psi)	69.81310787	64.60861603	65.23509456	65.86279853	66.49172236	67.1218605	67.75320763	62.94248109	63.5257856	64.1101881	64.6956838	65.28226795	65.86994	61.40532	61.95028938	62.496251	63.0432	63.59112	64.14003	59.98156

Centrifugal Pump:

Vendor #	DesignVolumetric Flowrate (gpm)	Power Req (HP)	Rated Efficiency	Design Differential Head (ft)	Design Differential Pressure (psi)	Net Positive Suction Head Required (ft)	Nominal Diameter (in)
1	6500	1971.667	0.6	720	318.7296	200	16
2	6600	1930.891	0.61	706	312.5321	214	16
3	6700	1923.068	0.62	704	311.6467	216	16
4	6800	1915.333	0.63	702	310.7614	218	16
5	6900	1907.682	0.64	700	309.876	220	16
6	7000	1900.111	0.65	698	308.9906	222	16
7	7100	1892.616	0.66	696	308.1053	224	16
8	7200	1885.194	0.67	694	307.2199	226	16
9	7300	1877.842	0.68	692	306.3346	228	16
10	7400	1870.556	0.69	690	305.4492	230	16
11	7500	1863.333	0.7	688	304.5638	232	18
12	7600	1856.172	0.71	686	303.6785	234	18
13	7700	1849.069	0.72	684	302.7931	236	18
14	7800	1842.023	0.73	682	301.9078	238	18
15	7900	1835.03	0.74	680	301.0224	240	18
16	8000	1828.089	0.75	678	300.137	242	18
17	8100	1821.197	0.76	676	299.2517	244	18
18	8200	1814.354	0.77	674	298.3663	246	18
19	8300	1807.556	0.78	672	297.481	248	18
20	8400	1800.802	0.79	670	296.5956	250	18

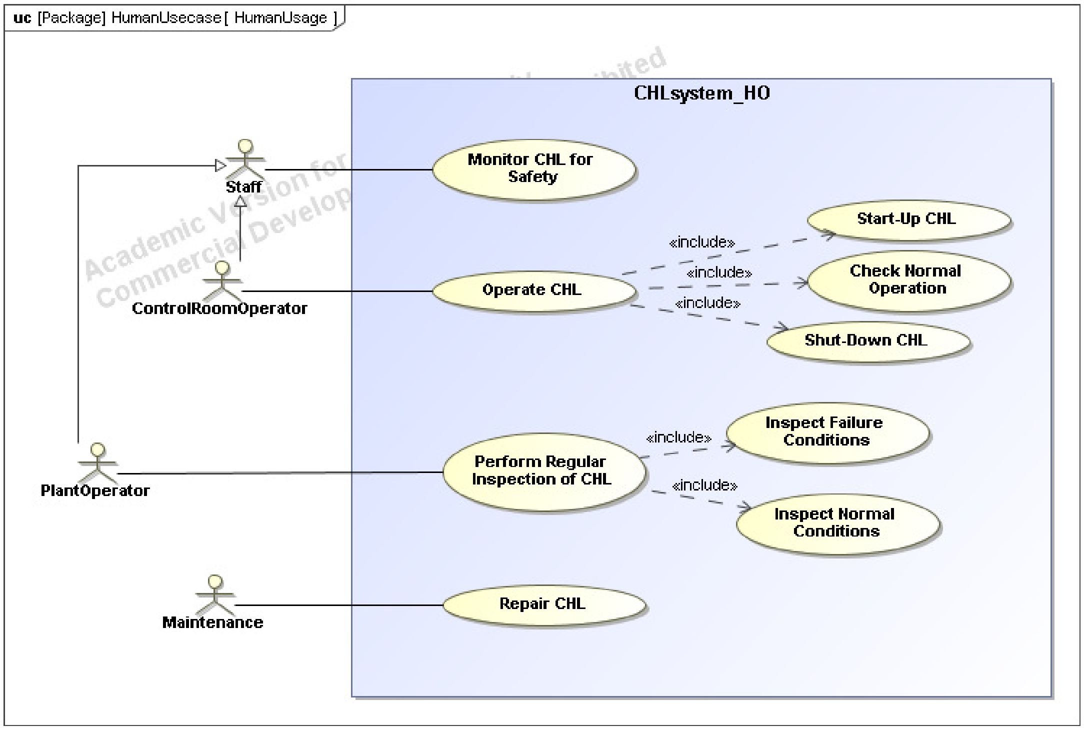
CHL System:

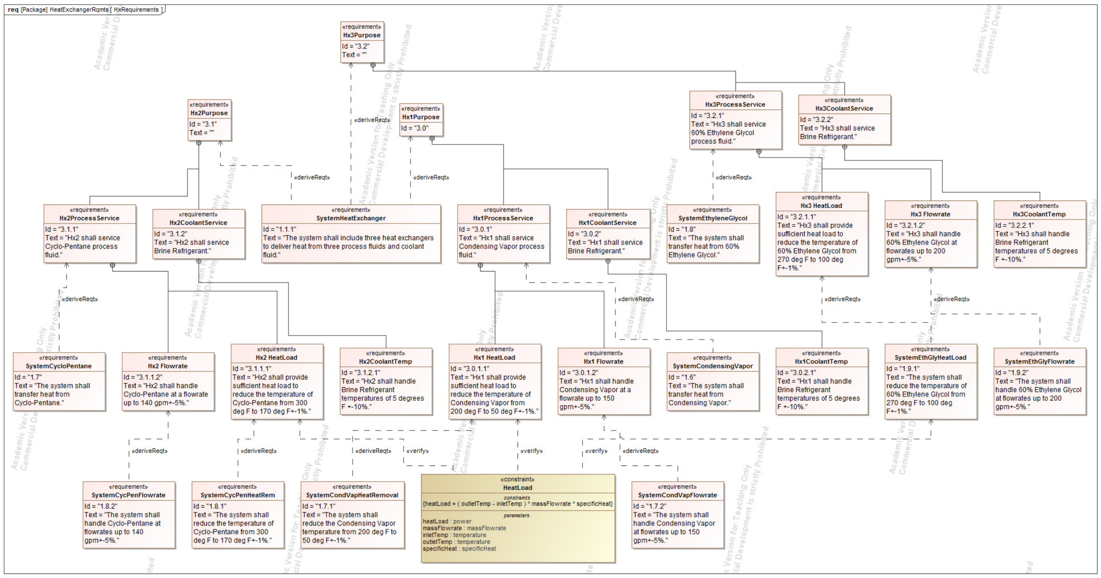
	Values
Design Cool Flowrate (gpm)	6500
Max Total Cool Flowrate (gpm)	8500
Min Total Cool Flowrate (gpm)	5000
Design Process Flowrate (gpm)	3000
Max Total Process Flowrate (gpm)	3500
Min Total Process Flowrate (gpm)	2700
Minimum Coolant Temp (F)	45
Maximum Coolant Temp (F)	75
Design Cool Supply Temp (F)	50
Design Cool Return Temp (F)	70

