Shipboard Integrated Engineering Plant Survivable Network Optimization

by

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Abstract

Due to the complexity of naval ship systems, and the iterative nature of classical design, the U.S. Navy has struggled to meet the spirit of Cost-as-an-Independent Variable (CAIV) policy. In particular, distinguishing between best-value concept variants is not well suited to Pareto-style tradeoff analysis unless the variants can be shown to be at or approximately minimum cost. This thesis presents a systematic process for minimum cost, survivable design of an integrated engineering plant (IEP). The mathematical optimization techniques used are suitable for early-stage design. There are three major contributions of this work. First, a straightforward method for "designed-in" survivability of early stage concepts at guaranteed minimum cost is presented, and with flexibility for multiple operating and casualty conditions. Second, interdependence between the electrical and cooling domains is modeled in detail, forming a new computational structure that could be extended to other domains as well. Third, a method for the integral design of minimum cost shipboard stored energy in consideration of casualty and operating conditions is shown. The overall methodology developed in this work can provide program managers assurance that design concepts all represent minimum cost and best value, thus reducing the trade space at an early stage when cost savings can be maximized in the acquisition program.

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"He hath made every thing beautiful in his time..." - Ecclesiastes 3:11

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Acronyms

AES	All Electric Ship
CAIV	Cost as an Independent Variable
CHX	Component Heat Exchanger
CM	Converter Module
DoD	Department of Defense
FC	Fixed Cost
FHX	Freshwater Heat Exchanger
FWL	Freshwater Loop
FWP	Freshwater Pump
IEP	Integrated Engineering Plant
IM	Inverter Module
IPS	Integrated Power System
LCS	Littoral Combat Ship
LP	Linear Programming
MCF	Multicommodity Flow
NCST	Naval Combat Survivability Testbed
NFO	Network Flow Optimization
NSMCF	Non-simultaneous Multicommodity Flow
PD	Propulsion Drive
PDCB	Primary DC Bus
PM	Propulsion Motor
PS	Power Supply
QoS	Quality of Service
SED	Stored Energy Device
SM	Synchronous Machine
SWB	Seawater Branch
SWP	Seawater Pump
VC	Variable Cost
ZDCB	Zonal DC Bus
ZED	Zonal Electrical Distribution

Chapter 1

Introduction

1.1 Background

Ships that go in harm's way need to be designed assuming they will take damage. Survivability and "fight-through" are among the most important mission performance specifications. What we have learned even in the modern era, with the USS STARK incident (1987), and events on USS ROBERTS (1988), USS PRINCETON (1991), and USS COLE (2000), is that there is always room for improvement in the design of survivable and resilient ship systems. However, designing survivability and fight-through capability into warships is a challenging task in the current cost-as-an-independent variable (CAIV) policy era. The method demonstrated in this thesis allows the program office to determine early in the process what is the minimum cost for a specific survivability performance.

The integrated engineering plant (IEP) is the core of the functionality of a naval vessel. It supplies reliable, quality electrical power, allowing the ship to perform its mission and provide essential services for the crew to work and live. Quality, reliability, survivability, and resiliency of the IEP through redundancy and reconfiguration is necessary during surveillance operations, battle, and especially when damage has occurred. The survivability of the IEP can easily be the difference between victory and defeat in battle for a naval vessel and can have similar implications for commercial vessels in the harsh ocean environment. The complexity, number, size and sensitivity of electrical loads continues to increase on today's ships. New architectures are sought to support the loads with quality of service.

Improved methods for integrated engineering plant (IEP) optimization, modeling and testing are needed to determine best survivability value. A shipboard integrated engineering plant (IEP), for the purpose of this thesis, consists of an electrical generation and distribution plant and an associated thermal (cooling) plant. A simplified IEP example is shown in Figure 1-1.

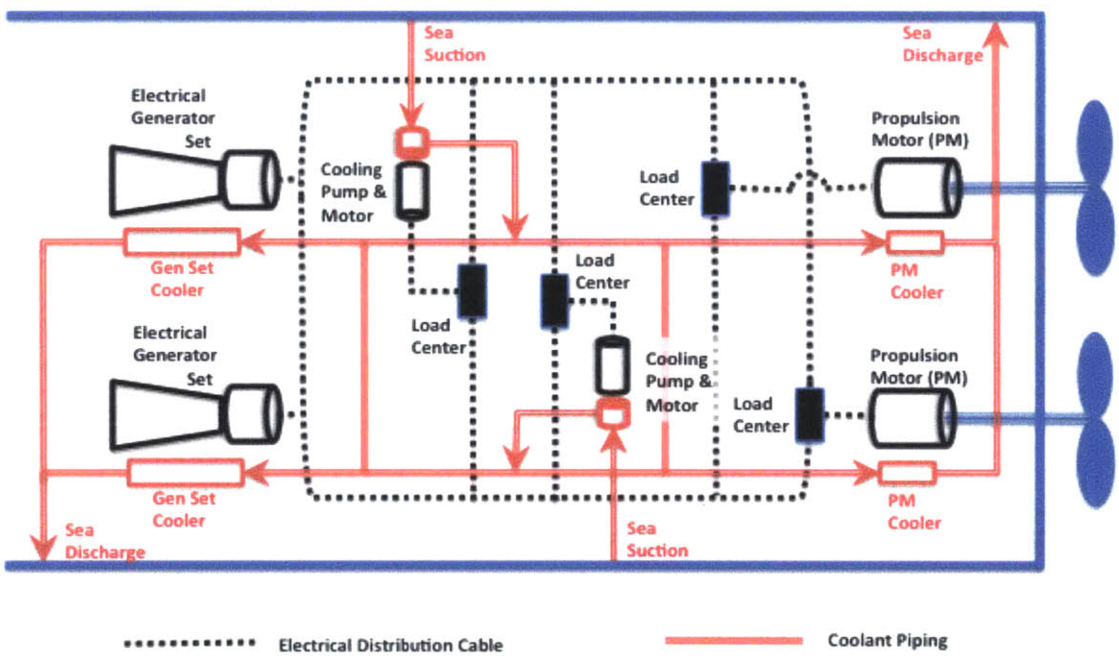


Figure 1-1: Simplified Integrated Engineering Plant

1.1.1 Motivation

For at least the last 30 years, U.S. defense budgets have dramatically dropped, especially in acquisition of new weapon systems. This has happened simultaneously with rising costs of acquiring those systems. In 1996, the Department of Defense (DoD) implemented Cost-as-an-Independent-Variable (CAIV) policy [44] to attempt to meet three objectives for acquiring defense systems. First, to set aggressive but realistic cost goals and objectives and meeting them; second, to balance mission needs with projected future resources while accounting for anticipated process improvements in DoD and industry; and third, to determine best-value for total ownership cost (TOC). Since CAIV was implemented, program managers have traditionally used Pareto-optimal techniques to narrow the variant trade space and to determine whether there is a "knee-in-the-curve" in which a high investment return on performance can be gained. In order to obtain best-value, it is useful for the program to keep cost as independent as possible throughout the tradeoff process.

Ship systems such as the IEP are complex and have many interdependencies that make designing for best-value survivability very difficult. Ship designers are using indirect methods to design for survivability which rely on design rules and past practice. Detailed design phase simulations are not equipped to minimize cost in the early-design stage.

Current guidance and practice for U.S. Navy IEP design cannot guarantee a minimum cost solution due to the complexity of the interdependence between the electrical and cooling plants in the presence of survivability requirements and mission operating conditions. Casualties are simulated on IEP concept designs to determine their performance with respect to competing designs. Best survivability value can be determined among a pool of IEP concept design candidates, but none can be shown to be the minimum capacity (cost) topology.

1.1.2 Shipboard Electrical Distribution Architecture

Between WWII and near the end of the Cold War, common design practice for U.S. Navy surface ship electrical systems was radial distribution (see Figure 1-2) with redundant generating equipment, spatial separation, and alternate power supplies for selected, vital loads. This gave the electric plant a measure of reliability and survivability. By the end of the Cold War, the number and size of electrical loads had grown dramatically. The sensitivity of combat system electronics also became a factor, requiring higher power quality as well as additional protected busses. The shipboard electric plants had become very complex

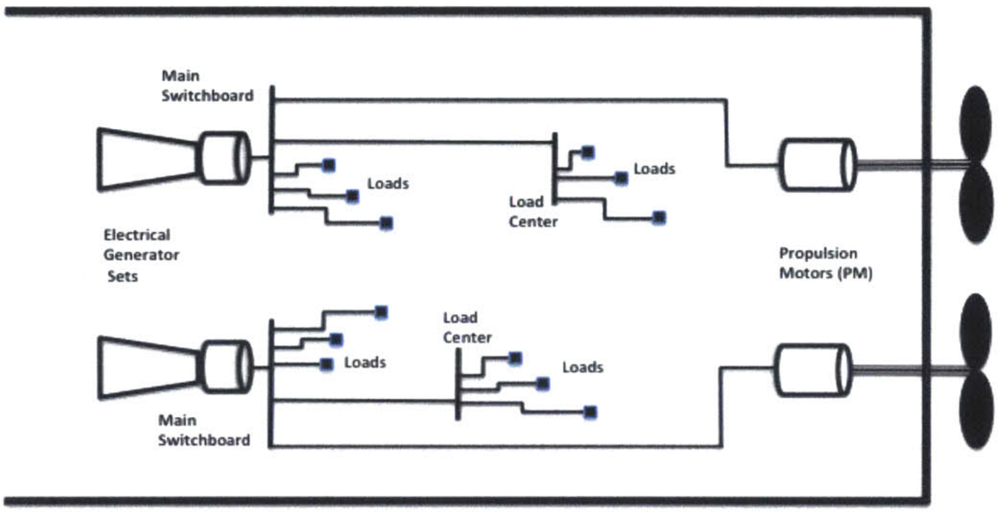


Figure 1-2: Shipboard Radial Electrical Distribution System

and difficult to protect and to restore from casualty damage. Around the same time, due to shrinking defense budgets, the focus for electric plant design began to shift toward affordability and flexibility. Other distribution topologies, such as ring bus with zonal electrical distribution (ZED) were being considered.

Although Navy design practice [2] published in 1992 included ring bus with ZED, this topology was not widely used until new ship class designs following the Cold War. It was shown by Petry and Rumberg [42] that a ring bus and ZED could offer comparable or better survivability and less cost and weight than existing radial distribution systems. In Figure 1-3, note the clear redundant power supplies, the zonal separation, and the implied ease of control and restoration from a casualty. Following Petry & Rumberg's initial studies, ZED design practice was widely accepted and refined for years by many published articles and U.S. Navy policy documents. Doerry has worked to define standard metrics for the study of quality of service (QoS), and reliability and survivability [24]. Also, general design criteria has been established for all-electric ships (AESs) using ring bus and ZED [22], [23]. Recently, other electric plant topologies have been investigated; one example is

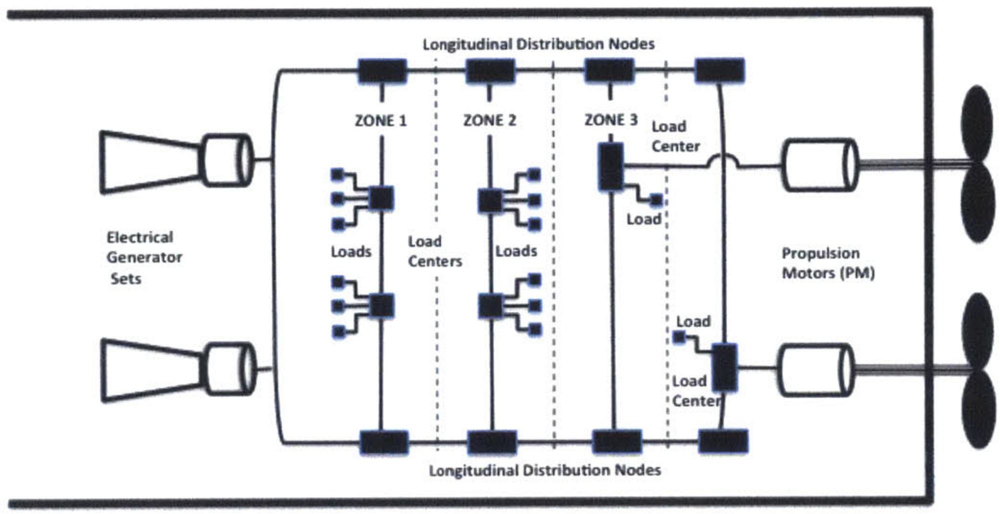


Figure 1-3: Shipboard Zonal Electrical Distribution System

the breaker-and-a-half arrangement. Along the lines of Petry and Rumberg's work, Chalfant, et.al. performed a weight and volume comparison of breaker-and-a-half vs. ring bus distribution systems [12]. This work demonstrates a continued need to find shipboard electrical distribution topologies that offer the best power quality, reliability and survivability at minimum weight, volume and cost.

1.1.3 Integrated Power Systems (IPSs)

The U.S. Navy is moving forward with development and implementation of electric propulsion, as are other navies and the commercial shipping industry. Propulsion has traditionally been by far the largest power requirement for a vessel; for a warship roughly 80% of the power being produced by a transiting ship is for propulsion; however this is changing as combat system loads are rapidly increasing. Combat system loads may eclipse propulsion loads in the near future. Traditionally, ships have used separate sets of gas or steam turbines or diesel engines; one set for propulsion, another for generation for ship electrical loads. A disadvantage to this scheme is that the potential power from propulsion turbines at idle is unusable by the rest of the ship for electrical power generation.

The integrated propulsion system (IPS) approach centralizes power generation and makes it available for other ship loads, such as combat systems. As combat system (high resolution, long range radars, pulse power weapons, railguns, electromagnetic aircraft launch systems, etc.) electrical load is dramatically increasing, the paradigm has shifted regarding how power is produced and shared by shipboard loads. The IPS approach allows less power production equipment for the same overall capability than would be required if propulsion and generation were handled separately. The USS ZUMWALT (DDG-1000) is the first U.S. Navy ship implementing IPS, currently under construction and scheduled for delivery to the U.S. Navy in early 2016. ZUMWALT has the ability to distribute centralized power to all ship's loads, including the electric propulsion motors [37].

In 2007, Naval Sea Systems (NAVSEA) Command issued the technical report titled "Next Generation Integrated Power System (NGIPS) Technology Development Roadmap" [21] to guide future ship design and acquisition, propulsion and ship combat systems to support the IPS concept. In 2013, NAVSEA updated this guidance, reaffirming the need for IPSs, including electric propulsion ("Naval Power Systems Technology Roadmap") [32]. With the combat system loads rivaling propulsion power load, there is great advantage to electric drive propulsion, allowing the operator to determine how to appropriately share the electric power produced for propulsion, combat systems or some combination of each. There is a need for design optimization tools commensurate with the increasing complexity and required flexibility of modern ship IPSs.

1.1.4 Cooling Systems

The cooling plants on a ship are designed to remove heat from engines, generators, power converters, large motors, and high power electronic systems such as radars and combat system computers. The source of heat removal is an open system with surrounding seawater. Due to the corrosiveness of seawater (and other factors), the heat exchange with thermal loads in the ship is commonly accomplished with multiple layers so that freshwater is the fluid in contact with surfaces in sensitive systems. As in the case of the electric plant, the cooling plant must also be survivable and reliable. A similar philosophy to the ring bus and zonal distribution arrangement is used in cooling plant design through the use of port and starboard supply headers and cross-connections in the system [1], [38]. There has been some recent interest in the adequacy and efficiency of cooling system designs. Holsonback and Kiehne [31] and Fang, et.al. [26] among others have focused on modeling thermal considerations for the all-electric ship (AES) integrated engineering plant (IEP). A parametric-based early stage design tool for shipboard cooling systems has been developed by Fiedel [27]. A notional cooling system arrangement is shown in Figure 3-12. This is another example of the need for better tools to design optimum shipboard systems.

1.1.5 IEP System Interdependency

Current standard practice for IEP design, at least in early stage design, decouples and treats separately the two major interdependent systems - the electric distribution and cooling systems. Since these two systems are highly interdependent, casualties in one can greatly affect the other, which could in turn cause additional failures in the first affected system and ultimate failure of the entire IEP. There have been recent studies to simulate the dynamics to account for this interdependence of the IEP [17], [16], [13], [19] and for the purpose of measuring reliability and survivability. It is possible to include other interdependent domains of the ship systems that could possibly cause cascading mission failure. In work by Cramer, Zivi, Sudhoff and Chan [17], [16], [19], there are six "layers" of interdependent domains (Spatial, Automation, AC power, DC power, Seawater and Thermal). The work done is related to modeling & simulation and survivability metric analysis. The two most significant domains in the IEP are the electrical distribution and cooling domains. In the work presented in this thesis, a direct design method is presented and two domains is sufficient to demonstrate.

This work can possibly be applied to other situations where interdependent systems can cause cascading failure of one another. An example of this is a terrestrial power distribution system. These systems are currently reliant on communication systems (cell or landline telephone or other) that receive power from the grid itself. The communication system is used for control of the distribution system through remote breaker and transformer activation. A loss of power can cause a loss of communication and control, which can in turn cause additional power loss, etc. This is also true for ship systems.

Determining best value for particular designs has been traditionally performed by indirect methods in which IEP candidate designs are tested in damage simulation for survivability performance. Details of the current simulation methods for determining warship survivability are unpublished due to classification. The simulation testing of specific IEP candidates occurs much later in the acquisition process; closer to the detail design phase.

1.2 Related Literature

This work combines many different aspects of marine engineering design and network flow optimization. In the following section, related literature is summarized in each of the major areas of work.

1.2.1 IEP Design

The Navy has published technical requirements for survivability [14], general design criteria for components, systems and architecture in the areas of shipboard electrical systems [2], seawater cooling systems [38], and freshwater cooling systems [1]. Naval Sea Systems Command (NAVSEA) issued guidance for integrated propulsion system (IPS) design and acquisition into the middle of the 21^{st} century [21]. Important works by Doerry are useful for defining in more detail QoS, reliability and survivability. [23], [24], [22], [25]. These documents lay out guidance for redundancy and spatial separation of equipment, power margins and quality specifications, to name a few examples. However, the guidance delivers the minimum requirements, and does not give optimization methods to the designer for weight, volume or cost minimization. The guidance also does not address the IEP as a set of interdependent systems. Survivability is a major design consideration for U.S. Navy ships and currently, the Littoral Combat Ship (LCS) has been criticized by analysts for survivability shortcomings [40]. This design method can be useful for the integrated engineering plant (IEP) portion of a ship early-stage design to guarantee specified survivability requirements.

1.2.2 IEP Modeling & Simulation

Some of the recent works involving IEP modeling for the purpose of studying IEP transient behavior and reconfiguration and survivability are by Whitcomb [52], Cramer [16], [17], Chan [13], Zivi [19]. Marden [34], and Chalfant at MIT SeaGrant have developed object-oriented models of notional IEPs. Butler [11], Taylor [49] and Cramer [18] are works related to linear programming (LP) modeling and simulation for reconfiguration and survivability. Thc Naval Combat Survivability Testbed (NCST), a land-based prototype located at Purdue University is the subject of many modeling studies due to accessibility and documentation of the system. The NSMCF approach proposed in this thesis is applied using the NCST IEP as a candidate topology. Results are shown in Chapter 5.

1.2.3 Mesh Restorable Network Design

A mesh restorable network is a distribution system that is not necessarily symmetrical or intuitive in topology, but usually has many redundant flow arcs. The design and performance of a mesh restorable network considers and meets requirements for flow delivery for a set of specified casualty and operating conditions. This is a focus of the work described in this thesis, and in contrast to the current, indirect approach to IEP survivability design, mesh restorable network design can be described as direct survivability design. The formulation commonly used in this area is the NSMCF formulation. Mesh restorable networks are commonly designed and used in internet and other communication networks. Some recent works that address the survivability direct design of network flow problems are Woungang [54], Grover [29], Alevras, et.al. [5] and [28]. Other similar works that focus more on solver algorithms for these complex problems are Rioux [50], Labbé [33], Dahl [20], Stoer [48] and Bin [8].

1.3 Problem Statement

CAIV is a Department of Defense (DoD) policy that is intended to drive best-value acquisition and reduce life-cycle costs in defense systems [46]. Due to the complexity of the total ship system, and the iterative nature of the design process, the U.S. Navy has struggled to meet the spirit of the CAIV policy. Selecting best-value concept variants in the common Pareto optimal strategy [10], [9], [41] does not guarantee cost optimality if there is not already a method to find cost minimized variants. There is a need to give program managers designs meeting performance specifications at true minimum cost. Due to shrinking annual defense budgets, and the increasing costs of Navy maintenance and acquisition, the current build rate for ships that are needed for national defense is not achievable financially. [3]. The problem statement for this thesis is as follows:

> Shipboard IEP design for survivability is a complex, iterative process that does not guarantee a minimum cost solution. The process is not well matched for the Pareto-optimal tradeoff process used to support cost-as-an-independent-variable (CAIV) DoD policy.

1.4 Contributions

The proposed method supports cost-as-an-independent-variable (CAIV) policy by incorporating survivability specifications into the early stage IEP design cost optimization. This is in contrast to the current method in which survivability is measured after detail design. The proposed method demonstrates a step forward in cost optimization of the ship design process. The designer inputs for the method are the required loads for the survivable IEP, all casualty and operating conditions required by policy or mission, and an over-redundant candidate topology. The optimization solver systematically explores the entire early-stage design space and returns the minimum cost, survivable IEP design. Instead of focusing on achieving survivability through iterative adjustments during the late phases of design (a process which itself is costly), the designer can be guaranteed minimum cost survivability in the early-stage and can then focus on finding best value among pareto-optimal solutions for various survivability performance levels.

CAIV is a Department of Defense (DoD) policy that is intended to drive best-value acquisition and reduce life-cycle costs in defense systems [46]. Due to the complexity of the total ship system, and the iterative nature of the design process, the U.S. Navy has struggled to meet the spirit of the CAIV policy. Selecting best-value concept variants in the common Pareto optimal strategy [10], [9], [41] does not guarantee cost optimality if there is not already a method to find cost minimized variants. There is a need to give program managers designs meeting performance specifications at true minimum cost. Due to shrinking annual defense budgets, and the increasing costs of Navy maintenance and acquisition, the current build rate for ships that are needed for national defense is not financially sustainable [3].

The method presented in this thesis is a systematic quantitative process for minimum cost survivable IEP design. The method especially supports early-stage design where knowledge and design freedom should be maximized; while cost committed should be minimized [35]. It is a needed step forward to support CAIV by giving program managers true best-value, minimum cost design variants. The method presented in this thesis can help enable the acquisition of a survivable, resilient and most importantly, affordable fleet. The three major contributions of this work are as follows:

> First, a straightforward method for "designed-in" survivability of early stage concepts at guaranteed minimum cost, and with flexibility for multiple operating and casualty conditions is demonstrated. Second, interdependence between the electrical generation and cooling domains is modeled in detail, forming a new computational structure that could be extended to other domains as well. Third, a method for the integral design of minimum cost shipboard stored energy in consideration of casualty and operating conditions is shown. The overall methodology developed in this work can provide program managers assurance that design concepts all represent minimum cost and best value, thus reducing the trade space at an early stage when cost savings can be maximized in the acquisition program [35].

1.5 Outline of the Thesis

Chapter 2 is a brief introduction to linear programming (LP) and tutorial leading up to the implementation of non-simultaneous multicommodity flow (NSMCF) as applied to integrated engineering plant (IEP) design. Chapter 3 describes the general modeling principles used in this work, namely the physics of IEPs related to network flow principles. Chapter 4 is a description of NSMCF applied to a simple IEP design to illustrate all the concepts explored in this work, including network flow, fixed cost consideration using binary programming, linear approximation of nonlinear physics, and the treatment of stored energy devices (SEDs). Chapter 5 is a description with results of the proposed method applied to the Naval Combat Survivability Testbed (NCST) IEP, a land-based IEP prototype which is located at Purdue University. Chapter 6 contains conclusions and recommendations for future work. Appendix A explores the scalability of the method for the benefit of the reader who is considering applying the proposed method in early stage design to evaluate the feasibility and economics based on computational cost. Appendix B discusses numerical precision concerns when using the optimization solver and Appendix C is a sample IBM CPLEX® input file for the Notional IEP optimization demonstrated in Chapter 4.

Chapter 2

Network Flow Optimization

Network flow optimization (NFO) is an applied mathematics method to find optimal solutions and has been generalized and applied to many disciplines. A NFO problem is one in which there is generation, distribution, and demand of a commodity. A commodity can be anything that can be modeled in terms of flow. There are many variations of the NFO problem in which it is not obvious that the problem can be modeled in terms of flow. This is the challenge of the designer, to formulate the problem such that the optimization exactly suits their need.

One of the most recent business successes using network flow (specifically, integer programming) is in the airline industry [4] [51]. Southwest Airlines is known as one of the airlines that took an early lead in the use of network flow optimization (NFO) techniques to optimize flight and crew scheduling, maximizing profit. After the acquisition of AirTran Airways in 2011, Southwest Airline's Chief Executive Officer, Gary Kelly, stated as a first order of business "we must optimize our route network" [39]. Use of network flow optimization (NFO) also includes some other applications that don't necessarily imply flow such as finance [6], multi-vehicle path planning [47], and many others. It should be noted that optimization applied indiscriminately can have adverse results. For example, in the airline industry, optimization has been used to maximize profits; the focus has been on maximizing plane occupancy. There is a portion of passengers on any particular flight that are flying direct, but the majority are laying over and some, many times due to optimization, using airport "hubs." This has caused more passengers to have multiple layovers, longer travel times and in general a worse travel experience. Over time, this could result in loss of customers and profit. The designer needs to ensure all important factors are considered in the system model to ensure optimization is achieved as desired.

For network flow optimization (NFO) formulation, the nature and units of the flow are determined and the equations describing the continuity at various supply, demand and distribution nodes are formulated. Other conditions, such as capacity limits, supply and demand limits, and any unique cost considerations are described mathematically in the form of equality and inequality constraints. A prescribed cost function (also called the objective) is minimized (or maximized) by the solver, subject to the continuity and capacity constraints. This approach has been used effectively in communication and transportation network design optimization where continuity, survivability, flow maximization, and cost minimization are critical. In this thesis, which describes the minimization of the capacity (cost) of an early-stage survivable integrated engineering plant (IEP) design, the physical domains have been described in Chapter 1: they are the electrical and thermal (cooling) domains. In the context of NFO, each domain is treated as a flow network; the electrical power flow and cooling water mass flow are the parameters used for design optimization.

2.1 Linear Programming

Linear programming (LP) is a field of applied mathematics that is the framework of network flow optimization (NFO). LP was first invented by Russian Leonid Kantorovich around 1939 to optimize production processes. During World War II, LP was used to optimize the flow of logistic supply chains. American George Dantzig developed many advances to the theory and use of LP throughout the 20^{th} century.

In a LP formulation, linear equality and inequality constraints define the physics of the problem. An expression (called the "cost function" or "objective") is used by the designer to focus the solver to the optimal solution to the problem. The entire set of constraints and cost function is called the optimization formulation. A LP formulation expressed in canonical form is:

$$\text{minimize} \quad \mathbf{c}^{\mathbf{T}}\mathbf{x} \tag{2.1}$$

$$\text{subject to} \quad \mathbf{Ax} \leq \mathbf{b} \tag{2.2}$$

$$\text{and} \quad \mathbf{x} \geq \mathbf{0} \tag{2.3}$$

In the cost function (or objective function), expression 2.1, the vector $\mathbf{x}$ is referred to as the set of decision variables. Vector $\mathbf{c}$ makes up the cost coefficients for the decision variables. The solver determines what value each of the variables in $\mathbf{x}$ should take in order to minimize (or maximize, whichever is specified) the cost function. Equation 2.2 is referred to as the set of constraints for the formulation. Equation 2.3 is also a set of constraints, but is generally referred to as "the nonnegativities" or the "bounds."

In the case of the work presented in this thesis, the constraints describe the physics of the electrical distribution and cooling systems. The laws of conservation (continuity) are modeled using these constraints. For example, in the electrical system, at any node (electrical junction), power flow in and out is conserved. The sum of power flows at a node (including any power generated byor consumed at that node) equal zero. A conservation constraint equation is created for each node. More discussion regarding modeling of the integrated engineering plant (IEP) is found in Chapter 3. The nonnegativity constraints are used in this case to reflect the fact that, in some cases, power can only flow in one direction, electrical generators cannot consume power, loads cannot generate power, and converters and inverters can only supply power in one direction.

Applied mathematicians have improved the performance of numerical solvers to the point that very large scale problems have become tractable. The solvers take advantage of the fact that the optimal solution is found at a corner of the multi-dimension polyhedrons formed by the intersections of the many linear equations and inequalities. This has enabled the solvers to be very efficient compared to a standard linear algebra solving algorithm. The task of the designer is to adapt the technique of linear programming (LP) to correctly model the optimization problem and to manipulate the solver to do the work of giving the correct and appropriate solution for the application. The use of LP techniques has spread to many disciplines. More information regarding LP theory and application can be found in the textbook by Bertsimas [7].

2.2 LP Network Flow Example

Network flow optimization (NFO), in its basic form, is a discipline using linear programming (LP) that finds the lowest cost flow of a commodity from a set of sources to a set of sinks (loads) through a network containing various flowpaths. Each of the flowpaths has a cost per unit flow associated with it. The sources and sinks are represented by nodes and the commodity flows through the edges of the network. The NFO problem can be used for many applications and is commonly used to minimize the cost of distribution in transportation networks in the presence of capacities (limitations) and costs in the routes. The costs could be as simple as the mileage and tolls or could include more complex factors, such as the cost of wear on vehicles or stochastic models of traffic delays. A variation of the problem is to maximize the total commodity distribution in the presence of the route capacities plus supply limitations where, say, cost is not the major concern.

A simple flow network is shown in Figure (2-1) and a description of the nodes is in Table 2.1.

Node	Value	Node Type
1	5	supply
2	-5	demand
3	0	distribution
4	0	distribution
5	10	supply
6	-10	demand

Table 2.1: Simple Network Flow Optimization Nodes

Nodes are represented by circles and are shown connected by directional (arrowed) line edges. Flow direction is limited in this case to that shown by the arrows. Nodes are annotated by number as shown in the figure, such as ① shown in the upper left corner of the figure. Edges are not numbered in this example, but are normally annotated in formulation

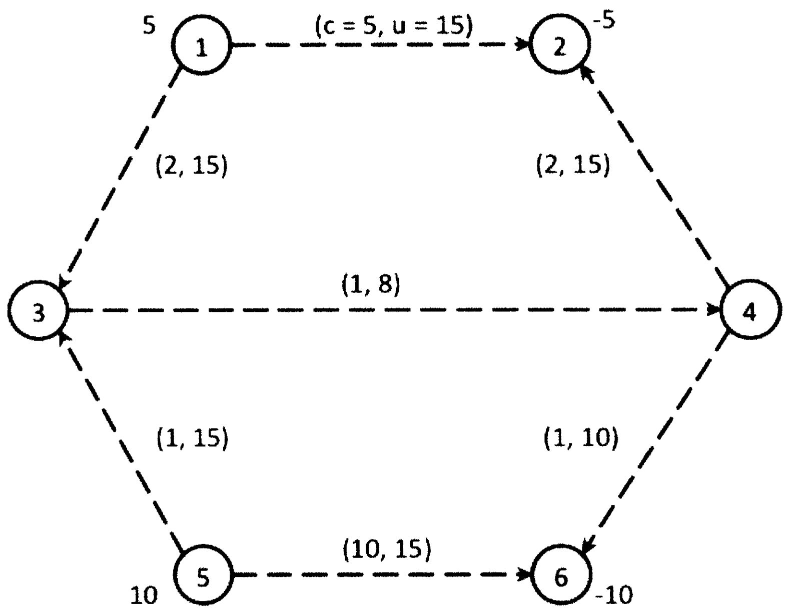


Figure 2-1: Simple Network Optimization Problem

Edge (i,j)	Cost c_{ij}	Capacity u_{ij}
(1,2)	5	15
(1,3)	2	15
(3,4)	1	8
(4,2)	2	15
(4,6)	1	10
(5,3)	1	15
(5,6)	10	15

Table 2.2: Simple Network Flow Optimization Edges

by referring to the connecting nodes (such as edge $(5,6)$ which is at the bottom, showing flow from node ⑤ $\rightarrow$ node ⑥). The cost per unit of commodity flow c on an edge is shown as the first number in the ordered pair displayed near each edge. The capacity u, or maximum flow limit for each edge is shown as the second number in each ordered pair. The supply nodes, ① and ⑤ generate commodity at rates of 5 and 10, respectively as shown. Likewise, the demand nodes, ② and ⑥ require commodity of 5 and 10, respectively. The demand flow is shown as negative because, according to standard convention, it is treated as negative commodity supply. Note in Figure 2-1 that nodes ③ and ④ do not have any supply or demand associated with them. They are referred to as distribution nodes.

2.2.1 Linear Programming Network Optimization Formulation

Described generally, an edge allowing one-way flow from node i to j is described by (i,j). Let E be the set of all edges. Each edge (i,j) can carry up to u_{ij} units of flow. There is a cost c_{ij} associated with the rate of flow in each edge of the network. Let N be the set of all nodes. Each node $i \in N$ generates a supply or a demand of b_i units of flow. For distribution nodes, $b_i = 0$. For a supply node, $b_i \geq 0$ and for a demand node $b_i \leq 0$.

The task of the solver is to find the minimum cost flow for the network such that all required demand is met. To do this, the solver must minimize total cost of transport over the edges while accounting for the variation in cost for each edge. To formulate as a linear programming problem, use flow variables x_{ij} where the annotated flow is in edge (i,j).

The formulation for basic network flow is as follows:

$$\textit{min.} \quad \sum_{(i,j)\in E} c_{ij}x_{ij} \qquad (i,j) \in E \tag{2.4}$$

$$s.t. \quad x_{ij} \leq u_{ij} \qquad (i,j) \in E \tag{2.5}$$

$$\textit{and} \quad \sum_{(i,j)\in E} x_{ij} - \sum_{(j,i)\in E} x_{ji} = b_i \qquad (i,j) \in E \qquad i \in N \tag{2.6}$$

$$\textit{and} \quad x_{ij} \geq 0 \qquad (i,j) \in E \tag{2.7}$$

Expression 2.4 is the cost function (objective) to be minimized. It represents the total cost of all flow throughout all edges in the network. Inequality constraints in 2.5 limit the flow to given edge capacities. Equation 2.6 represents the continuity of each node in the system. All flow into and out of the node must equal the supply or demand at each node. Finally, bounds in 2.7 ensure that flow is unidirectional in accordance with the physics of the problem.