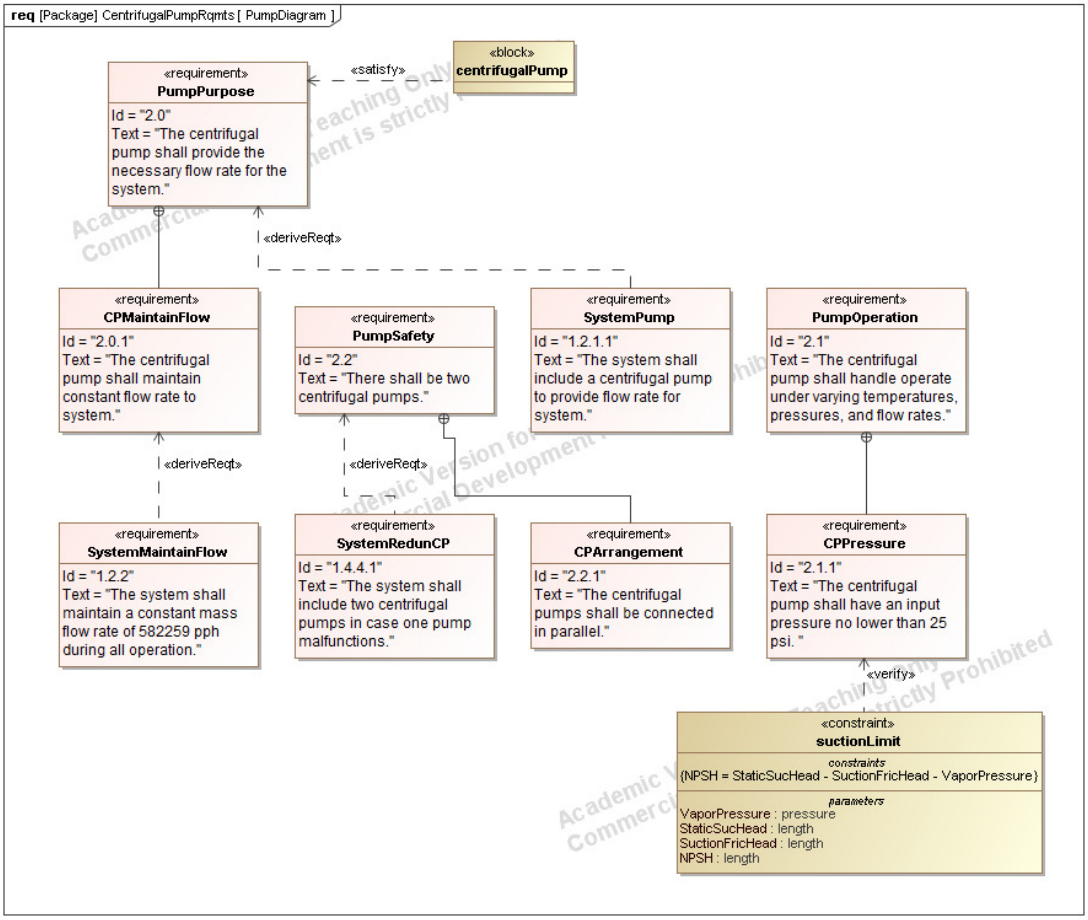
Design Process Supply Temp (F)	90
Design Process Return Temp (F)	65
Maximum Power (HP)	2000
Net Positive Suction Head Available (ft)	150
Total Water Volume (gallons)	16000
Min. Connection Diameter (in)	16
Max Differential Head (ft)	700
Max Differential Pressure (psi)	309.876
Design Differential Head (ft)	650

Design Differential Pressure (psi)	287.742
Req. Piping Length (ft)	200
Pipe Material Type	3
Hx Req Efficiency	0.74
Static Head (ft)	200
Cool Vol. Flow rate Margin (gpm)	1000
Pump Efficiency	0.6
Pressure Margin (ft)	0

Appendices C: SysML Diagrams







«requirement»
PumpPurpose
Id = "2.0"
Text = "The centrifugal pump shall provide the necessary flow rate for the system."

«requirement»
CPMaintainFlow
Id = "2.0.1"
Text = "The centrifugal pump shall maintain constant flow rate to system."

«requirement»
PumpSafety
Id = "2.2"
Text = "There shall be two centrifugal pumps."

«requirement»
SystemPump
Id = "1.2.1.1"
Text = "The system shall include a centrifugal pump to provide flow rate for system."

«requirement»
PumpOperation
Id = "2.1"
Text = "The centrifugal pump shall handle operate under varying temperatures, pressures, and flow rates."