2.2.2 Simple Network Flow Problem Solution

The formulation for the network flow problem in Section 2.2 and Figure 2-1 is:
Minimize:

$$5x_{12} + 2x_{13} + x_{34} + 2x_{42} + x_{46} + x_{53} + 10x_{56}$$

Subject To:

$$-x_{12} - x_{13} = -5 \qquad x_{34} - x_{42} - x_{46} = 0$$

$$x_{12} + x_{42} = 5 \qquad -x_{53} - x_{56} = -10$$

$$x_{13} - x_{34} + x_{53} = 0 \qquad x_{56} + x_{46} = 10$$

Bounds:

$$x_{12} \leq 15 \qquad x_{46} \leq 10 \qquad x_{34} \geq 0$$

$$x_{13} \leq 15 \qquad x_{53} \leq 15 \qquad x_{42} \geq 0$$

$$x_{34} \leq 8 \qquad x_{56} \leq 15 \qquad x_{46} \geq 0$$

$$x_{42} \leq 15 \qquad x_{12} \geq 0 \qquad x_{53} \geq 0$$

$$x_{13} \geq 0 \qquad x_{56} \geq 0$$

Although the solution may appear obvious, larger scale problems of course would be extremely difficult or impossible to solve by intuition. The problem is chosen to allow clear explanation and validation of the method. The solution can be easily explained in light of the constraints. Although the solver iterates to the mathematically optimal solution, it is helpful to describe the solver's "intentions" in a dynamic context to discuss some of the conclusions that can be drawn:

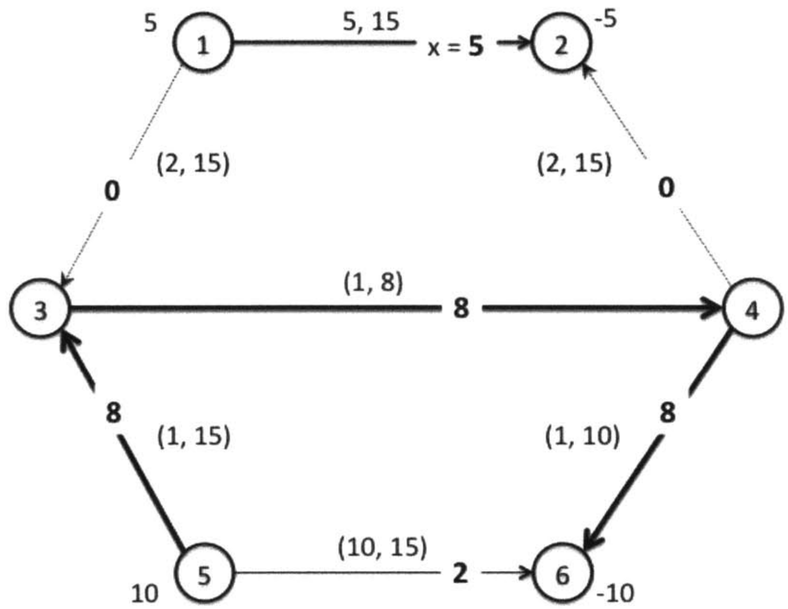


Figure 2-2: Simple Network Flow Optimization Solution

Edge	Cost	Capacity	Flow
(1,2)	5	15	5
(1,3)	2	15	0
(3,4)	1	8	8
(4,2)	2	15	0
(4,6)	1	10	8
(5,3)	1	15	8
(5,6)	10	15	2

Table 2.3: Solution Values Network Flow Optimization

- The solver would have "preferred" not to use the most expensive edge $(5,6)$ while minimizing cost. However, the only other path for the network to provide the 10 units of commodity flow demanded by node 6 would be through edge $(3,4)$. Edge $(3,4)$ has a capacity limit of 8 which would not allow it to carry the full 10 units of flow. So the solver was required to use edge $(5,6)$ to transport at least 2 units and appears to have minimized the flow through edge $(5,6)$ to two units in finding the lowest cost solution.

- The solver avoided sharing distribution of commodity between the upper and lower supply/demand, because, due to directional constraints on the network, the only way to deliver commodity to node 2 from node 5 would be to use edge $(3,4)$. Edge $(3,4)$ is at capacity (8) based on the discussion above. Sharing commodity flow between the upper and lower parts of the network would require use of edge $(1,3)$ and $(2,4)$ which would be unnecessarily costly.

Although it is useful to discuss the solver's "intentions" the solver is simply taking the formulation in matrix form, and iterating to the mathematical minimum of the objective with no inherent understanding of the physics of the problem. If there is a feasible solution, the solver will provide the optimal solution and will also provide certification that the solution is the global optimal for the given formulation. The user's responsibility is to verify the formulation has no modeling or data entry errors and to check the solution to ensure that it is reasonable and doesn't reveal a modeling error.

2.3 Multicommodity Flow Network Optimization

An extension of basic network flow optimization (NFO) is the multicommodity flow (MCF) problem. One of the simplest visualizations of MCF is the case of a shipping company that is transporting multiple products from various origins to their destinations through a network of roadways. The different products are different flow commodities (k) and they can be shipped together simultaneously on a roadway. The roadways are represented by edges of the network flow problem and the nodes are representative of the manufacturing facilities (supply nodes), retailers (demand nodes) and common waypoints or distribution warehouses (distribution nodes). The different costs are taken into account for each edge (roadway) based on, for example, the distance traveled and perhaps tolls. There are limitations to the rate that the commodities can be transported on a roadway (capacity limits) due to speed limits or number of lanes, for example. The formulation is shown below:

$$min. \quad \sum_{k \in K} \sum_{(i,j) \in E} c_{ij}^k x_{ij}^k \qquad (i,j) \in E \qquad k \in K \tag{2.8}$$

$$s.t. \quad \sum_{k \in K} x_{ij}^k \leq u_{ij} \qquad (i,j) \in E \qquad k \in K \tag{2.9}$$

$$and \quad \sum_{(i,j) \in E} x_{ij}^k - \sum_{(j,i) \in E} x_{ji}^k = b_i \qquad (i,j) \in E \qquad i \in N \qquad k \in K \tag{2.10}$$

$$and \quad x_{ij}^k \geq 0 \qquad (i,j) \in E \qquad k \in K \tag{2.11}$$

In the NSMCF formulation, the set of commodities is annotated as K. Similar to the objective of the simple network flow optimization (NFO) problem in Section 2.2, the sum of the costs of the flow of all commodities through each edge is minimized (Expression 2.8). In the capacity constraints (2.9), the sum total of all commodity flows in a particular edge must be less than or equal to the capacity of that edge. In the continuity constraint 2.10, the sum of the flows going into and out of a node must be equal to the total commodity sourced or sinked by that node. Inequality 2.11 represents the directional constraints.

In this multicommodity flow (MCF) formulation, the cost of transport on an individual edge is the same for both commodity 1 and commodity 2. This is not necessarily always the case; there could be different transport costs associated with each commodity. The edge capacities in this model are limits to the sum of both commodities' flow on each edge. This could, in other problems, be a more complex relationship between the commodities if they vary widely in size, weight, fragility or any other factor.

The MCF example problem is setup in the network in Figure 2-3.

The same nodes that are supply and demand nodes in the example in Section 2.2 are supply and demand nodes here in the multicommodity flow (MCF) example. The superscript on the values for supply and demand annotate the commodity that is supplied or demanded

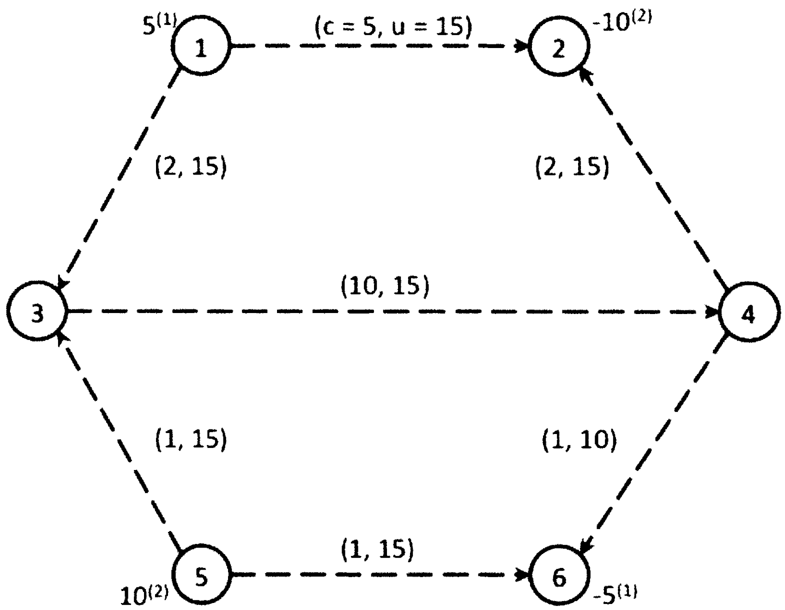


Figure 2-3: MCF Optimization Example Problem

Node	Value	Node Type	Commodity
1	5	supply	1
2	-10	demand	2
3	0	distribution	-
4	0	distribution	-
5	10	supply	2
6	-5	demand	1

Table 2.4: MCF Optimization Nodes

Edge (i,j)	Cost c_{ij}	Capacity u_{ij}
(1,2)	5	15
(1,3)	2	15
(3,4)	10	15
(4,2)	2	15
(4,6)	1	10
(5,3)	1	15
(5,6)	1	15

Table 2.5: MCF Optimization Example Edges

at that node. For this example, there is only one commodity supplied or demanded at those nodes. Again, this is a simplified problem and in a more complex problem, there could be multiple commodities supplied or demanded at a single node.

Note that at supply node 1, where commodity 1 has a supply rate of five (annotated as $5^{(1)}$), continuity is expressed as a balance with the supply of commodity 1 and flow of commodity 1 out of the node. With regard to commodity 2 flow, node 1 appears as a distribution node, as it has no supply or demand. This concept is the same for the other supply and demand nodes 5, 2 and 6.

2.3.1 MCF Formulation

As can be seen in the solution in Figure 2-4, both commodities transport from their respective supply nodes to their demand nodes which are in opposite corners. Due to edge direction limitations, they both need to use the center edge (3,4), which is also the most expensive edge. Edge (3,4) has the capacity for the sum of both commodities otherwise the solution would be infeasible (no solution).

The multicommodity flow (MCF) solution is also shown in tabular form (Table 2.7).

2.4 Non-Simultaneous Multicommodity Flow (NSMCF)

Section 2.3 describes multicommodity flow (MCF) and an example problem is shown. An interesting variation of MCF is called non-simultaneous multicommodity flow (NSMCF). Although NSMCF is a closely related variation of MCF, the application of NSMCF and the

Objective Function
Minimize:

$$5x^1_{12}+5x^2_{12}+2x^1_{13}+2x^2_{13}+2x^1_{42}+2x^2_{42}+x^1_{34}+x^2_{34}+x^1_{46}+x^2_{46}+x^1_{53}+x^2_{53}+10x^1_{56}+10x^2_{56}$$

Subject To:
Continuity Equation (by commodity)

$$-x^1_{12}-x^1_{13}=-5 \qquad x^1_{13}+x^1_{53}-x^1_{34}=0 \qquad -x^1_{53}-x^1_{56}=0$$
$$-x^2_{12}-x^2_{13}=0 \qquad x^2_{13}+x^2_{53}-x^2_{34}=0 \qquad -x^2_{53}-x^2_{56}=-10$$
$$x^1_{12}+x^1_{42}=0 \qquad x^1_{34}-x^1_{42}-x^1_{46}=0 \qquad x^1_{46}+x^1_{56}=5$$
$$x^2_{12}+x^2_{42}=10 \qquad x^2_{34}-x^2_{42}-x^2_{46}=0 \qquad x^2_{46}+x^2_{56}=0$$

Capacity Constraints:

$$x^1_{12}+x^2_{12}\leq 15 \qquad x^1_{13}+x^2_{13}\leq 15 \qquad x^1_{42}+x^2_{42}\leq 15$$
$$x^1_{34}+x^2_{34}\leq 8 \qquad x^1_{46}+x^2_{46}\leq 10$$
$$x^1_{53}+x^2_{53}\leq 15 \qquad x^1_{56}+x^2_{56}\leq 15$$

Nonnegativities:

$$x^1_{12}\geq 0 \quad x^2_{12}\geq 0 \quad x^1_{13}\geq 0$$
$$x^2_{13}\geq 0 \quad x^1_{42}\geq 0 \quad x^2_{42}\geq 0$$
$$x^1_{34}\geq 0 \quad x^2_{34}\geq 0 \quad x^1_{46}\geq 0$$
$$x^2_{46}\geq 0 \quad x^1_{53}\geq 0 \quad x^2_{53}\geq 0$$
$$x^1_{56}\geq 0 \quad x^2_{56}\geq 0$$

Table 2.6: MCF Formulation Constraints

Edge	**Cost**	**Capacity**	**Flow of Commodity 1**	**Flow of Commodity 2**
(1,2)	5	15	0	0
(1,3)	2	15	5	0
(3,4)	10	15	5	10
(4,2)	2	15	0	10
(4,6)	1	10	5	0
(5,3)	1	15	0	10
(5,6)	10	15	0	0

Table 2.7: MCF Example Solution Flow Values

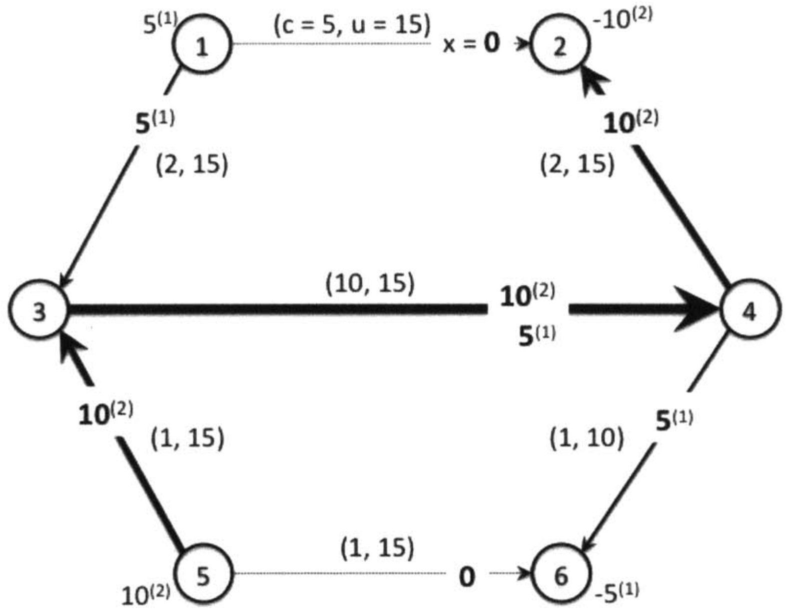


Figure 2-4: MCF Optimization Solution

formulation are quite different from MCF. First of all, NSMCF is almost always used to minimize capacity cost, not flow cost (as in MCF); which significantly changes the structure of the formulation. For most MCF problems, edge capacity is an upper bound and not a decision variable. Secondly, the NSMCF problem is treated as if only one commodity may flow at a time (hence "non-simultaneous") and there is a unique formulation for each commodity flow. The unique formulation for each commodity can be called a "set" of flow constraints. The number of constraints in the NSMCF formulation can become quite large, as for example, the existence of only two commodities in the problem creates two sets of constraints and will roughly double the size of the formulation with respect to a single commodity formulation. This is not the case in the more basic MCF formulation where adding a commodity will add terms to the existing constraints and will have a lesser effect on the formulation size.

The distinguishing feature of NSMCF is that global variables for each edge capacity are used to "roll-up" or "capture" the maximum flow that any edge experiences while meeting the demands for each commodity flow constraint set as shown in inequality constraint 2.12.

$$U_{ij} \geq x_{ij}^{k} \qquad (i,j) \in E \qquad k \in K \tag{2.12}$$

where K is the set of unique flow situations, casualties or unique operating conditions. The constraint in 2.12 shows that U_{ij}, the capacity of edge (i,j) is greater than any of the unique flow values x_{ij}^{k}. This ensures that the capacity is sufficient to carry the flow in any given condition. U_{ij} is then the minimum required capacity to accommodate all unique flow situations.

Although the formulation is closely related to multicommodity flow (MCF), it is not useful to think of these sets of constraints as commodities in the same sense because in a typical non-simultaneous multicommodity flow (NSMCF) application, there are likely not multiple commodities flowing. It is more useful to consider these "commodity" flow sets as unique flow situations. Each unique flow situation, k, can be a casualty, for example, in which an edge is modeled as disabled (flow = 0) or supplies, demands and other parameters can be changed and treated differently to simulate unique operating conditions. NSMCF is commonly used to design networks with the minimum capacity to survive all given casualty flow and operating conditions.

The NSMCF formulation is shown below. The cost coefficient for each edge capacity is annotated as c_{ij}.

$$\text{min.} \quad \sum_{(i,j)\in E} c_{ij}U_{ij} \qquad (i,j) \in E \tag{2.13}$$

$$\text{s.t.} \quad x_{ij}^k \leq U_{ij} \qquad (i,j) \in E \qquad k \in K \tag{2.14}$$

$$\text{and} \quad \sum_{(i,j)\in E} x_{ij}^k - \sum_{(j,i)\in E} x_{ji}^k = b_i \qquad i \in N \qquad k \in K \tag{2.15}$$

$$\text{and} \quad x_m^k = 0 \qquad (i,j) \in E \qquad k \in K \qquad m \in M \tag{2.16}$$

M is the set of casualty edges (the edges that are lost; flow set to zero).