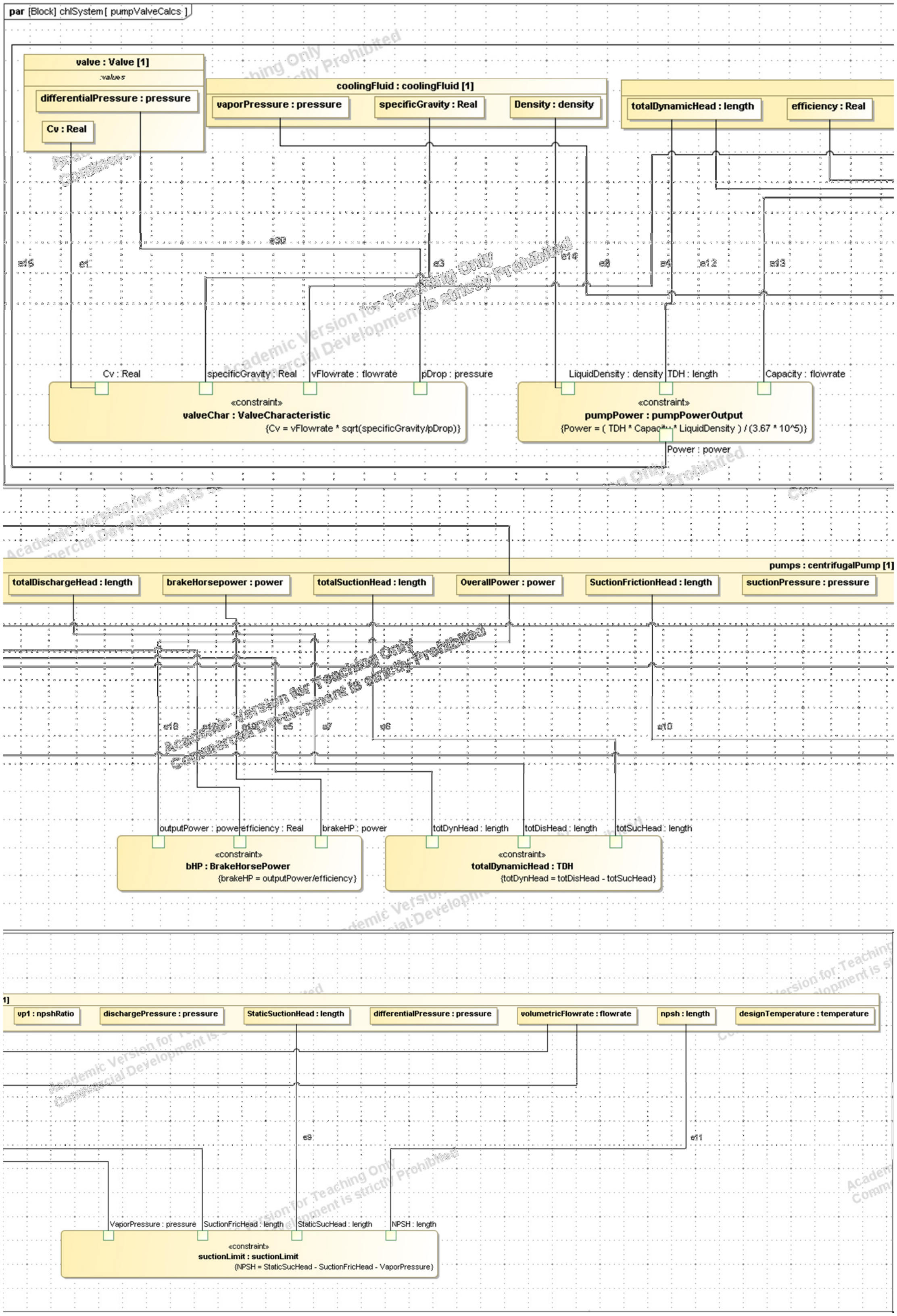
«requirement»
SystemMaintainFlow
Id = "1.2.2"
Text = "The system shall maintain a constant mass flow rate of 582259 pph during all operation."

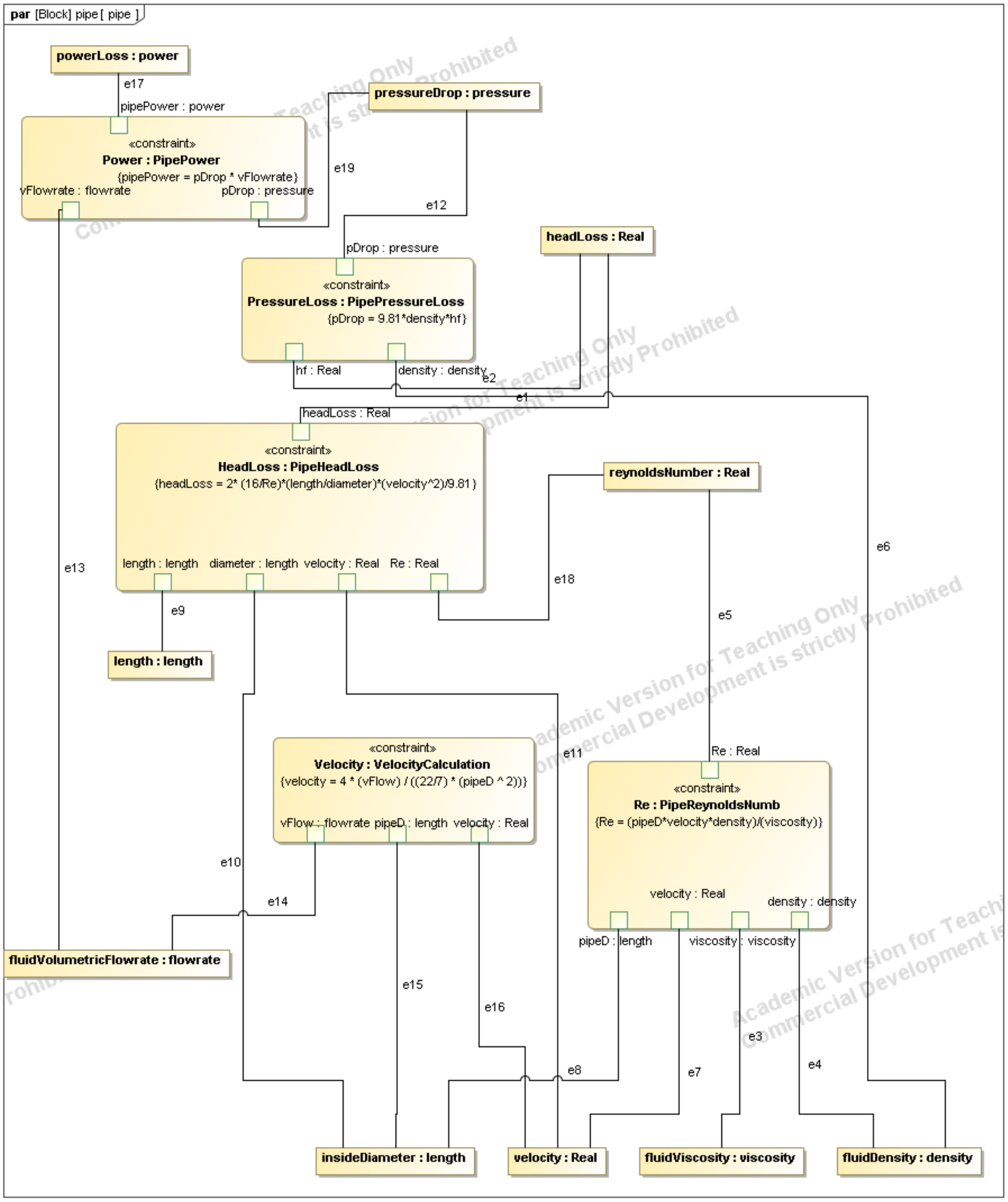
«requirement»
SystemRedunCP
Id = "1.4.4.1"
Text = "The system shall include two centrifugal pumps in case one pump malfunctions."

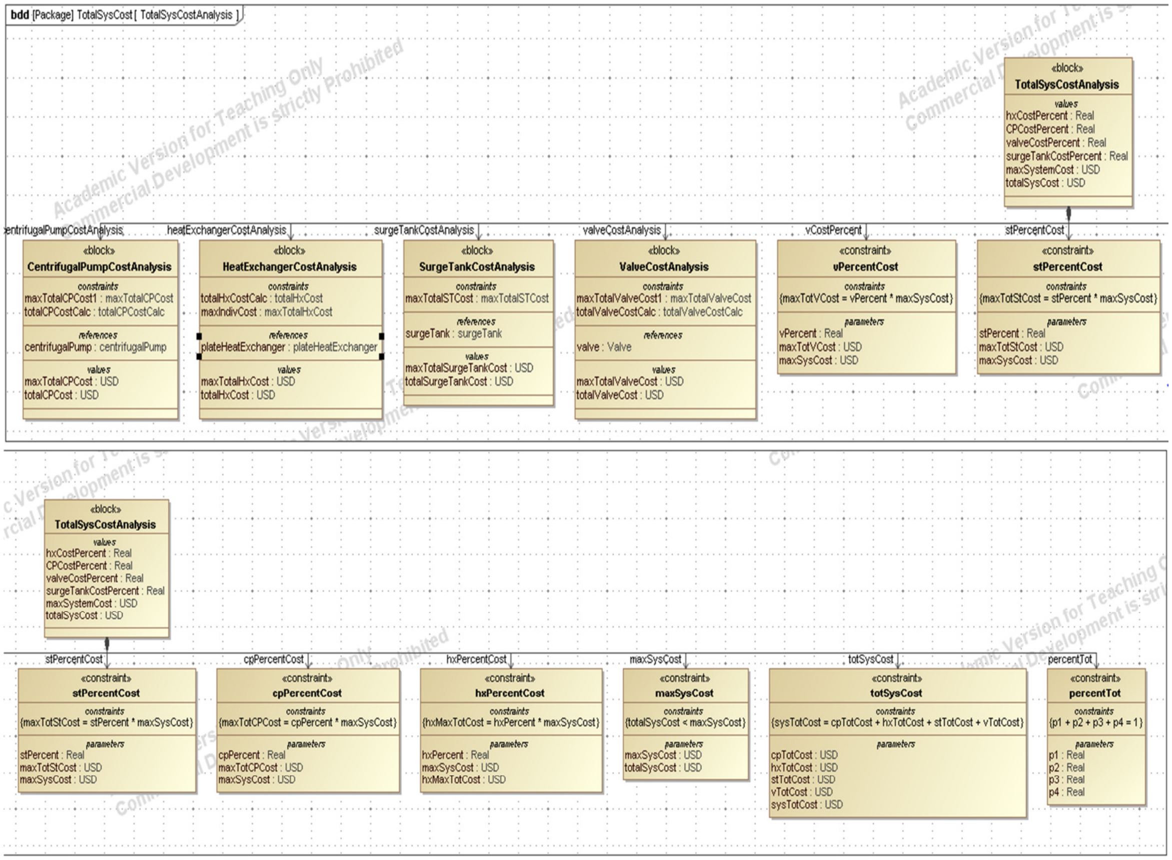
«requirement»
CPArrangement
Id = "2.2.1"
Text = "The centrifugal pumps shall be connected in parallel."

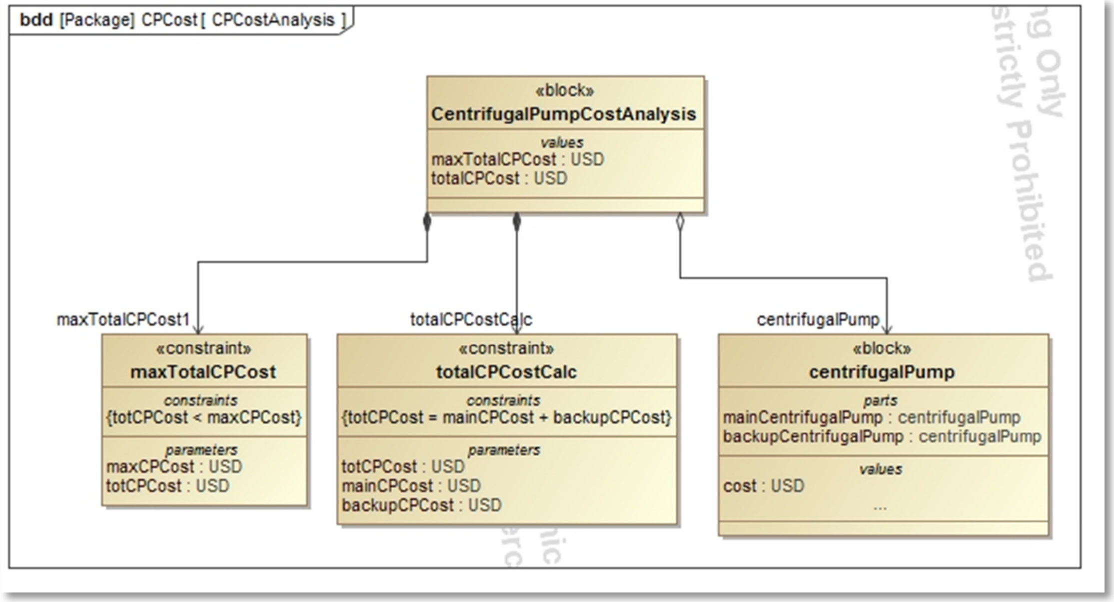
«requirement»
CPPressure
Id = "2.1.1"
Text = "The centrifugal pump shall have an input pressure no lower than 25 psi. "

«constraint»
suctionLimit
constraints
{NPSH = StaticSucHead - SuctionFricHead - VaporPressure}
parameters
VaporPressure : pressure
StaticSucHead : length
SuctionFricHead : length
NPSH : length


par [Block] chlSystem [pumpValveCalcs]
valve : Valve [1]
values
differentialPressure : pressure
Cv : Real
coolingFluid : coolingFluid [1]
vaporPressure : pressure
specificGravity : Real
Density : density
totalDynamicHead : length
efficiency : Real
e15
e1
e30
e3
e14
e8
e4
e12
e13
Cv : Real
specificGravity : Real
vFlowrate : flowrate
pDrop : pressure
«constraint»
valveChar : ValveCharacteristic
{Cv = vFlowrate * sqrt(specificGravity/pDrop)}
LiquidDensity : density
TDH : length
Capacity : flowrate
«constraint»
pumpPower : pumpPowerOutput
{Power = (TDH * Capacity * LiquidDensity) / (3.67 * 10^5)}
Power : power
pumps : centrifugalPump [1]
totalDischargeHead : length
brakeHorsepower : power
totalSuctionHead : length
OverallPower : power
SuctionFrictionHead : length
suctionPressure : pressure
e18
e5
e7
e6
e10
outputPower : power
efficiency : Real
brakeHP : power
totDynHead : length
totDisHead : length
totSucHead : length
«constraint»
bHP : BrakeHorsePower
{brakeHP = outputPower/efficiency}
«constraint»
totalDynamicHead : TDH
{totDynHead = totDisHead - totSucHead}
vp1 : npshRatio
dischargePressure : pressure
StaticSuctionHead : length
differentialPressure : pressure
volumetricFlowrate : flowrate
npsh : length
designTemperature : temperature
e9
e11
VaporPressure : pressure
SuctionFricHead : length
StaticSucHead : length
NPSH : length
«constraint»
suctionLimit : suctionLimit
{NPSH = StaticSucHead - SuctionFricHead - VaporPressure}