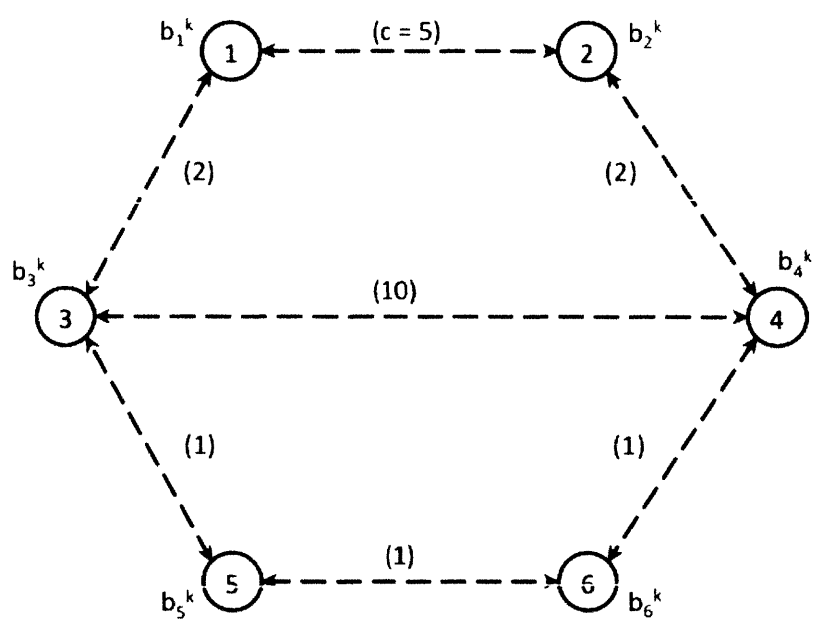


Figure 2-5: NSMCF Example Problem

Note in Figure 2-5 the similarities with the multicommodity flow (MCF) example given in Figure 2-1. The supply, demand and distribution nodes are the same, however their variables now have a k superscript. This is to annotate that each variable is unique to each casualty and operating condition as shown in the non-simultaneous multicommodity flow (NSMCF) formulation in Section 2.4.2. In the NSMCF formulation examples in Sections 2.4.1 and 2.4.2, network flow allowed is bidirectional. This is unlike the network flow optimization (NFO) and MCF examples already discussed, which allow directed flow (one direction) only. This is not required for NSMCF and flow direction can be allowed in one or both directions for any of the edges in the network. The allowance of bidirectional flow for all edges in the NSMCF examples below is arbitrary.

2.4.1 NSMCF Formulation - No Casualties

The formulation shown in Table 2.8 represents a NSMCF problem in which there is only one flow condition. In the context of casualty and operating conditions and survivability, this optimization is for the simplest case in which the network is intact and no special flow conditions are accounted for. It can be seen in the formulation below that only the 0 flow condition is formulated and therefore there is only one "set" of constraints. Figure 2-6 shows the graphical solution to this example problem. In Section 2.4.2 a more extensive formulation is demonstrated in which the possible loss of all edges, any one edge at a time is accounted for.

2.4.2 NSMCF Formulation - M-1 Survivability

M-1 ("M minus one") survivability is the assurance that the system can survive the loss of all edges, any one edge at a time. M-2 survivability is the assurance that the system can survive the loss of all edges, any two edges at a time. In this example, M-1 survivability is described. In general, the more extensive and complex the casualty and operating conditions are, the optimized design network has more redundancy (more connected edges) and more reserve capacity (more capacity required for each edge above that required for "normal" operations).

Figures 2-7 and 2-8 shows the complete set of flow values associated with the solution

Objective Function
Minimize:

$$c_{12}U_{12} + c_{13}U_{13} + c_{24}U_{24} + c_{34}U_{34} + c_{35}U_{35} + c_{46}U_{46} + c_{56}U_{56}$$

Subject To:
Continuity Equations (by commodity):

$$-x_{12}^0 - x_{13}^0 + S_1^0 = 0 \qquad x_{34}^0 + x_{24}^0 - x_{46}^0 = 0$$
$$x_{12}^0 - x_{24}^0 - d_1^0 = 0 \qquad x_{35}^0 - x_{56}^0 + S_2^0 = 0$$
$$x_{13}^0 - x_{35}^0 - x_{34}^0 = 0 \qquad x_{46}^0 + x_{56}^0 - d_2^0 = 0$$

Capacity Rollup:

$$|x_{12}^0| \le U_{12} \qquad |x_{24}^0| \le U_{24} \qquad |x_{35}^0| \le U_{35} \qquad |x_{56}^0| \le U_{56}$$
$$|x_{13}^0| \le U_{13} \qquad |x_{34}^0| \le U_{34} \qquad |x_{46}^0| \le U_{46}$$

Bounds:

$$-\infty \le x_{12}^0 \le \infty \qquad -\infty \le x_{13}^0 \le \infty \qquad -\infty \le x_{24}^0 \le \infty$$
$$-\infty \le x_{34}^0 \le \infty \qquad -\infty \le x_{35}^0 \le \infty \qquad -\infty \le x_{46}^0 \le \infty$$
$$-\infty \le x_{56}^0 \le \infty$$

Operating Conditions:

$$b_1^0 \ge 0 \qquad b_2^0 = -10 \qquad b_3^0 = 0$$
$$b_4^0 = 0 \qquad b_5^0 \ge 0 \qquad b_6^0 = -5$$

Table 2.8: NSMCF Formulation - No Casualties

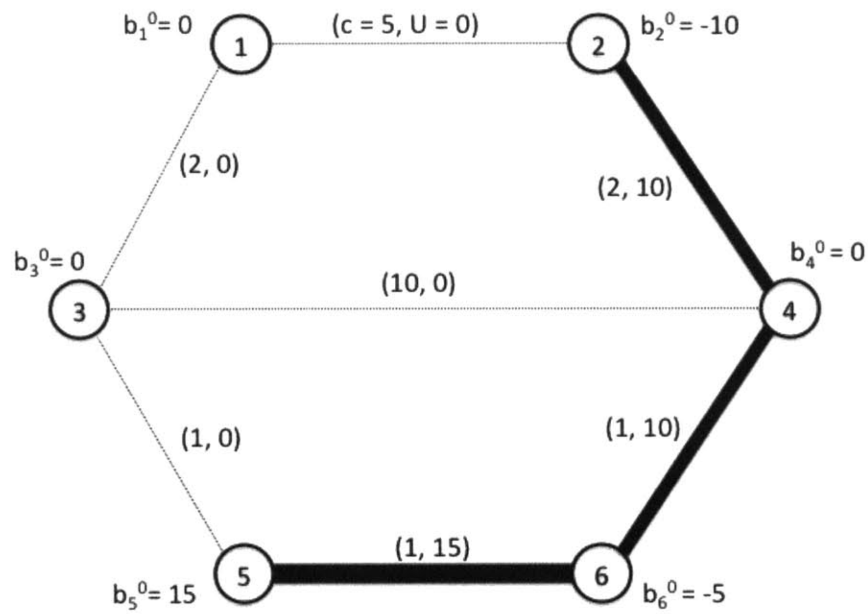


Figure 2-6: NSMCF No-Casualty Example Solution

Minimize:

$c_{12}U_{12} + c_{13}U_{13} + c_{24}U_{24} + c_{34}U_{34} + c_{35}U_{35} + c_{46}U_{46} + c_{56}U_{56}$

Subject To:

Continuity Equations (by commodity):

$$
\begin{array}{lll}
-x_{12}^0 - x_{13}^0 + b_1^0 = 0 & x_{12}^0 - x_{24}^0 - b_2^0 = 0 & x_{13}^0 - x_{35}^0 - x_{34}^0 - b_3^0 = 0 \\
x_{34}^0 + x_{24}^0 - x_{46}^0 = 0 & x_{35}^0 - x_{56}^0 + b_5^0 = 0 & x_{46}^0 + x_{56}^0 - b_6^0 = 0 \\
\vdots & \vdots & \vdots \\
-x_{12}^7 - x_{13}^7 + b_1^7 = 0 & x_{12}^7 - x_{24}^7 - d_1^7 = 0 & x_{13}^7 - x_{35}^7 - x_{34}^7 = 0 \\
x_{34}^7 + x_{24}^7 - x_{46}^7 = 0 & x_{35}^7 - x_{56}^7 + S_2^7 = 0 & x_{46}^7 + x_{56}^7 - b_6^7 = 0
\end{array}
$$

Capacity Rollup:

$$
\begin{array}{llll}
|x_{12}^0| \le U_{12} & |x_{13}^0| \le U_{13} & |x_{24}^0| \le U_{24} & |x_{34}^0| \le U_{34} \\
|x_{35}^0| \le U_{35} & |x_{46}^0| \le U_{46} & |x_{56}^0| \le U_{56} & \\
\vdots & \vdots & \vdots & \vdots \\
|x_{12}^7| \le U_{12} & |x_{13}^7| \le U_{13} & |x_{24}^7| \le U_{24} & |x_{34}^7| \le U_{34} \\
|x_{35}^7| \le U_{35} & |x_{46}^7| \le U_{46} & |x_{56}^7| \le U_{56} &
\end{array}
$$

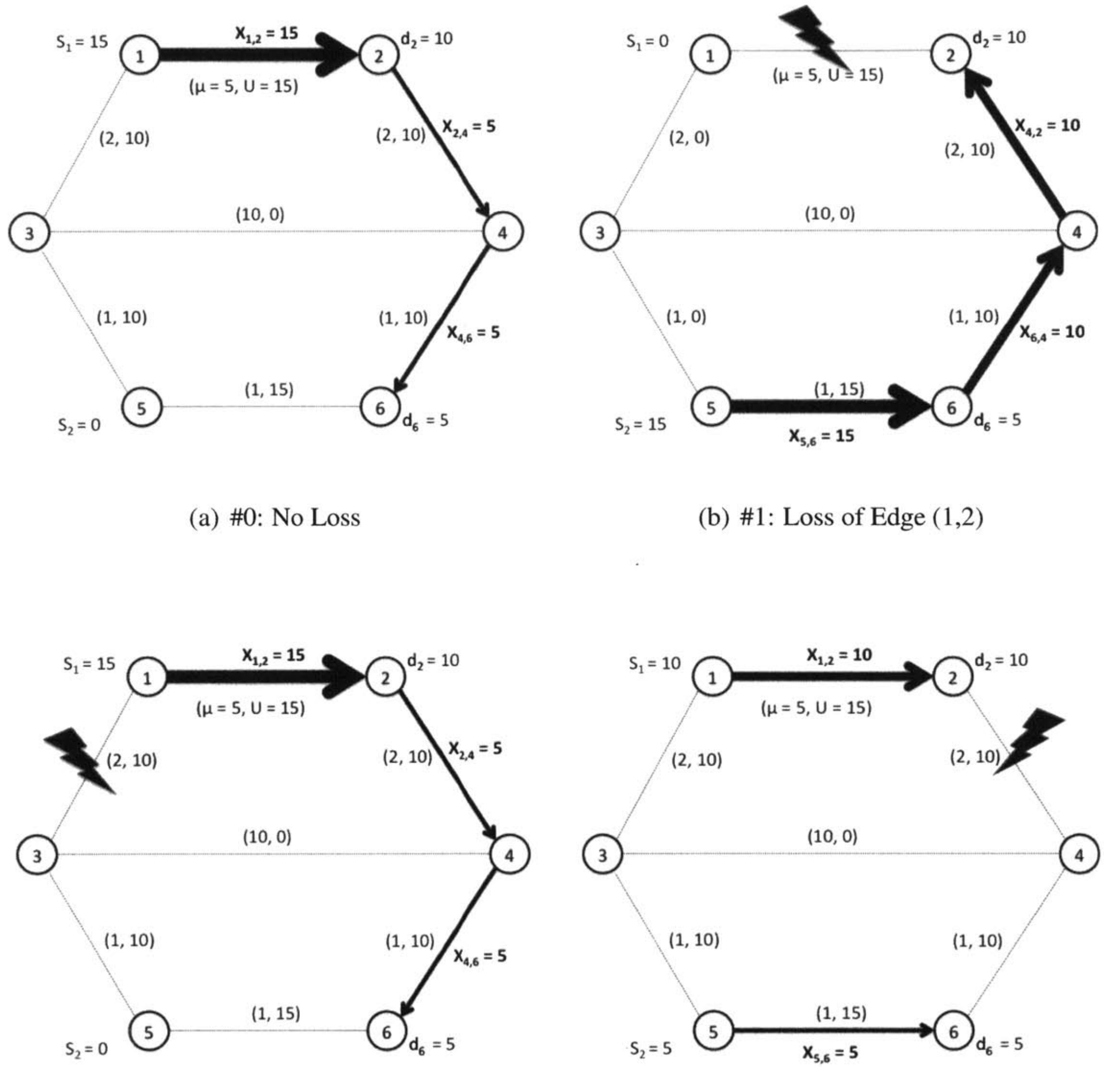
Bounds:

$$
\begin{array}{lll}
-\infty \le x_{12}^0 \le \infty & -\infty \le x_{13}^0 \le \infty & -\infty \le x_{24}^0 \le \infty \\
-\infty \le x_{34}^0 \le \infty & -\infty \le x_{35}^0 \le \infty & -\infty \le x_{46}^0 \le \infty \\
 & -\infty \le x_{56}^0 \le \infty & \\
\vdots & \vdots & \vdots \\
-\infty \le x_{12}^7 \le \infty & -\infty \le x_{13}^7 \le \infty & -\infty \le x_{24}^7 \le \infty \\
-\infty \le x_{34}^7 \le \infty & -\infty \le x_{35}^7 \le \infty & -\infty \le x_{46}^7 \le \infty \\
 & -\infty \le x_{56}^7 \le \infty &
\end{array}
$$

Casualty & Operating Conditions:

$$
\begin{array}{llll}
x_{12}^1 = 0 & x_{13}^2 = 0 & x_{24}^3 = 0 & x_{34}^4 = 0 \\
x_{45}^5 = 0 & x_{46}^6 = 0 & x_{56}^7 = 0 & \\
b_1^0 \ge 0 & b_2^0 = -10 & b_3^0 = 0 & b_4^0 = 0 \\
b_5^0 \ge 0 & b_6^0 = -5 & & \\
\vdots & \vdots & \vdots & \\
b_1^7 \ge 0 & b_2^7 = -10 & b_3^7 = 0 & b_4^7 = 0 \\
b_5^7 \ge 0 & b_6^7 = -5 & &
\end{array}
$$

Table 2.9: NSMCF Formulation - M-1 Survivability



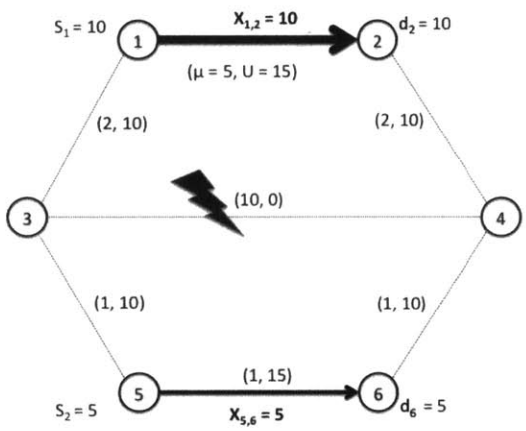
(a) #0: No Loss

(b) #1: Loss of Edge (1,2)

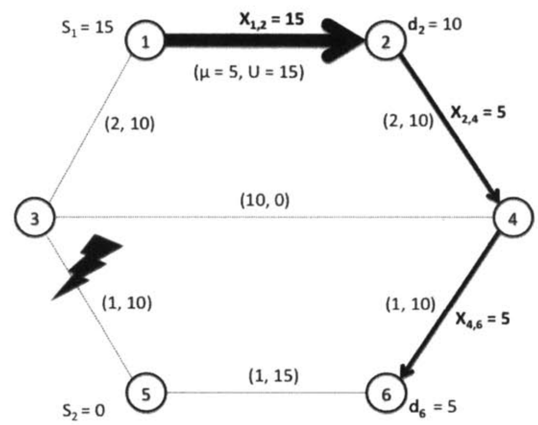
(c) #2: Loss of Edge (1,3)

(d) #3: Loss of Edge (2,4)

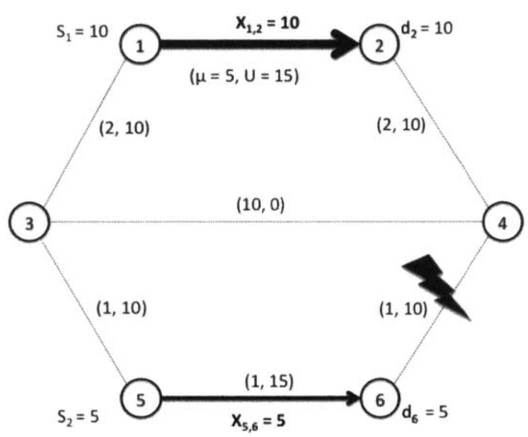
Figure 2-7: NSMCF M-1 Survivable Optimization Flows #0 - #3



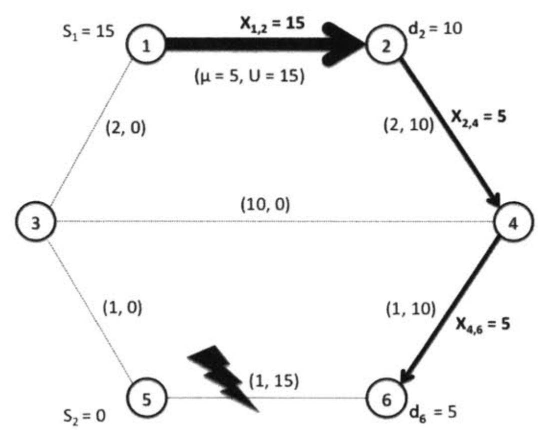
(a) #4: Loss of Edge (3,4)



(b) #5: Loss of Edge (3,5)



(c) #6: Loss of Edge (4,6)



(d) #7: Loss of Edge (5,6)

Figure 2-8: NSMCF M-1 Survivable Optimization Flows #4 - #7 to the minimum capacity M-1 survivability optimization problem. For each casualty & operating condition shown in the subfigures, the solver has "chosen" a feasible flow solution that satisfies all the constraints of the formulation. It cannot be said that any flow solution chosen by the solver shown in Figures 2-7 and 2-8 is an optimal flow reconfiguration. The solver is minimizing total capacity of the flow network, so any flow configurations that support the minimum overall capacity are possible solutions to the flow variables. Figure 2-7(a) shows the value of the flow variables for the case when there is no loss of any edge in the system. This case is annotated as $k = 0$; where k is in the set K of all casualty and operating conditions applied to the network. Note that in Figure 2-7(a) all the demands are met; $d_2^0 = 10$, and that it is conceivable to meet this flow condition another way: $x_{12}^0 = 10$, $x_{56}^0 = 5$ and all other $x_{ij}^k = 0$. Since the cost c_{ij} associated with capacity U_{ij} is indirectly related to flow, it could be said that the alternate flow solution for $k = 0$ would be less costly than the one shown in Figure 2-7(a). This is immaterial, however because (1) the cost in the optimization is not the cost of flow, it is the cost of capacity, and (2) the flow solution in the $k = 0$ case is only part of the overall optimization. The flow solution for an individual casualty and operating condition supports the global capacity minimization although it may represent a local minimum. Note that the flow values in Figure 2-7(a) are less than or equal to the capacity solution in Figure 2-9. From surveying all the flow solutions in Figures 2-7 and 2-8, it can be seen that the flow values are all less than or equal to the minimum capacity solution in Figure 2-9.

Figure 2-9 shows the optimized (minimized) capacities for the edges in the NSMCF M-1 survivable network. This network design will survive the loss of all edges any one at a time and will meet all casualty and operating conditions. Note that edges $(1,3)$, $(3,4)$ and $(5,6)$ have zero capacity and therefore are not needed in the network. If the network were in the early stage design process, and M-1 was the required survivability of the network, edges $(1,3)$, $(3,4)$ and $(5,6)$ and node 3 could be deleted from the final design, saving cost. The network solution shown in Figure 2-9 is the minimum cost network for M-1 survivability requirement.

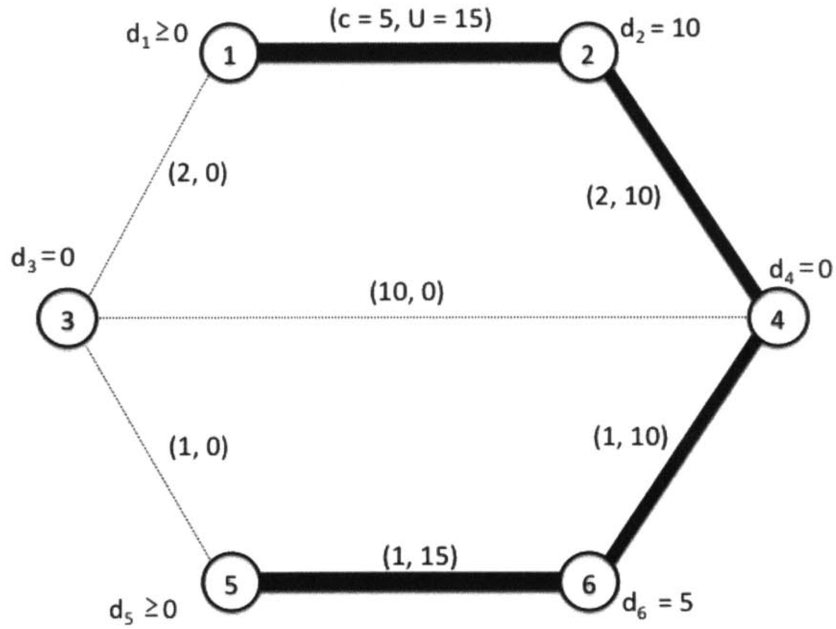


Figure 2-9: NSMCF M-1 Survivability Example Solution

2.5 Conclusion

Network flow optimization (NFO) takes on many forms and has many applications. In this chapter, a tutorial given, leading from the most simple application of linear programming (LP) NFO to mulitcommodity flow (MCF), and finally to an example of perhaps one of the most complex variations of NFO, the non-simultaneous multicommodity flow (NSMCF) formulation. This was necessary due to the fact that NSMCF is not an intuitive variation of MCF and there is value in the reader or potential user of NSMCF to understand the major differences between MCF and NSMCF. The main difference being that non-simultaneous multicommodity flow (NSMCF), in spite of its name, is not usually (and not in the application of this thesis) considering different types of commodity flows. Rather, the different "commodities" in application are actually unique flow conditions. This enables the designer to model unique casualty and operating conditions and to rollup into global capacity variables the minimum network edge capacities. This approach allows for the direct, simultaneous design of a minimum cost, survivable network.

Chapter 3

IEP Modeling in NSMCF Formulation

Shipboard integrated engineering plant (IEP) concept design is currently performed starting with historically survivable topologies and verifying that loads are supplied with a certain minimum redundancy. Then, the designer evaluates the system using survivability, reliability and quality of power metrics [25], [22], [23], [13]. In addition to survivable design efforts, there is also current work in the area of optimal reconfiguration following a casualty [13], [17], [11]. In this thesis, an alternative design optimization approach is proposed that allows the survivability specifications to be input in the front-end of the design process so there is no excess redundancy (cost) built into the system. A specific network topology can be assumed, or as many possible edge candidates between nodes representative of generators, load centers, loads, pump/heat exchangers, and coolers is allowed. The survivability metrics are inserted into the network optimization formulation in the form of constraints describing loss of flow between applicable nodes or complete loss of nodes. Individual electrical loads can also be specified unique to operating conditions. These constraints represent casualty or operating conditions that need to be survived or supported, respectively, by the IEP. This network optimization approach for survivability is in the family of "non-simultaneous multicommodity flow" (NSMCF) problems [36] and lends itself well to the design optimization of a survivable network such as an IEP.

The optimization solver used for this work is IBM CPLEX®. The programming language used to create the CPLEX input file is Matlab® script. The CPLEX input file is written in the CPLEX linear programming file format [15]. The output graphics shown in this thesis are created using Matlab script.

3.1 Current Uses of NSMCF

Non-simultaneous multicommodity flow (NSMCF) is used in survivable communication and transportation network design [29], [54]. It is an extension of the MCF problem where the problem size is enlarged to treat each casualty condition as a single commodity flow problem, but in the case of NSMCF, the capacity of each edge of the network becomes a decision variable to be minimized. The global minimum capacity of each edge is captured as the maximum flow required for the system to operate under all casualty conditions (commodities). Current work in the field is the addition of detail and complexity to the formulation and also development of solver algorithms [50], [48], [45]. The output of the solver, the capacities for all the lines become the design specifications. Some of the line capacities may be zero, which means those cables (or pipes) are unnecessary. The extra capacity that is built into the lines during the optimization (above that which is required for normal operation) is called the reserve capacity and the extra capacity can be treated as a supplemental network and is then referred to as the reserve network [33]. In a non-simultaneous multicommodity flow (NSMCF) problem, blocks (or sets) of constraints are formulated using casualty conditions. The continuity and the capacity equations are identical, except for the use of unique variables to describe each casualty condition (See Section 3.9). In the formulation, each set of constraints represents the system with the loss of any desired combination of nodes or edges. The non-simultaneous multicommodity flow (NSMCF) framework treats each casualty condition as a commodity flow problem and minimizes the cost (weighted capacity) of the edges. This results in the minimum cost survivable network. In other words, the algorithm solution is the minimum cost system that continues to supply all required loads for all casualty and operating conditions.

3.2 The Role of the Designer in Optimization

The challenge for the engineer or designer using any mathematical optimization technique is to develop the formulation to reflect the physics of the problem, the constraints that govern the desired optimization, and the relevant objective function in such a way that it suits the format and function of the available solver. In addition, in the application of mathematical optimization to real-world problems, there is often a need for non-intuitive "tricks" to aid in obtaining the correct behavior of the solver when modeling nonlinear or discrete (integer or binary) physical properties. An example of this is the use of binary variables shown in Equations 3.13 and 3.14. This chapter explains the basic physical modeling of the IEP using NSMCF with modifications to allow the solver to optimize the design problem.

3.3 Simplifying Assumptions

In this thesis, a notional integrated engineering plant (IEP) is modeled. Included in the model are two domains: electrical and thermal (cooling) systems. Components that are modeled are: electrical generators, distribution lines, loads, load centers, AC/DC converters, propulsion motors, stored energy, seawater and freshwater cooling pumps, piping runs, heat exchangers and coolers. The units of flow in the electrical system are power (MW or kW) and the units of flow used in the cooling system are mass (kg/sec).

Electrical Power Flow Energy Losses

A main assumption in this work is that the flow energy losses are negligible due to the shipboard scale system. Lossless electrical distribution allows for the modeling of power flow and greatly simplifies the problem. If losses are considered, the model would need to account for the electrical physics and the flow variable would be electrical current. The formulation would be nonlinear and convex optimization or heuristic techniques would be used that could be significantly more computationally expensive and may not suit early-stage design.

To show the relative magnitude of expected losses in a cable, consider a copper 0000

Cable Resistivity	0.1608Ω/km
Length of Cable	100m
Total Resistivity	0.1608Ω/km (0.1km) = 0.01608Ω
Max Current	230A
Losses	$P_{loss} = I^2R = (230\text{A})^2(0.01608\Omega) = 850\text{W}$
Voltage	1000VDC
Max Power	P_{max} =VI= 1000VDC (230A)= 230kW
Loss %	P_{loss}/P_{max} = 850W/230kW = 0.00369 = 0.37%

Table 3.1: Negligible Electrical Power Flow Losses Assumption Justification

gage conductor. For a shipboard system, assume a reasonable cable length to be 100m (0.1km). The ampacity of a 0000 gage cable is 230A. For a medium voltage DC (MVDC) system such as the Naval Combat Survivability Testbed (NCST), a standard voltage is 1000V. As shown in Table 3.1, the losses experienced in a MVDC cable that is 100m long will experience approximately 0.37% electrical power loss. This is a negligible loss of power for early-stage design purposes. If the designer feels that it is important to account for electrical power losses, they can implement a very small (linear) design margin.

Additionally, for the MVDC plant, power generally goes through generation, rectification (AC to DC) and then inversion (DC to AC) before being consumed by the load. For a typical rectifier, or power supply, the efficiency is approximately 90%; similarly 90% efficiency for inversion devices [53]. The 10% loss at each conversion (approximately 20% total) is so much greater than the cable loss that it is not reasonable to include the cable loss solely for the sake of model accuracy.

Conductor Ampacity vs. Cross-Sectional Area

The relationship between maximum current flow and conductor cross-sectional area is assumed to be linear. This assumption allows the variable cost coefficients to be constants and the objective to be a linear expression. This assumption is good for this early-stage design application.

Cooling Mass Flow Energy Losses

Similarly, for the cooling plant, hydraulic friction losses are neglected for the same reason (shipboard scale and early-stage design) as the neglecting of losses in the electric plant. Shipboard cooling systems are limited to lower velocities (2.5-3.6 m/s [38]) than the pipe is capable of carrying to reduce corrosion and erosion. For this velocity range, the hydraulic friction head loss, and therefore mass flow rate power loss is on the order of 1.5% [43]. Again, if the designer finds that this is unacceptable, a small linear approximation margin can be added to the model to ensure capacities are not under-designed. Also, the purpose of the mass flow of coolant is to deliver it to the heat exchangers in the system, which, by design, have large surface area and large hydraulic friction losses. The entire system hydraulic friction losses are indirectly accounted for in the system coefficient $\mathscr{K}$, estimated and used in the pump power constitutive law (see Section 3.8.5).

Cooling Piping Maximum Flow vs. Cross-Sectional Flow Area

The relationship between maximum cooling piping flow and cross-sectional flow area is considered to be linear. This neglects hydraulic friction and assumes the velocity of the fluid is uniform throughout the cross-section of flow. For the purpose of early-stage design, and in light of the small shipboard scale, this assumption is satisfactorily used.

Cooling System Characteristic

Also neglected are changes in flow resistance experienced by the pumps (changes in system coefficent, $\mathscr{K}_{sys}$) due to changes from the starting cooling plant candidate topology to final optimized design configuration. In general the system coefficient will have minor changes for a small scale plant and due to the fact that the cooling pumps' power is a small fraction of the total system power, the affect on the solution is insignificant. Also, the important feature in the model is that the cooling system is interdependent with the electric plant and this is enough to capture the desired model features.

3.4 Design Optimization Approaches

It is important to note that there are at least three different approaches that can be used for design with the non-simultaneous multicommodity flow (NSMCF) optimization method proposed in this thesis. Depending on the designer's need, the NSMCF method offers flexibility by adding constraints to the formulation to maintain certain elements of the model as "given" or "free." The designer is also able to free the solver to choose any possible topology, which could further minimize the overall capacity of the network.

3.4.1 Approach #1: "Given Topology" Input

The first design approach is illustrated in Figures 3-1 and 3-2. This approach starts with a "candidate" integrated engineering plant (IEP) that is made up entirely of edges that are mandatory. The illustrations of network flow used in this chapter are simple examples, but a more practical example of the need for approach #1 is if the designer specified a ring bus ZED topology. This could be for the case where a design objective is to accomodate ease of operation and there is no desire to deviate from a symmetric plant as would be the case if the solver had freedom to "delete" edges. The function of the solver in this case would be to find the minimum capacities of the given edges considering all casualty and operating conditions. One way this approach would be implemented in the formulation is the designer could assign a minimum value to the capacity variables. A disadvantage to this approach is that limiting the solver in any way will limit the solver from finding a lower capacity plant that would be possible with all edges free for consideration as to their existence. The optimal solution for this approach is shown in Figure 3-2. Note that all edges have been given a nonzero capacity by the solver.

3.4.2 Approach #2: "Free Topology" Input

The second approach can be used if there are no design limitations to the network topology. The designer can start with any number of candidate edges. As shown in Figures 3-3 and 3-4, the extreme case of a complete graph, in which every node is connected to every other node, can be the design input. Since as explained in the previous paragraph, the solver

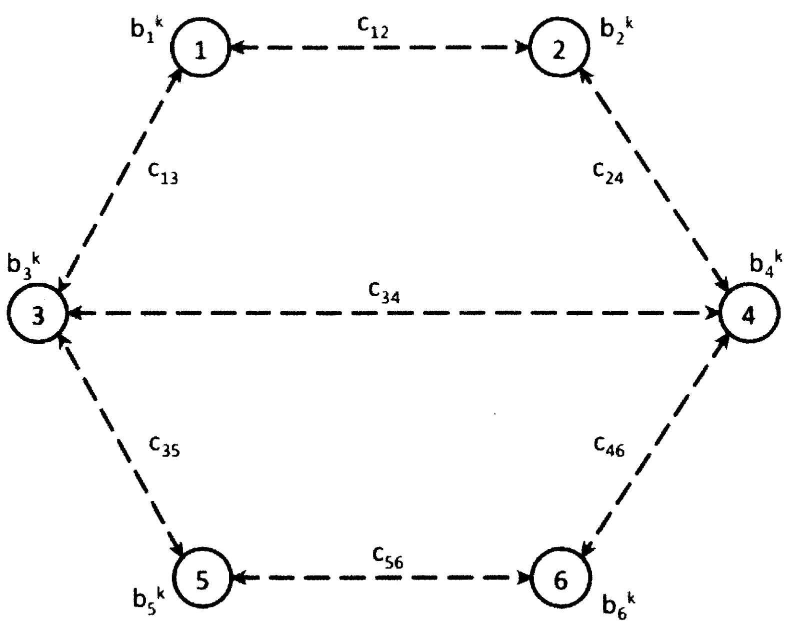


Figure 3-1: IEP "Given Topology"

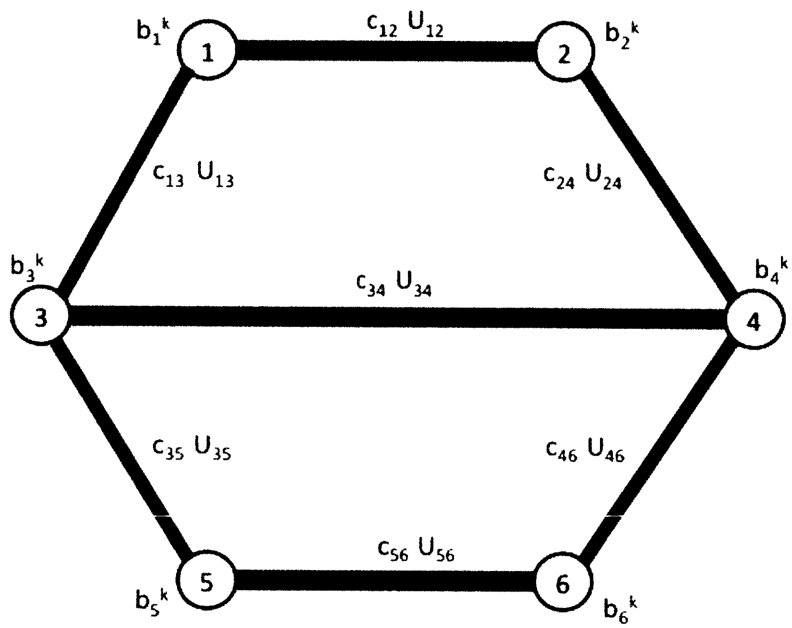


Figure 3-2: IEP "Given Topology" Solution

has the ability to zero the capacity of any edge that is unnecessary, this approach offers the advantage that it allows the solver the greatest flexibility in optimization. For identical design problems (the same demands and casualty and operating conditions), the second approach will likely result in a lower capacity network due to the fact that the solver can choose from any reconfiguration possible for all the unique flow conditions. A network that has been designed to survive a set of casualty conditions based on an arbitrary number of candidate edges is referred to as a mesh restorable network [29]. One disadvantage to this approach is that the design solution topology may be unsymmetrical and does not support ease of operation. This disadvantage can be counteracted if plant control is intended to be automated. Another disadvantage is the solution can be expensive computationally due to the size of the problem when starting with a complete graph. The continuity equations at each node, for example, contain a variable for each edge flow. Scalability of this design approach can become problematic as the number of edges grows polynomially with added nodes (see Appendix A for scalability discussion). The continuity equations at each node include the flow variable for every edge in the system.