par [Block] pipe [pipe]
powerLoss : power
e17
pipePower : power
pressureDrop : pressure
«constraint»
Power : PipePower
{pipePower = pDrop * vFlowrate}
vFlowrate : flowrate
pDrop : pressure
e19
e12
headLoss : Real
pDrop : pressure
«constraint»
PressureLoss : PipePressureLoss
{pDrop = 9.81*density*hf}
hf : Real
density : density
e2
e1
headLoss : Real
«constraint»
HeadLoss : PipeHeadLoss
{headLoss = 2* (16/Re)*(length/diameter)*(velocity^2)/9.81}
length : length
diameter : length
velocity : Real
Re : Real
reynoldsNumber : Real
e6
e13
e18
e9
e5
length : length
«constraint»
Velocity : VelocityCalculation
{velocity = 4 * (vFlow) / ((22/7) * (pipeD ^ 2))}
vFlow : flowrate
pipeD : length
velocity : Real
e11
Re : Real
«constraint»
Re : PipeReynoldsNumb
{Re = (pipeD*velocity*density)/(viscosity)}
velocity : Real
density : density
e10
e14
pipeD : length
viscosity : viscosity
fluidVolumetricFlowrate : flowrate
e15
e16
e3
e8
e7
e4
insideDiameter : length
velocity : Real
fluidViscosity : viscosity
fluidDensity : density