The design output shown in Figure 3-3 included 30 edges, while the design output shown in Figure 3-4 only includes 6 edges. This reduction reflects the cost savings that can be achieved through the proposed optimization method.

Only the different approaches and not the exact design results are intended to be compared, as results of the approaches will depend on the casualty and operating conditions for each design problem. In general, the more extensive and complex the casualty and operating conditions specifications, results in a more robust design, with the more edges and higher capacities (cost).

3.4.3 Approach #3: "Given-Free Topology" Combined Input

A third approach is a combination of approach #1 and approach #2. Some of the edges can be given and the rest can be free. Any number of free and given edges can be used for the design input. This approach could be used for the case where the designer is modifying an existing IEP, or for some other reason, edges are desired to be fixed.

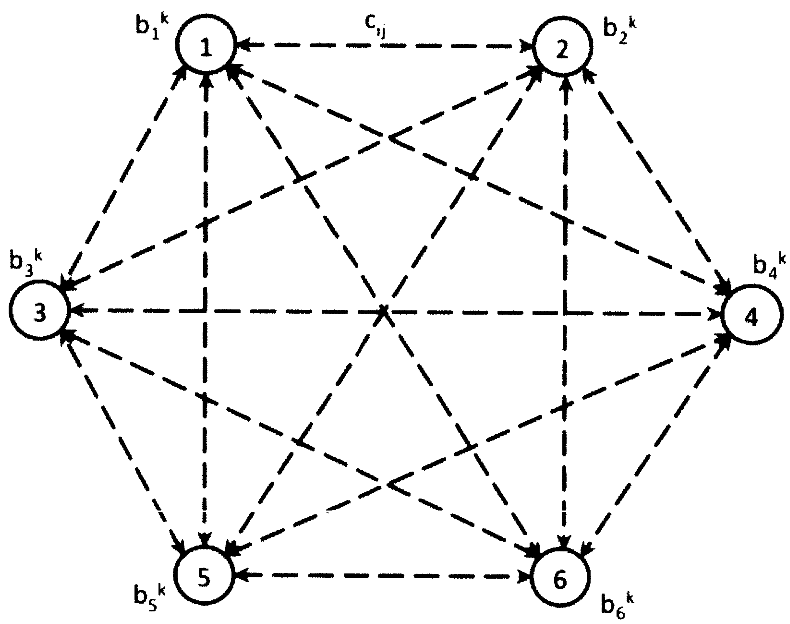


Figure 3-3: IEP "Free Topology"

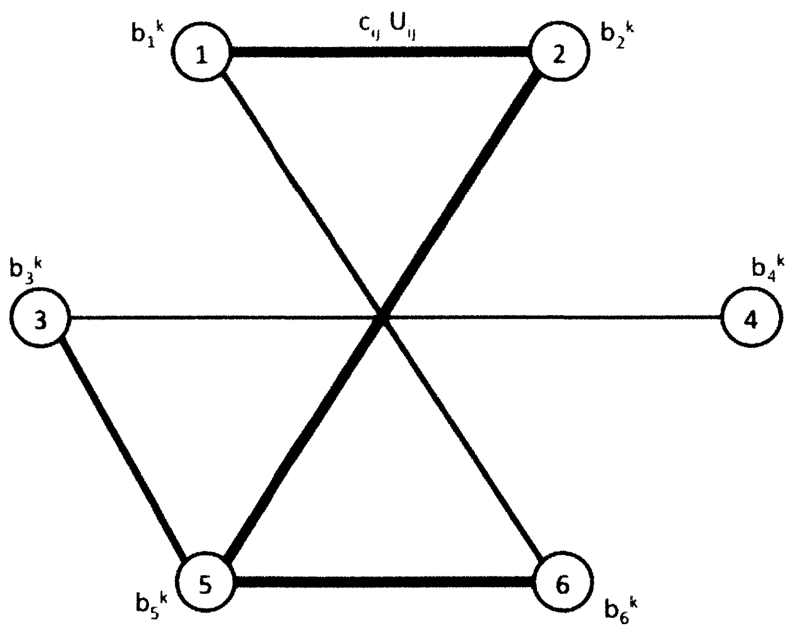


Figure 3-4: IEP "Free Topology" Solution

3.4.4 Accuracy vs. Computational Expense

There are many approaches to simulation, modeling, design and optimization of systems. There are various levels of detail and accuracy commensurate with the necessity of accuracy, stage of the design process and computational cost (speed) of calculation. Figure 3-5 illustrates the tradespace. There is a tradeoff between accuracy and computational expense of both the model and the casualties and operating conditions. The non-simultaneous multicommodity flow (NSMCF) is an improvement over the current indirect method of casualty simulation for three reasons. First, non-simultaneous multicommodity flow (NSMCF) can be adapted to capture the casualties of the traditional simulation method so there need not be any lost accuracy to the survivability specifications of the design. Second, the NSMCF is using LP optimization algorithms which provide a guaranteed global minimum solution, unlike iterative or heuristic techniques. Third, the NSMCF will be exact (within the accuracy of the models) where other traditional methods may be approximations. The NSCMF method can also be refined to reflect more detail, with careful development of constraints. The method could possibly be used in the detail design phase of acquistion (see Section 6.2 for proposed future work).

3.5 NSMCF Formulation

In this section, the non-simultaneous multicommodity flow (NSMCF) formulation is presented in canonical form. Some of the features of the formulation have not been discussed yet, including fixed costs of edges in the system, linear approximation to the pump power curves, constitutive relations between physical domains, generator cooling power limits, M-1 survivability and the handling of stored energy. The NSMCF formulation is presented and an explanation is given of the terms with reference to follow-on sections explaining the modeling approach.

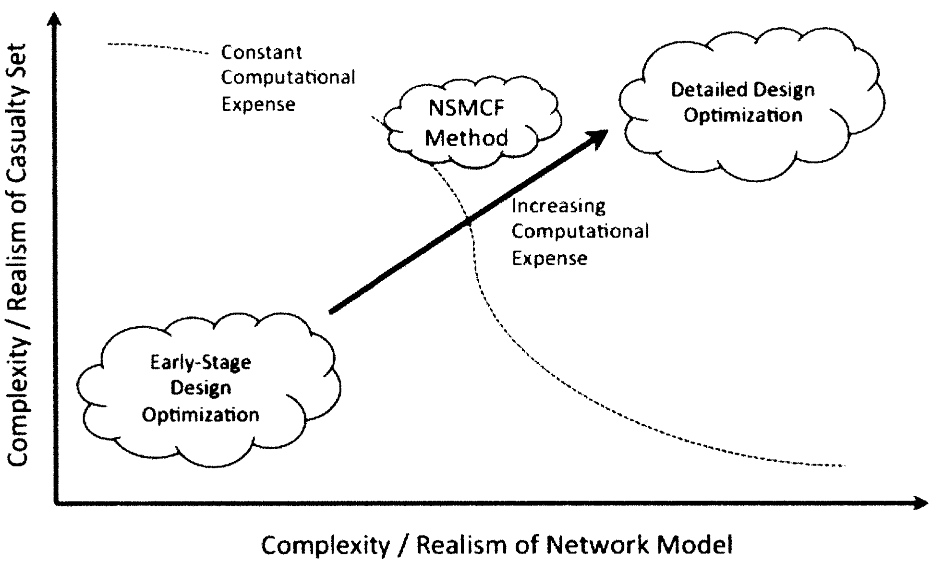


Figure 3-5: Accuracy of Model & Computational Expense Tradespace

(Section 3.4.4)

3.5.1 Dual Domain with M-1 Survivability

Problem Statement & Setup

The problem statement for NSMCF application to an integrated engineering plant (IEP) design is as follows:

> Design a dual domain integrated engineering plant topology that demonstrates M-1 survivability. Minimize the power and mass flow capacity of the edges of the electric and cooling plants (respectively). Take into account and minimize stored electrical energy.

Consider two interdependent networks described by node indices set N and edge indices set E. $\Psi = (N_e, E_e)$ is an electrical power flow network and $\Gamma = (N_t, E_t)$ is a thermal cooling mass flow network. The formulation is shown in Table 3.2. N_{se} (Expression 3.1 is the set of nodes that are electrical stored energy devices). N_r (Expression 3.8) is the set of nodes that are redundant (i.e. propulsion motors).

$$\text{minimize: } \sum_{(i,j)\in E_e} a_{ij}F_{ij} + \pi_{ij}P_{ij} + \sum_{(l,m)\in E_t} b_{lm}G_{lm} + \theta_{lm}Q_{lm} + \sum_{n\in N_{se}} \zeta_n d_n^k \tag{3.1}$$

$$\text{subject to: } \sum_{j:(i,j)\in E_e} p_{ij}^k = d_i^k \qquad i,j \in N_e k \in K \tag{3.2}$$

$$\sum_{m:(l,m)\in E_t} q_{lm}^k = g_l^k \qquad l,m \in N_t k \in K \tag{3.3}$$

and:

$$|p_{ij}^k| \leq P_{ij} \qquad (i,j) \in E_e \qquad k \in K \tag{3.4}$$

$$|q_{lm}^k| \leq Q_{lm} \qquad (l,m) \in E_t \qquad k \in K \tag{3.5}$$

$$q_{lm}^k \geq \beta_j d_j^k \qquad (l,m) \in E_t \qquad j \in N_e \quad j,(l,m) \in H \quad k \in K \tag{3.6}$$

$$d_i^k \geq \alpha_j \left(q_{lm}^k\right)^3 (lin.app.) \qquad i \in N_e \quad (l,m) \in N_t \quad i,(l,m) \in S \quad k \in K \tag{3.7}$$

$$d_i^k + d_j^k \geq \mathscr{D}^k \qquad i,j \in N_r \qquad k \in K \tag{3.8}$$

$$p_{me}^k = 0 \qquad me \in M_e \tag{3.9}$$

$$q_{mc}^k = 0 \qquad mc \in M_c \tag{3.10}$$

For M-1 survivability, take the set of all edges and set flow equal to zero (one at a time) distinguished by $k \in K$ ($p_{ij}^k = 0$ and $q_{lm}^k = 0$).

Table 3.2: NSMCF Formulation - Dual Domain with Full Features

3.5.2 Description of Variables

The following description of variables refers to the NSMCF formulation in Table 3.2:

- Used in the Objective (3.1):

  $a_{ij} \in \{0,1\}$ is the binary variable that allows selection and deselection of electrical edge $(i,j) \in E_e$ for the fixed cost feature (See discussion of Fixed Cost in Section 3.6.3).

F_{ij} is the fixed cost associated with electrical edge $(i,j) \in E_e$ (Section 3.6.3).

$b_{lm} \in \{0,1\}$ is the binary variable that allows selection and deselection of thermal edge $(l,m) \in E_t$ for the fixed cost feature (Section 3.6.3).

G_{lm} is the fixed cost associated with thermal edge $(l,m) \in E_t$ (Section 3.6.3).

π_{ij} is the variable cost coefficient for electrical edge $(i,j) \in E_e$ (See Section on Variable Cost 3.6.2).

θ_{lm} is the variable cost coefficient for thermal edge $(l,m) \in E_t$ (Section 3.6.2).

P_{ij} is the capacity of electrical edge $(i,j) \in E_e$ (Section 3.6.2).

Q_{lm} is the capacity of thermal edge $(l,m) \in E_t$ (See Section 3.6.2).

$\zeta_n \quad n \in N_{se}$ is the cost weighting factor for stored energy power flow (See Sections 3.6.1 and 3.7.5).

- K is the set of indices k of casualty and operating conditions.

- p_{ij}^k is the power flow in electrical edge $(i,j) \in E_e$ for casualty k

- d_i^k (3.2) is the electrical power demand (or generation) for each node (designer input). This is used to satisfy the continuity equations. A unique variable exists to accomodate each casualty and operating condition. d_n^k is the stored energy power flow for each electrical node which represents a stored energy device.

- q_{lm}^k is the cooling mass flow in thermal edge $(l,m) \in E_t$ for casualty k

- H (3.6) is the set of paired indices of cooled electrical power nodes and their corresponding pumps / heat exchangers.

- β (3.6) is the proportional constant and conversion factor between electrical supply / load power and thermal removal demand.

- α (3.7) is the proportional constant and conversion factor between electrical heat load and pump power required.

- S (3.7) is the set of paired indices of powered thermal pump / hx nodes and their corresponding electrical power supply nodes.

- For the electrical continuity constraint equation (3.2), $p_{ij} > 0$ (i receiving node) $p_{ij} < 0$ (i sending node)

- For the thermal continuity constraint equation (3.3), $q_{ij} > 0$ (i receiving node) $q_{ij} < 0$ (i sending node)

- $\mathscr{D}^k$ (3.8) is the combined limit for a redundant load requirement. For example, in Equation 3.8, $\mathscr{D}^k$ is the total propulsion power required by the ship. See Section 3.7.3 for more discussion.

- M_e (3.9) is the set of casualty edges in the electric plant

- M_c (3.10) is the set of casualty edges in the cooling plant

In the non-simultaneous multicommodity flow (NSMCF) formulation (Table 3.2), the objective, (3.1), shows that the cost of both the electrical plant and the cooling plant are being minimized. Factors explained in Section 3.6.2 are used to provide cost weighting to cables and piping by length and other considerations as determined by the designer. Equations (3.2) and (3.3) represent the continuity constraints for each node in the system. The net sum of flows must equal the supply and demand for each node. Equations (3.4) and (3.5) represent the capture of the maximum flow for all casualty and operating condition flow situations into the global capacity variable for each cable and pipe. The sum of the global variables for each edge cost is minimized in the objective as stated above. The casualty conditions are specified by adding constraints that set an edge flow to zero (loss of an edge) or all flows adjacent to a node to zero (loss of a node). Other casualty or operating conditions can be specified by the addition of appropriate constraints. The solution of the optimization shows the minimum capacity integrated engineering plant (IEP) that can survive the specified casualties (and support desired operating conditions).

3.6 Cost Function (Objective)

The cost function, or objective is the expression that is being minimized by the solver subject to all the constraints of the formulation. The cost function for the non-simultaneous multicommodity flow (NSMCF) formulation is shown in canonical form in Expression 3.1 in Table 3.2. In the NSMCF IEP optimization formulation presented in this thesis, there are 3 distinct elements in the cost function. These are listed below with references to the sections that discuss them.

The **variable costs** are those costs related (linearly) to the capacity of each of the edges of the dual domain network. The edges in this case are the electrical cabling (with power flow capacity) and the cooling piping (with mass flow capacity). Variable cost modeling of the edges is described in more detail in Section 3.6.2.

The **fixed costs** are those costs associated only with the existence of each of the edges of the dual domain network. Fixed cost is described in more detail in Section 3.6.3.

The **stored energy power flow cost** is that cost associated with the power flow out of a stored energy device. This cost element is used as a tool to sufficiently "penalize" the solver for using stored energy. If the cost coefficient is too low, the solver may find it less expensive to use the stored energy for normal operations. Stored energy power flow cost is described in more detail in Section 3.7.5.

3.6.1 Cost Function Solver Dynamics

The solver, when minimizing on cost for the non-simultaneous multicommodity flow (NSMCF) formulation described in this thesis, will find in the design space the minimum overall capacity of the dual domain plant. The fixed costs and variable costs of both domains are taken into account. The higher the relative magnitude of the fixed costs compared to the variable costs, the solver will find a minimum capacity network that will exclude more edges (deselect the edges using the binary variable associated with each). The extent that the solver can reduce the number of edges depends on the number and complexity of the casualty and operating conditions. More extensive casualty and operating conditions will require the plant to have more redundancy to survive. The solver will not violate any constraints in finding a feasible solution, and the constraints include powering and cooling all required loads. Because of the interdependence of the electrical and cooling domains, the solver may exclude branches of the network from both domains, if possible.

The stored energy power flow cost, if set appropriately high, will not affect the minimization of the dual domain network. The stored energy power flow cost is not used as a true material cost as are the variable and fixed costs of the dual domain network. The stored energy power flow cost works as a tool to ensure that stored energy is only used to power required electrical loads when all normal power to the bus is lost, usually for a casualty when all lines leading to a required load are lost and there is a stored energy device on the bus available to power the load. To obtain the dollar value for the optimized network, the designer will need to subtract out the artificial cost of the stored energy power flow from the final objective value. The modeling of stored energy for this application is discussed in more detail in Section 3.7.5.

3.6.2 Variable Cost Edge Modeling

Variable costs are those associated with the cost of capacity of the edges in the system (electrical cable and cooling piping). The cost is assumed to be linearly proportional to the capacity of the edge. As shown in the objective (Expression 3.1), the constants of proportionality are π_{ij} (electrical) and θ_{ij} (thermal). These constants are determined by the designer. The most obvious factor that would go into a selection for these constants is the material cost related to the increasing capacity of the edges. The diameter (gage) of the electrical cabling, for example, is roughly proportional to the power flow capacity of the cable (given the same conducting material). The cost coefficient could include a factor for the length of the cable, which should be known or can be closely estimated by the early-stage design ship dimensions.

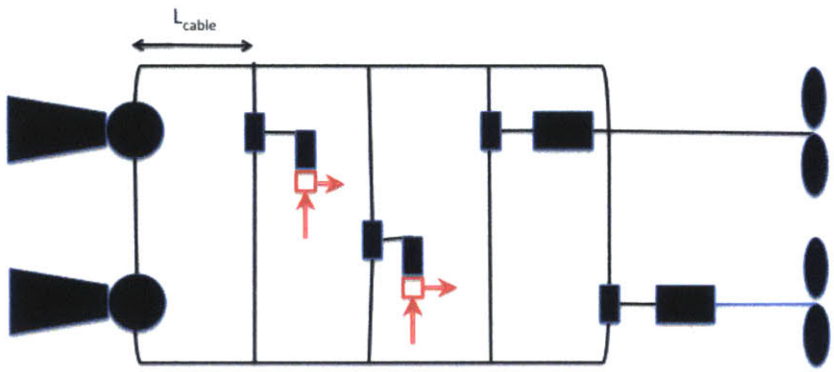


Figure 3-6: Electric Plant Cable Length

Figure 3-7: Electric Plant Cable Cross Section

(Skycraft Surplus)

Electrical Edge Variable Cost

$$\pi_{ij} = \frac{\$_{ij}}{P_{ij}}$$
$$k_V = \frac{\$_{ij}}{V_{ij}}$$
$$k_P = \frac{P_{ij}}{A_{ij}}$$
$$\frac{V_{ij}}{A_{ij}} = L_{ij}$$
$$\pi_{ij} = \frac{k_V}{k_P} L_{ij}$$

Table 3.3: Derivation of Electrical Edge Variable Cost Coefficient

- π_{ij} is the cost in dollars per unit power flow capacity of conductor (i, j).
- $\$_{ij}$ is the cost in dollars of conductor (i, j).
- P_{ij} is the power flow capacity of conductor (i, j)
- V_{ij} is the material volume of the conductor (i, j).
- A_{ij} is the cross-sectional area of the conductor (i, j).
- k_V is the cost per unit volume of the conductor (i, j).
- L_{ij} is the length of the conductor (i, j).
- k_P is the maximum power flow per unit cross sectional area of the conductor (for given voltage).

Vendor pricing for marine power cable is usually given in cost per unit length for a specific gage cable. When calculating the dollars per power flow capacity, the cost per unit length can be used as-is. The power flow capacity of the cable can be calculated by multiplying the ampacity with the voltage of the cable. Dividing the cost per unit length by the ampacity times the voltage gives the variable cost coefficient per unit length. This assumes that the ampacity is linearly related to the cross-sectional area of conductor (a good assumption for early-stage design). Example: A manufacturer quote for a conductor that has power flow capacity of 720 kW and has cost \$110.50 per meter. The variable cost per meter per unit power flow capacity of the cable is shown:

$$\pi_{ij} = \frac{\$110.50/m}{720\ kW} L_{ij} = \frac{\$0.1535}{kW\ m} L_{ij}$$

Each cable's length is substituted for L_{ij} and π_{ij} gives the cost per unit power flow capacity.

Cooling Edge Variable Cost

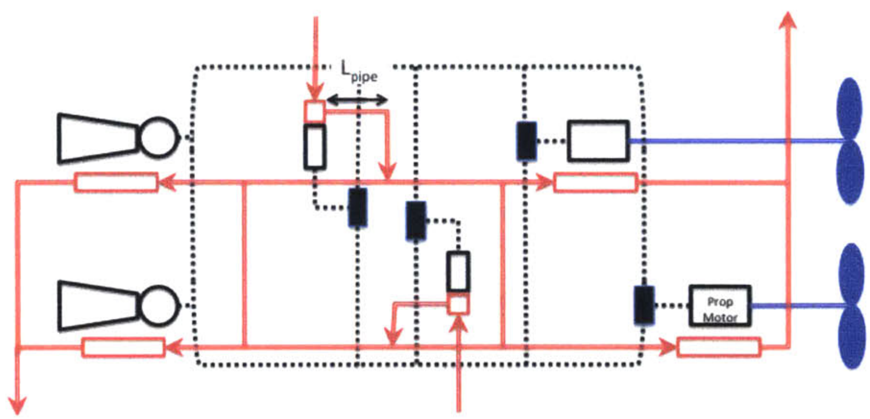


Figure 3-8: Cooling Plant Piping Length

- θ_{lm} is the cost in dollars per unit mass flow rate capacity of pipe (l,m).
- $\$_{lm}$ is the cost in dollars of pipe (l,m).
- Q_{lm} is the mass flow rate capacity of pipe (l,m)
- V_{lm} is the flow volume of the pipe (l,m) (length times cross-sectional flow area).

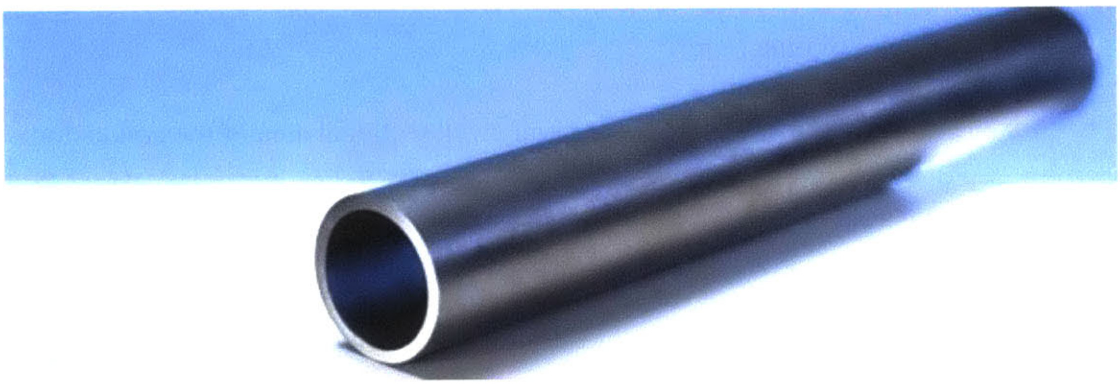


Figure 3-9: Cooling Plant Piping Cross Section

(Vishal Steel)

$$
\begin{aligned}
\theta_{lm} &= \frac{\$_{lm}}{Q_{lm}} \\
k_X &= \frac{\$_{lm}}{V_{lm}} \\
k_M &= \frac{\rho_w \vec{V}_{max}}{A_{lm}} \\
\frac{V_{lm}}{A_{lm}} &= L_{lm} \\
\theta_{lm} &= \frac{k_X}{k_M} L_{lm}
\end{aligned}
\tag{3.11}
$$

Table 3.4: Derivation of Cooling Edge Variable Cost Coefficient

- A_{lm} is the cross-sectional flow area of pipe (l,m).
- k_X is the cost per unit flow volume of pipe (l,m).
- L_{lm} is the length of pipe (l,m).
- k_M is the maximum mass flow rate per unit cross sectional area of the conductor.
- ρ_w is the density of the cooling fluid (water).
- $\vec{V}_{max}$ is the maximum design velocity of the cooling fluid.

Vendor pricing for piping is usually given in cost per unit length for a specific size and wall thickness. When calculating the dollars per mass flow rate capacity, the cost per unit length can be used as-is. The mass flow rate capacity of the cable can be calculated by multiplying $\rho_w\,\vec{V}_{max}\,A_{lm}$. Dividing the cost per unit length by this flow rate capacity gives the variable cost coefficient per unit length. This assumes that the max flow rate capacity is linearly related to the cross-sectional flow area of pipe (a good assumption for early-stage design). $\vec{V}_{max}$ is a constant defined for minimization of corrosion and erosion wear in cooling piping systems. [38] Example: A manufacturer quote for a pipe that has $A_{lm} = 2.163x10^{-3}\ m^2$, $\rho_w = 1000kg/m^3$, $V_{max} = 2.5\ m/s$, and has cost \$705.47 per meter. Calculate the variable cost per meter per unit mass flow rate capacity of the pipe.

$$\theta_{lm} = \frac{\$705.47/m}{5.4\ kg\ m^2/s} L_{lm} = \frac{\$130.46}{kg\ m/s} L_{lm}$$

3.6.3 Fixed Cost Edge Modeling

The cost of an edge in the distribution system is generally proportional to the capacity of the edge. The constant of proportionality is based on the length of the edge. The cost then becomes a material volume calculation, as discussed in Section 3.6.2. In addition to the cost per unit capacity of these edges, there is also a fixed cost associated with the existence of an edge. The fixed costs are the costs of design, engineering, planning, documentation and installation associated with the edge. It is desirable to minimize the existence of edges if possible to simplify the design and avoid these costs which can be substantially higher than variable (material) costs. Fixed cost can be modeled in the non-simultaneous multi-commodity flow (NSMCF) formulation by the use of binary variables. With the addition of binary variables, the formulation then becomes what is called "mixed integer LP" or MILP. The advantage to using binary in the formulation is that the solver can select and deselect candidate edges to minimize the overall cost of the system. If the fixed cost is modeled accurately, the result has much more cost fidelity than simply minimizing material volume cost of the edges. The graphical representation of total cost including fixed cost of an edge is shown in Figure 3-11(a).

In order to allow the solver to choose whether an edge exists or not, a binary variable is used. The objective, including fixed and variable costs is shown in expression 3.12.

minimize:

$$\sum_{(i,j)\in E_e} a_{ij}F_{ij} + \pi_{ij}P_{ij} + \sum_{(l,m)\in E_t} b_{lm}G_{lm} + \theta_{lm}Q_{lm} \tag{3.12}$$

$$a_{ij}, b_{lm} \in \{0,1\} \qquad (i,j) \in E_e \qquad (l,m) \in E_t$$

$$P_{ij} \leq \mathcal{N} a_{ij} \tag{3.13}$$

$$Q_{lm} \leq \mathcal{N} b_{lm} \tag{3.14}$$

As can be seen in the objective (3.12), if the edge (i,j) (or (l,m)) is selected by the solver, $a_{ij} = 1$ (or $b_{lm} = 1$) and the cost incurred is equal to a fixed cost F_{ij} (or G_{ij}), which is set by the designer and is unique to each edge in the system. A particular distribution line in the electric plant could have a much higher fixed cost than another. An example of this is a longitudinal cable that has a high design and installation cost due to passing through multiple bulkheads versus a transverse cable that connects two load centers in one zone and traverses no bulkheads. A cable passing through a bulkhead requires design consideration for watertight integrity and fire protection. Also there is significant labor cost during installation associated with a cable that is passed through a bulkhead. This is just one example of significant fixed cost considerations.

Equations 3.12, 3.13 and 3.14 show the technique for zeroing the fixed and variable costs of a deselected edge in the system. If the solver is able to find a solution that excludes an edge, the binary variable will be zero ($a_{ij} = 0$ or $b_{lm} = 0$). Equations 3.13 and 3.14 ensure that the capacities of any deselected edges (P_{ij} or Q_{lm}), which are decision variables in the formulation, will be zero. $\mathscr{N}$ is a constant, set large ($\mathscr{N} \geq Pij$; $\mathscr{N} \geq Qij$) so that if edge (i, j) or (l, m) is selected by the solver, the capacity variable is free to take any necessary value to give the correct and feasible solution to the minimization problem.

3.7 Shipboard Electrical Systems

Electrical generators supply various loads throughout a ship via distribution cables and load center switchboards. The electric plant is designed to provide quality of service, ease of operation, survivability and reliability. This is usually accomplished through redundancy, spatial separation, load shedding (vital vs. non-vital) and casualty reconfiguration by design and operating procedures. A redundant topology commonly used in naval shipboard electrical plant design is a ring bus and zonal distribution arrangement [2], [23], [24]. This ensures mission-critical, vital and many non-vital loads are supplied independently and redundantly from both port and starboard busses (Figure 1-3).

ZED has clearly been accepted as an improvement in cost, weight, control and survivability over radial distribution. It has been implemented as standard design practice but there has not been a method for determining if designed systems were optimized for cost and weight, and hence minimum cost. To determine if a design is minimum cost, the design criteria must also include specific survivability and mission operating conditions.

3.7.1 Electrical Generators NSMCF Modeling

A generator, in this lossless power flow model, will supply whatever the demand is from the various loads throughout the plant. Since there are two generators in both notional plants demonstrated in this thesis, and there are usually multiple generators in an integrated

Electrical Generator Rating Power Limitation

$b_i^k \leq P_i^k$	$k \in K$	$i \in N_g$		(3.15)
$b_i^k \geq 0$	$k \in K$	$i \in N_g$		(3.16)
$b_i^k \leq \delta q_{lm}^k$	$k \in K$	$i \in N_g$	$(k,l) \in E_c$	(3.17)

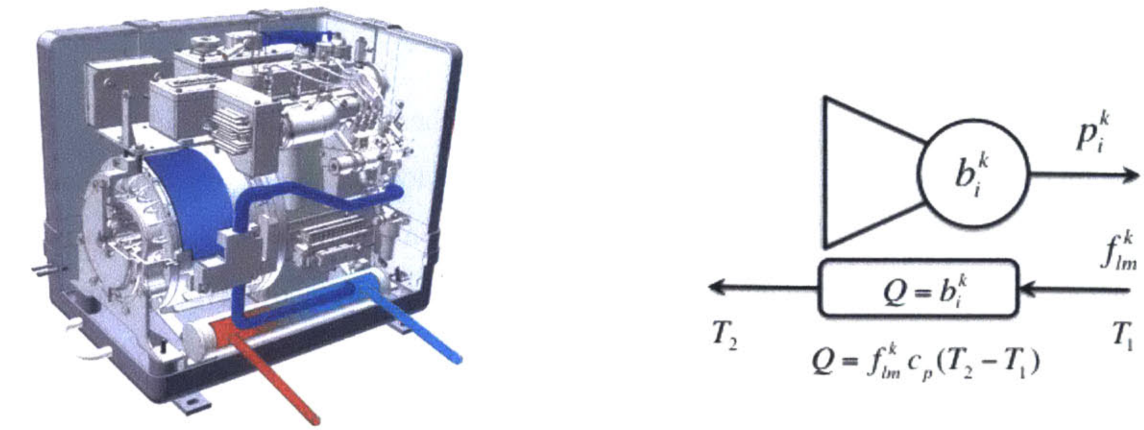
Table 3.5: Electrical Generator Modeling Constraints

engineering plant (IEP) design, when one generator reaches a power limit during a casualty, the other generator will need to pick up the remaining load or the optimization solution will be infeasible. An infeasible solution is an indication that there is insufficient power generation or insufficient redundancy available for the casualty and operating conditions given. The power limit may affect the optimal solution for a NSMCF capacity optimized formulation. Using constraints in the non-simultaneous multicommodity flow (NSMCF) formulation, we are able to simulate the limitation of generator power due to a loss of cooling flow to the machine.

The electrical generators are treated as network flow optimization (NFO) supply nodes. The unit of flow is power (kW) and they have a lower limit so the solver does not allow them to take a negative value. If they were allowed to take a negative value, that would not reflect a physical possibility and would return an impractical solution. Also, the generators are given an upper limit to reflect that they are not infinite power sources. The designer can decide what is the appropriate upper limit to give based on the phase of design and circumstances. For instance, the upper limit could be simply the rating of a specific machine or a margin could be included. In this thesis, there is no provision in the proposed method for time dependency or for how long a machine can operate above its rating. The constraints for the generator are formulated generally as follows:

Where $b_i^k \in N_g$ is the generator node power at node *i*, N_g is the set of generator nodes and K is the set of casualty and operating conditions. The variable b_i^k is a unique variable for the k casualty and operating condition and can take a unique value to ensure the electrical system is supplied with power necessary to meet load demand for the specific casualty. In the inequality 3.15, the generator is constrained to less than the value P_i^k which represents a power rating or other limit imposed by the designer. The limit can be casualty and operating condition specific. Inequality 3.16 represents the physical property that

Electrical Generator Cooling Power Limitation



(a) Water-Cooled Marine Generator (Fischer Panda)

(b) Generator Cooling Variables

Figure 3-10: Modeling Generator Cooling

In addition to an upper and lower generator power limit, there is a limitation imposed by the interdependence of the cooling system. This relationship is shown in constraint 3.17 and identical constraint 3.20. In the inequality, δ is the constant that relates cooling mass flow to electrical generator heat loss. This cooling flow parameter needs to be determined by the designer from the cooler and generator specifications according to the thermodynamic relations:

$$\dot{Q} = q_{lm}^k c_p (T_2 - T_1) \tag{3.18}$$
$$\dot{Q} = R b_i^k \tag{3.19}$$
$$b_i^k \leq \delta q_{lm}^k \tag{3.20}$$

Table 3.6: Generator Thermodynamic Cooling Relationships

Equation 3.18 is the standard heat exchanger heat removal equation. The heat energy per unit mass stored in the fluid, $c_p(T_2 - T_1)$ applies as long as there is no phase change in the fluid [30]. It can be assumed that the generator also needs cooling to operate above a certain power level and that the generator can operate without cooling at a certain power level. The cooling interdependency in the model described in this thesis is assumed linear with power production. Specifically, it is assumed that $R = 10\%$ of the generation power needs to be removed from the machine as heat [53]. This is shown in Equation 3.19. Standard early-stage design practice is to assume a $T_2 - T_1 = 20°C$ across the inlet to outlet of the heat exchanger [38]. Also, a linear relationship is assumed between mass flow of the generator cooler and the heat removed. This is shown in Equation 3.20. Equation 3.20 is the final constitutive relationship between cooling fluid mass flow and heat removal with δ being the proportionality constant. The assumption of percent electrical power that needs to be removed as heat and can be set by the designer to whatever the system components warrant. Also, if the designer is not satisfied with the assumption that the constitutive relationship between cooling and electrical generation is linear, the model can be further refined. As long as the nonlinear relationship is convex (having no local minima), the relationship can be approximated using linear approximation techniques which are described later in this thesis and used to model the cooling pump law, which is a cubic (power vs. mass flowrate) relationship.

3.7.2 Electrical Distribution Cable NSMCF Modeling

Modeling of electrical distribution cables encompasses three aspects. First the power flow physics is modeled using unique variables for the power flow in each cable in each casualty and operating condition. Second, the local power flow variables of each cable are "rolled up" into the minimum global capacity variable. And third, a design decision needs to be made based on the availability of either continuous or discrete cable capacities whether to use continuous, integer or binary variables for capacity, as shown in Figure 3-11.

Electrical Cable Power Flow Modeling

Using network flow optimization (NFO), edges are used to model the function of electrical cables in the power distribution system. The unit of flow in this case is power (MW or kW). If the system was all one voltage or if there were distribution losses assumed, it may be necessary to use current (A or kA) as a unit of flow in the model. For a shipboard integrated engineering plant (IEP), assuming lossless distribution, and that conversion of voltages is occurring in the distribution, power flow is an appropriate unit for the model.