bdd [Package] TotalSysCost [TotalSysCostAnalysis]
«block»
TotalSysCostAnalysis
values
hxCostPercent : Real
CPCostPercent : Real
valveCostPercent : Real
surgeTankCostPercent : Real
maxSystemCost : USD
totalSysCost : USD
centrifugalPumpCostAnalysis
heatExchangerCostAnalysis
surgeTankCostAnalysis
valveCostAnalysis
vCostPercent
stPercentCost
«block»
CentrifugalPumpCostAnalysis
constraints
maxTotalCPCost1 : maxTotalCPCost
totalCPCostCalc : totalCPCostCalc
references
centrifugalPump : centrifugalPump
values
maxTotalCPCost : USD
totalCPCost : USD
«block»
HeatExchangerCostAnalysis
constraints
totalHxCostCalc : totalHxCost
maxIndivCost : maxTotalHxCost
references
plateHeatExchanger : plateHeatExchanger
values
maxTotalHxCost : USD
totalHxCost : USD
«block»
SurgeTankCostAnalysis
constraints
maxTotalSTCost : maxTotalSTCost
references
surgeTank : surgeTank
values
maxTotalSurgeTankCost : USD
totalSurgeTankCost : USD
«block»
ValveCostAnalysis
constraints
maxTotalValveCost1 : maxTotalValveCost
totalValveCostCalc : totalValveCostCalc
references
valve : Valve
values
maxTotalValveCost : USD
totalValveCost : USD
«constraint»
vPercentCost
constraints
{maxTotVCost = vPercent * maxSysCost}
parameters
vPercent : Real
maxTotVCost : USD
maxSysCost : USD
«constraint»
stPercentCost
constraints
{maxTotStCost = stPercent * maxSysCost}
parameters
stPercent : Real
maxTotStCost : USD
maxSysCost : USD
«block»
TotalSysCostAnalysis
values
hxCostPercent : Real
CPCostPercent : Real
valveCostPercent : Real
surgeTankCostPercent : Real
maxSystemCost : USD
totalSysCost : USD
stPercentCost
cpPercentCost
hxPercentCost
maxSysCost
totSysCost
percentTot
«constraint»
stPercentCost
constraints
{maxTotStCost = stPercent * maxSysCost}
parameters
stPercent : Real
maxTotStCost : USD
maxSysCost : USD
«constraint»
cpPercentCost
constraints
{maxTotCPCost = cpPercent * maxSysCost}
parameters
cpPercent : Real
maxTotCPCost : USD
maxSysCost : USD
«constraint»
hxPercentCost
constraints
{hxMaxTotCost = hxPercent * maxSysCost}
parameters
hxPercent : Real
maxSysCost : USD
hxMaxTotCost : USD
«constraint»
maxSysCost
constraints
{totalSysCost < maxSysCost}
parameters
maxSysCost : USD
totalSysCost : USD
«constraint»
totSysCost
constraints
{sysTotCost = cpTotCost + hxTotCost + stTotCost + vTotCost}
parameters
cpTotCost : USD
hxTotCost : USD
stTotCost : USD
vTotCost : USD
sysTotCost : USD
«constraint»
percentTot
constraints
{p1 + p2 + p3 + p4 = 1}
parameters
p1 : Real
p2 : Real
p3 : Real
p4 : Real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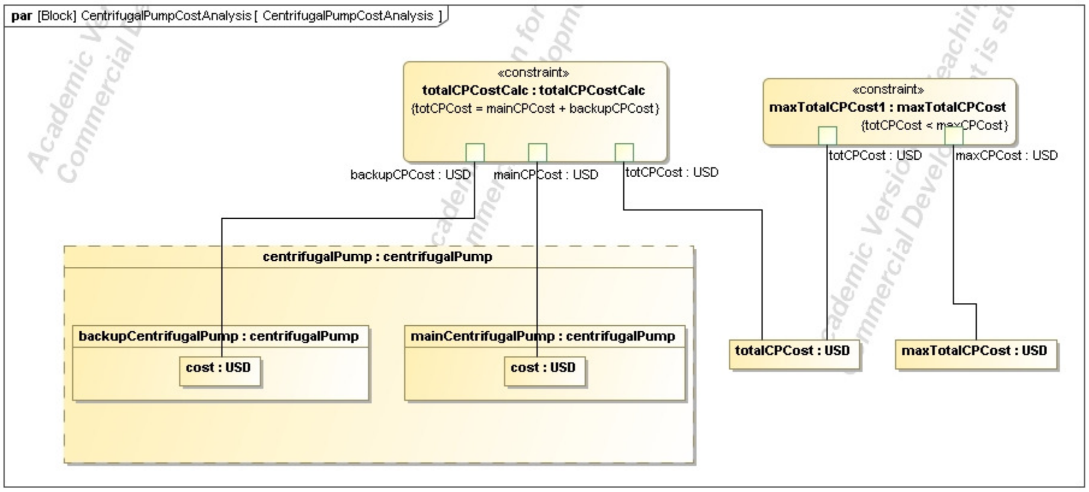
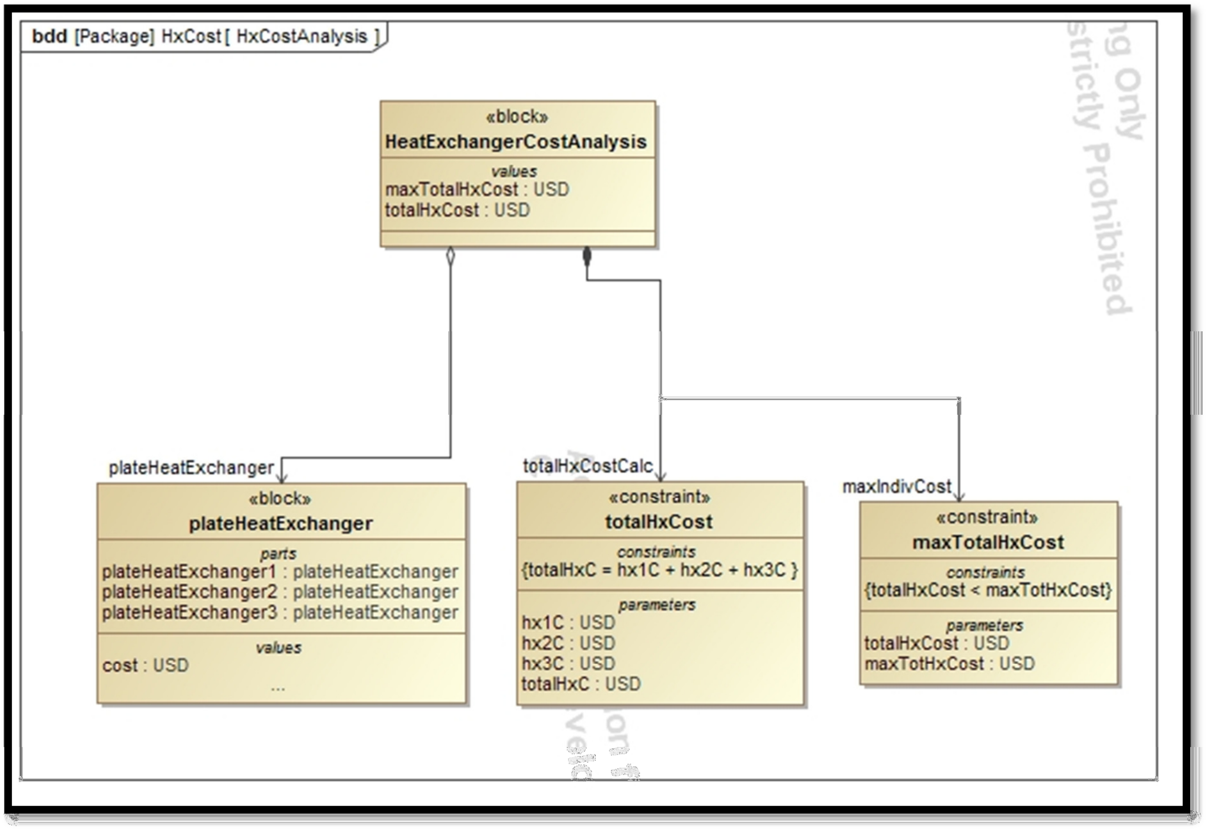
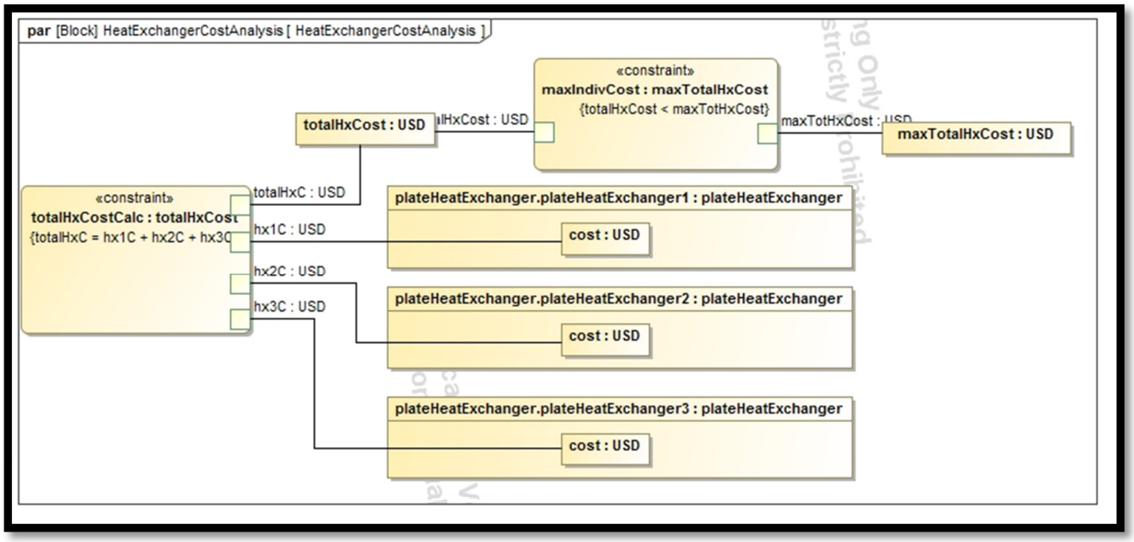
CentrifugalPumpCostAnalysis
values
maxTotalCPCost : USD
totalCPCost : USD
maxTotalCPCost1
totalCPCostCalc
centrifugalPump
«constraint»
maxTotalCPCost
constraints
{totCPCost < maxCPCost}
parameters
maxCPCost : USD
totCPCost : USD
«constraint»
totalCPCostCalc
constraints
{totCPCost = mainCPCost + backupCPCost}
parameters
totCPCost : USD
mainCPCost : USD
backupCPCost : USD
«block»
centrifugalPump
parts
mainCentrifugalPump : centrifugalPump
backupCentrifugalPump : centrifugalPump
values
cost : USD
...


par [Block] CentrifugalPumpCostAnalysis [CentrifugalPumpCostAnalysis]
«constraint»
totalCPCostCalc : totalCPCostCalc
{totCPCost = mainCPCost + backupCPCost}
«constraint»
maxTotalCPCost1 : maxTotalCPCost
{totCPCost < maxCPCost}
backupCPCost : USD
mainCPCost : USD
totCPCost : USD
totCPCost : USD
maxCPCost : USD
centrifugalPump : centrifugalPump
backupCentrifugalPump : centrifugalPump
cost : USD
mainCentrifugalPump : centrifugalPump
cost : USD
totalCPCost : USD
maxTotalCPCost : USD


bdd [Package] HxCost [HxCostAnalysis]
«block»
HeatExchangerCostAnalysis
values
maxTotalHxCost : USD
totalHxCost : USD
plateHeatExchanger
«block»
plateHeatExchanger
parts
plateHeatExchanger1 : plateHeatExchanger
plateHeatExchanger2 : plateHeatExchanger
plateHeatExchanger3 : plateHeatExchanger
values
cost : USD
...
totalHxCostCalc
«constraint»
totalHxCost
constraints
{totalHxC = hx1C + hx2C + hx3C }
parameters
hx1C : USD
hx2C : USD
hx3C : USD
totalHxC : USD
maxIndivCost
«constraint»
maxTotalHxCost
constraints
{totalHxCost < maxTotHxCost}
parameters
totalHxCost : USD
maxTotHxCost : USD


par [Block] HeatExchangerCostAnalysis [HeatExchangerCostAnalysis]
«constraint»
maxIndivCost : maxTotalHxCost
{totalHxCost < maxTotHxCost}
totalHxCost : USD
maxTotHxCost : USD
maxTotalHxCost : USD
totalHxCost : USD
«constraint»
totalHxCostCalc : totalHxCost
{totalHxC = hx1C + hx2C + hx3C
totalHxC : USD
hx1C : USD
hx2C : USD
hx3C : USD
plateHeatExchanger.plateHeatExchanger1 : plateHeatExchanger
cost : USD
plateHeatExchanger.plateHeatExchanger2 : plateHeatExchanger
cost : USD
plateHeatExchanger.plateHeatExchanger3 : plateHeatExchanger
cost : USD

Appendices D: Tabular Requirements

#	Id	Name	Text
1	1	SystemPurpose	The system shall transfer heat from three process fluids to a cooling fluid.
2	1.1	SystemHeatTransEquip	The system shall require three equipment to transfer heat from the three process fluids.
3	1.1.1	SystemHeatExchanger	The system shall include three heat exchangers to deliver heat from three process fluids and coolant fluid.
4	1.2	SystemFlowRate	The system shall provide the necessary flowrate for the heat exchangers to cool the process fluid.
5	1.2.1	SystemFlowEquipment	The system shall include an equipment that maintains the pressure and flowrate of the cooling fluid.
6	1.3	SystemCoolingFluid	The system shall circulate cooling fluid.
7	1.3.1	SystemCoolingFluidType	The system shall use Brine Refrigerant as a cooling fluid.
8	1.3.2	SystemCoolingFluidHeatRem	The system shall remove heat feedback cooling fluid.
9	1.3.2.1	SystemRefrigerantSystem	The system shall include a heat exchanger to reduce the temperature of feedback cooling fluid from 35 degrees F to 5 degrees F +-10%.
10	1.3.3	SystemCoolingWaterVolume	The system shall handle 2,000 m3 of cooling water (70,629.33 ft3).
11	1.4	SystemSafety	The system shall be safe from temperature, pressure, and flow abnormalities.

12	1.4.1	SystemPressureProblems	The system shall be able to withstand pressure deviations in the system.
13	1.4.2	SystemTemperatureProblems	The system shall be able to handle fluctuations in the cooling fluid temperature.
14	1.4.3	SystemFlowrateProblems	The system shall be able to handle flowrate fluctuations in the system.
15	1.5	SystemPower	The system shall use offsite and onsite power.
16	1.5.1	SystemPowerType	The system shall use Class 1E power supplies for onsite and offsite power.
17	1.5.2	SystemPowerUsage	The system shall use a maximum of 10,000 Watts.
18	1.6	SystemCondensingVapor	The system shall transfer heat from Condensing Vapor.
19	1.7.1	SystemCondVapHeatRemoval	The system shall reduce the Condensing Vapor temperature from 200 deg F to 50 deg F+-1%.
20	1.7.2	SystemCondVapFlowrate	The system shall handle Condensing Vapor at flowrates up to 150 gpm+-5%.
21	1.7	SystemCycloPentane	The system shall transfer heat from Cyclo-Pentane.
22	1.8.1	SystemCycPenHeatRem	The system shall reduce the temperature of Cyclo-Pentane from 300 deg F to 170 deg F+-1%.
23	1.8.2	SystemCycPenFlowrate	The system shall handle Cyclo-Pentane at flowrates up to 140 gpm+-5%.

24	1.8	SystemEthyleneGlycol	The system shall transfer heat from 60% Ethylene Glycol.
25	1.9.1	SystemEthGlyHeatLoad	The system shall reduce the temperature of 60% Ethylene Glycol from 270 deg F to 100 deg F+-1%.
26	1.9.2	SystemEthGlyFlowrate	The system shall handle 60% Ethylene Glycol at flowrates up to 200 gpm+-5%.
27	1.9	SystemConnection	The system shall be a closed loop system.
28	1.10	SystemOperation	The system shall operate at normal conditions.

#	Id	Name	Text
1	2.0	PumpPurpose	The centrifugal pump shall provide the necessary flow rate for the system.
2	2.0.1	CPMaintainFlow	The centrifugal pump shall maintain constant flow rate to system.
3	2.1	PumpOperation	The centrifugal pump shall handle operate under varying temperatures, pressures, and flow rates.
4	2.1.1	CPPressure	The centrifugal pump shall have an input pressure no lower than 25 psi.
5	2.2	PumpSafety	There shall be two centrifugal pumps.
6	2.2.1	CPArrangement	The centrifugal pumps shall be connected in parallel.

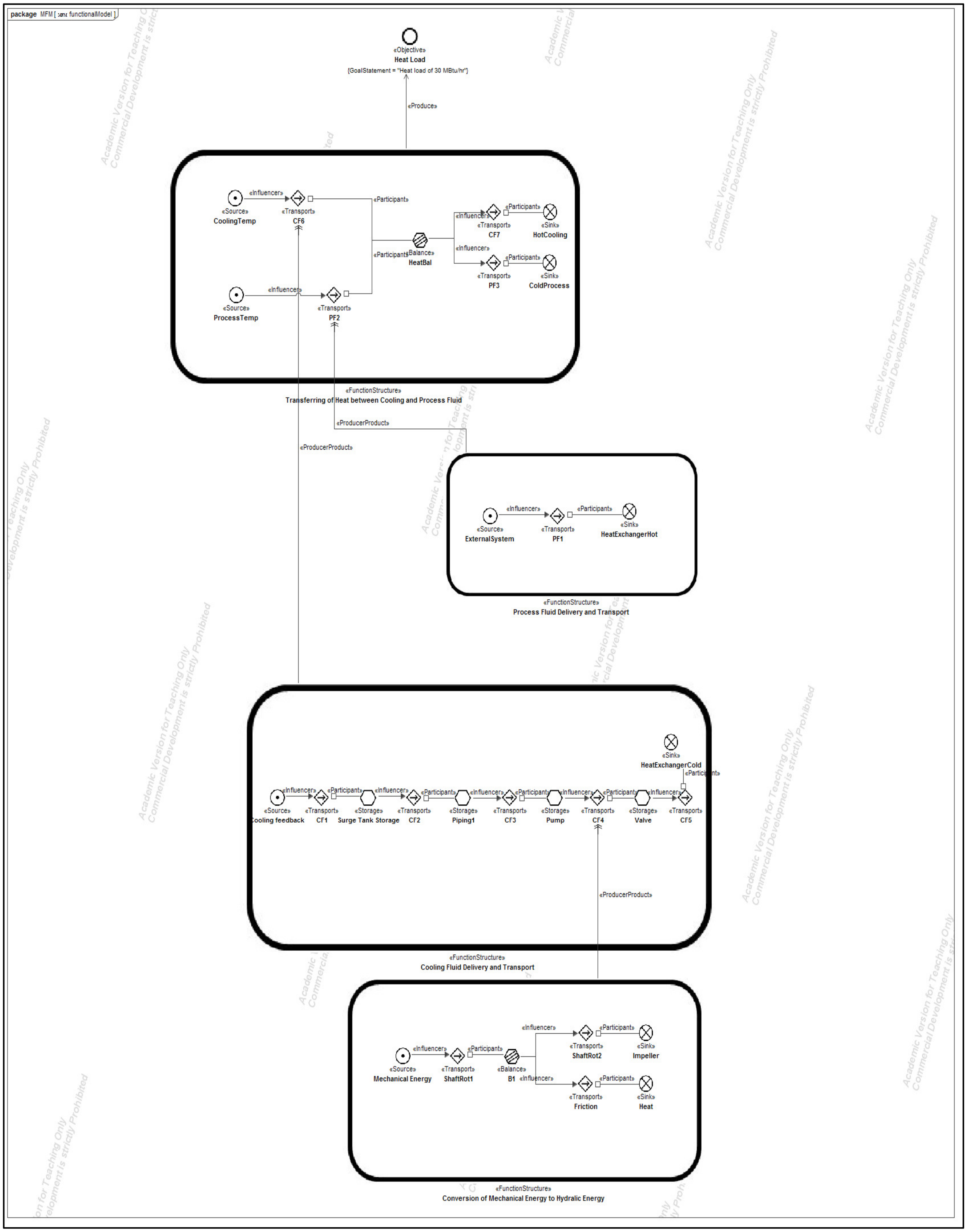
#	Id	Name	Text
1	3.0	Hx1Purpose	
2	3.0.1	Hx1ProcessService	Hx1 shall service Condensing Vapor process fluid.
3	3.0.1.1	Hx1 HeatLoad	Hx1 shall provide sufficient heat load to reduce the temperature of Condensing Vapor from 200 deg F to 50 deg F+-1%.
4	3.0.1.2	Hx1 Flowrate	Hx1 shall handle Condensing Vapor at a flowrate up to 150 gpm+-5%.
5	3.0.2	Hx1CoolantService	Hx1 shall service Brine Refrigerant.
6	3.0.2.1	Hx1CoolantTemp	Hx1 shall handle Brine Refrigerant temperatures of 5 degrees F +-10%.
7	3.1	Hx2Purpose	
8	3.1.1	Hx2ProcessService	Hx2 shall service Cyclo-Pentane process fluid.
9	3.1.1.1	Hx2 HeatLoad	Hx2 shall provide sufficient heat load to reduce the temperature of Cyclo-Pentane from 300 deg F to 170 deg F+-1%.
10	3.1.1.2	Hx2 Flowrate	Hx2 shall handle Cyclo-Pentane at a flowrate up to 140 gpm+-5%.
11	3.1.2	Hx2CoolantService	Hx2 shall service Brine Refrigerant.
12	3.1.2.1	Hx2CoolantTemp	Hx2 shall handle Brine Refrigerant temperatures of 5 degrees F +-10%.

13	3.2	Hx3Purpose	
14	3.2.1	Hx3ProcessService	Hx3 shall service 60% Ethylene Glycol process fluid.
15	3.2.1.1	Hx3 HeatLoad	Hx3 shall provide sufficient heat load to reduce the temperature of 60% Ethylene Glycol from 270 deg F to 100 deg F+-1%.
16	3.2.1.2	Hx3 Flowrate	Hx3 shall handle 60% Ethylene Glycol at flowrates up to 200 gpm+-5%.
17	3.2.2	Hx3CoolantService	Hx3 shall service Brine Refrigerant.
18	3.2.2.1	Hx3CoolantTemp	Hx3 shall handle Brine Refrigerant temperatures of 5 degrees F +-10%.

#	Id	Name	Text
1	5.0	ValvePurpose	The valves shall control the flow rate of cooling fluid to each heat exchanger.
2	5.0.1	ValveFlowrate	The valves shall be able to operate over a range of flow rates.
3	5.0.1.1	ValveMassFlowrate	All valves shall be able to handle a maximum mass flowrates of 582,259 pounds/hour (264,108.24 kg/h)+-5%.
4	5.0.2	ValveDifferentialPressure	The valves shall have a differential pressure no greater than 30 psid (or a differential head no greater than 40 feet) +-5%.

#	Id	Name	Text
1	4.0	SurgeTankPurpose	The surge tanks shall hold and supply cooling fluid to the system.
2	4.0.1	SurgeTankNPSH	The surge tank shall provide the npsh for the centrifugal pumps.
3	4.0.2	SurgeTankMaintainEquilibrium	The surge tanks shall provide cooling fluid storage to compensate for temperature and pressure fluctuations in the system.
4	4.1	SurgeTankCost	The max cost for the surge tank shall be a percentage of the maximum system cost.

Appendices E: CHL MFM Model



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