Although power is able to flow in either direction through an electrical cable (even in a direction it is not intended to flow), it is still good practice to limit the power flow in the model to one direction for edges in which power is only expected to flow in one direction. For example, edges that represent the connection between a generator and its switchboard, or a load and its switchboard. Power would never be expected to flow "backwards" from a switchboard to the generator or from a load to its associated switchboard. This domain knowledge added to the model helps minimize the solver time and ensures that feasible solutions (in the optimization sense) are not generated that represent infeasible physics.

The power flow through a cable is modeled as a variable p^k_{ij} where $(i, j) \in E_e$ and $k \in K$ as described in Table 3.2. For a cable where power is free to and expected to flow in either direction (through a cross-connecting or "tie" distribution cable), a constraint is added (for a specific edge (i, j) and casualty k): $-\infty \leq p^k_{ij} \leq \infty$. Where the cable is expected to only conduct power in one direction, the constraint is added (again, for a specific edge (i, j) and casualty k): $p^k_{ij} \leq 0$ or $p^k_{ij} \geq 0$, depending on the flow direction convention of the edge (i, j). To model casualties involving loss of electrical cables, a constraint is added to the formulation setting the lost cable power flow equal to zero: $p^k_{ij} = 0$, this is done for a specific cable (i, j) and a specific casualty k. This is discussed in more detail in Section 3.9.

Electrical Cable Power Capacity Modeling

Electrical cable capacity was discussed in Section 3.6 in the context of the cost function in the non-simultaneous multicommodity flow (NSMCF) formulation. Cable capacity is the quantity being minimized in this application of the method proposed (with cost weighting factors). To have a survivable electric plant, the capacity of each cable in the system must meet or exceed the highest of any flow condition experienced by that cable. This flow condition is among all the flow conditions that the cable will experience in every casualty and operating condition. For example, a tie bus may not experience any flow when the system is operating normally with each generator supplying its own side (port or starboard) distribution busses and loads. In a casualty condition that causes loss of a generator, the tie bus may experience the full load of a longitudinal distribution bus as the surviving generator supplies the opposite side loads through it. The capacity of the tie bus must then meet or exceed the flow that provides power to half of the electric plant even though it may, under normal conditions, experience zero flow. This is modeled in canonical form as: $|p^k_{ij}| \leq P_{ij}$ where $(i,j) \in E_e$ and $k \in K$. P_{ij} is the power flow capacity of cable (i,j). The absolute value for p^k_{ij} ensures that the capacity is equal to or exceeds the highest power flow in the cable in either direction. In the example formulations of this thesis shown in Chapters 4 and 5, no design margin is used in the optimization. However, if the designer desires to add a margin ($\mathscr{M} \geq 1$) to the cable capacity, it could be done as simply as $\mathscr{M}|p^k_{ij}| \leq P_{ij}$.

Discrete Electric Cable Power Capacity

There may be a desire for the designer to have the solver select from only standard cable capacities. This can be accomplished using integer or binary variables in the formulation. The formulation then becomes what is called "mixed integer" or "mixed integer" linear programming (MILP). The disadvantage to introducing discrete variables is the solver algorithms are more complex and may require more computation time. The advantage is that, if only discrete cable capacities are available, using mixed integer programming will provide the true minimum. Using continuous variables and "rounding up" to the closest standard cable can actually result in a solution that is far from the true optimal solution. For example, if only standard discrete capacities are available and the solver is constrained to them using integer or binary variables, by using a much larger capacity cable for a tie, it may reduce other cables to zero. If allowed to use continuous variables, the designer's final solution with cables "rounded up" may be significantly more costly due to fixed cost of cables that could have been eliminated and also the cost of larger than necessary cables throughout the design.

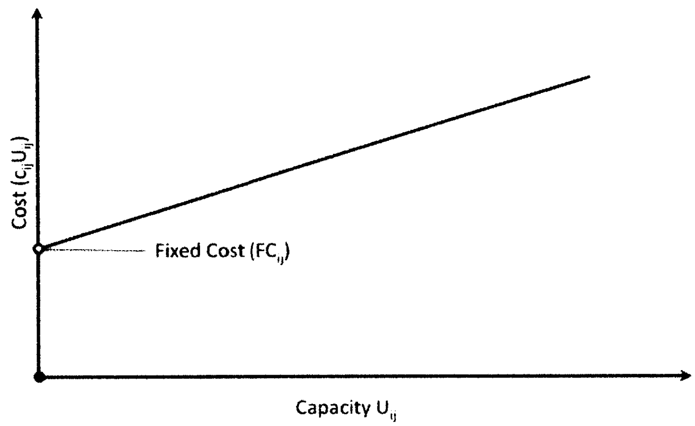
In Figure 3-11, cases for the use of continuous, integer, and binary cable capacity variables are shown. Figure 3-11 shows cases when continuous, integer or binary variables would be used in the formulation. In Figure 3-11(a), it can be seen that if there is a continuum (or near continuum) of cable capacities available, continuous variables for cable capacity should be used. In Figure 3-11(b), if available cable capacities are discrete, but are linearly spaced, integer variables can be used. The integer variable would be used with the interval as a coefficient in the formulation. And finally, if cable capacities are discrete but not linearly spaced with respect to cost (Figure 3-11(c), binary variables must be used to allow selection of each individual cable capacity.

For the purpose of this thesis, the assumption is made that electrical cables used for marine applications are ordered from the manufacturer and they are assembled by adding strands of relatively thin gage wire to make a cable very close to the design capacity. Thus the system can be accurately modeled using continuous variables for cable capacity. The proposed method examples in this thesis use binary variables for fixed cable cost and the effect on computation time is insignificant for the small scale problems presented. It is not clear what the effect would be on solver computation time by adding more integer or binary variables to the formulation. Using discrete variables may actually reduce computation time in some cases.

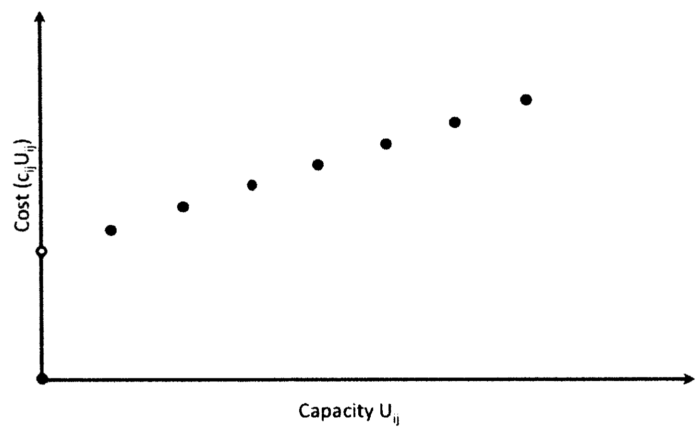
3.7.3 Electrical Loads

Loads are modeled as network demand nodes in the non-simultaneous multicommodity flow (NSMCF) formulation, having demand equal to the expected electrical power draw of the load. Each node obeys power flow continuity, as modeled in the constraints (Equation 3.2). Additionally, every node obeys power flow continuity in every casualty and operating condition. The loads can be specified for each casualty and operating condition, making a complete set of required and expected conditions that the integrated engineering plant (IEP) is intended to survive and meet mission requirements. Casualty modeling for loss of a node is described in Section 3.9.

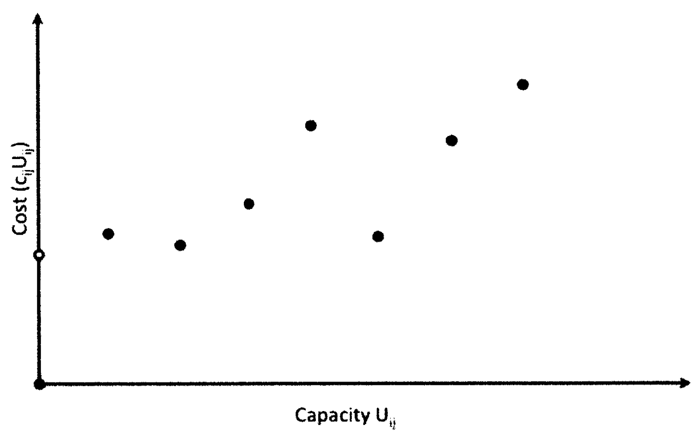
Unique variables are given in the formulation for each load and for each casualty and operating condition. This allows the designer to set the loads for any operating condition. For example, in the integrated propulsion system (IPS) concept, it is desirable to share gen-



(a) Case For Continuous Cable Capacity Variables



(b) Case for Integer Cable Capacity Variables



(c) Case for Binary Cable Capacity Variables

Figure 3-11: Cases for Continuous, Integer and Binary Capacity Variables erator power between combat system and propulsion loads. The designer can specify that in one operating condition (ship transiting), propulsion motor loading is at or near maximum while combat system loads are minimized. In another operating condition, combat system loads are at maximum while propulsion motor loading is at minimum power to maintain maneuverability. This ensures that the minimized capacity design supports both these operating conditions (in addition to any other casualty and operating conditions).

Redundant Loads

$\mathscr{D}^k$ is the total power required for a ship function that is provided by redundant equipment. For example, there is a total power required to propel the ship at its design speed. Constraint 3.8 ensures that the minimum requirement is met but also allows it to be met by either propulsion motor load d_i^k, d_j^k or both. If one of the propulsion motors is lost in a casualty, the other one can propel the ship at the minimum required speed.

Prioritized Loads

Loads in the electric plant have varying importance and they should not all be maintained in every casualty and operating condition if power continuity is in jeopardy. For a warship, the mission critical loads are most important and the plant should be designed to maintain these loads in battle until the ship is lost. These, along with life safety electrical loads are called vital loads and are on protected busses with redundant power supplies. Non-vital loads are those for which the ship and crew can continue to carry out the mission without, at least for a limited time. Loads that are for convenience of the crew would have the lowest priority and these can be referred to as hotel loads. Loads can be categorized in any way as seen fit by the designer to capture their priority and ensure that through load shedding, the mission can continue in the presence of casualties.

In the non-simultaneous multicommodity flow formulation, load requirements can be set for each casualty or operating condition and load priority can be set in general. Through the use of constraints, the designer can ensure that all vital loads are supplied under all conditions. This is accomplished by setting the load $d_{ij}^k = \mathscr{P}$ where $\mathscr{P}$ is the minimum power that the load requires for a particular operation. This can also be relaxed for an operating condition in which the ship is not expected to be using the load, such as transiting or performing humanitarian operations.

There are at least three ways non-vital and other lower priority loads can be modeled in the formulation. The first approach is that they can be set to zero for any casualty scenario, indicating that they are not mission critical and no reserve capacity should be designed into the system to account for them during a casualty. The second is they can be set to their minimum load draw for some or all casualties and operating conditions, (depending on the nature of the casualty or operating condition) so that they are accounted for and there was reserve capacity designed into the plant to accommodate those loads. The third approach is that the non-vital and lower priority loads could be set to $d_{ij}^{k} \geq 0$ and the objective could be used to give a cost advantage to the solver for powering the loads during certain conditions. The cost advantage would have to be a designer input. For the solver to choose to power a load, for example, the cost advantage would have to outweigh the cost disadvantage of the capacity cost of the cable supplying the load. The point is that the flexibility exists in the formulation to treat loads differently based on their priority and the actual cost weighting factors to achieve the desired solver behavior is an area for separate study that is not addressed in this work.

3.7.4 AC/DC Rectifiers, DC/AC Inverters and DC/DC Converters

AC/DC rectifiers take power from the rotating synchronous machines and convert it (filtered) to DC power for distribution to the electrical plant. DC/DC converters are designed to take a DC power and convert it to a lower voltage (sometimes higher) DC power for zonal load centers. DC/AC inverters are devices that take DC power and convert it to AC power for use by AC equipment, such as pumps or other gear that was designed for AC power. During the conversion process in each of these devices, there are electrical losses due to internal resistance in the device. For most shipboard scale devices, the efficiency, η is from $80-90\%$. Equation 3.26 shows the relationship between input power (P_{in}) and output power (P_{out}).

Converter Physics

$$P_{out} = \eta_{conv} P_{in} \qquad \eta_{conv} \in \{0 \dots 1\} \tag{3.21}$$

$$\dot{Q} = P_{in} - P_{out} \tag{3.22}$$

$$\dot{Q} = (1 - \eta_{conv}) P_{in} \tag{3.23}$$

The heat that is needed to be removed by the cooling system is shown in Equation 3.28. Some of the smaller inverters and converters may be air-cooled but (air) space cooling will still need to be provided. The larger devices, used for the main power bus and propulsion motors,j are usually freshwater cooled. The freshwater system is in turn cooled by seawater. It is the designer's prerogative whether to include in the model cooling for air-cooled devices; the cooling system for spot (compartment air) coolers is usually a chilled water system that is cooled by a refrigeration plant. The refrigeration plant heat sink is usually seawater. This resolution could be added to the model but it would depend on the level of detail necessary for the design, the design phase of the acquisition program, and whether the loads to be cooled are vital loads or not. Component cooling is discussed further in Section 3.8.4.

3.7.5 Electrical Stored Energy Devices

There are certain mission critical (MC) electrical loads for which it is desired to supply them with maximum quality of service (QoS). This can be achieved through redundancy in the distribution system. This may be unsatisfactory if there is a widespread loss of the system. Another method to achieve maximum QoS is to supply the load in a loss of normal power with a stored energy device (SED). The SED would normally be connected to the electric plant or alternately one switch away from being connected automatically or manually. The SED should be connected as close to the load it is intended to maintain continuity of power for, to minimize line losses when power is lost and the SED is activated to supply the load. There are many kinds of SEDs; for this work a generic electric charge storage device such as a battery (with DC/DC converter or DC/AC inverter if necessary) is assumed. The SED can be connected in a free exchange manner with the bus where it is maintained charged and automatically supplies the bus upon power loss. Once the SED is activated (assuming due to a casualty), it will supply the MC load and possibly other loads through the intact portion of the system. The SED needs to be sized to supply the electrical load (or bus) that is mission critical for the time period that is required for survivability. The formula for calculation of the minimum energy required is shown in Equation 3.24

$$E_{min} = d_{max} t_{min} \tag{3.24}$$

where E_{min} is the minimum energy required for the SED, d_{max} is the power of the load to be supplied by the stored energy device (SED), and t_{min} is the time of survival required. The SED can be modeled in the non-simultaneous multicommodity flow (NSMCF) formulation and to manipulate the solver to only "use" the SED when necessary during a casualty reconfiguration. Although the NSMCF approach does not provide a dynamic result, and does not operate in the time domain, the minimum power flow required from a SED is still an output of the solver. If the designer then takes this power and multiplies it by the time of survival required, the minimum energy is obtained (Equation 3.24).

For the NSMCF optimization, the formulation needs to be able to "switch on" the stored energy device (SED) at the appropriate time. The appropriate time, in the context of the formulation is not intuitive. Many factors could cause a need for the stored energy device to be needed at any given time in order for the system to meet all load demands. In practice, the SED will generally turn on when the connected bus voltage drops below a certain level. The formulation, however, recognizes only power flow (not voltage) and there is not a clear way of detecting loss of power in a traditional sense, such as low voltage or current.

The proposal in this thesis is a cost-based method for the modeling of stored energy switching in the NSMCF formulation. The solver is finding, in the design space, the lowest total capacity of the integrated engineering plant (IEP). The SED is given the same characteristics as a generator. It can supply power but not absorb it. There is one difference, however. For a SED, there is a cost assigned to the power produced at the node. The cost of the power flow from the node is added to the objective (See Equation 3.1). The cost assigned is large enough that the solver will only choose a value of power flow from the SED when there is no other solution that can supply the loads it has connectivity with. In this case, the cost itself is meaningless in the design, but is used as a tool to manage the SED switching. To obtain the true cost of the design optimization, the designer needs to subtract the cost of the SED power flow from the objective.

3.7.6 Pulse Power Weapon and Aircraft Launch Loads

Development and implementation of pulse power loads such as rail guns, high energy electromagnetic weapons and aircraft electromagnetic launch systems is advancing and systems are being installed on new ships, such as DDG-1000. Current schemes for powering these systems involve charging a stored energy device, either electrical charge or electromechanical in nature, and then connecting the device to the pulse power load during activation. The reason for using stored energy pulse loads generally exceed the power level of the peak rating of installed generating equipment and the pulse loads are not intended to be operated continuously. The non-simultaneous multicommodity flow (NSMCF) formulation can account for these loads to ensure the final integrated engineering plant (IEP) design can support them. The pulse power stored energy can be modeled as a continuous load to simulate its charging state. The activation state removes the stored energy from the bus momentarily; this can also be modeled as a zero load. In the future of the fleet, where pulse power loads may be powered directly from the bus with no stored energy, it will be important to ensure the IEP is designed for this challenging state. The designer can handle this powering scheme by modeling the maximum pulse power load on the system.

3.8 Shipboard Cooling System Modeling

The cooling plants on a ship are designed to remove heat from engines, generators, power converters, large motors, and high power electronic systems such as radars and combat system computers. The source of heat removal is an open system with surrounding seawater. Due to the corrosiveness of seawater (and other factors), the heat exchange with thermal loads in the ship is commonly accomplished with multiple layers so that freshwater is the fluid in contact with surfaces in sensitive systems. As in the case of the electric plant, the cooling plant must also be survivable and reliable. A similar philosophy to the ring bus and zonal distribution arrangement is used in cooling plant design through the use of port and starboard supply headers and cross-connections in the system [1], [38]. Parametric-based early stage design tool by Fiedel [27]. A notional cooling system arrangement is shown in Figure 3-12.

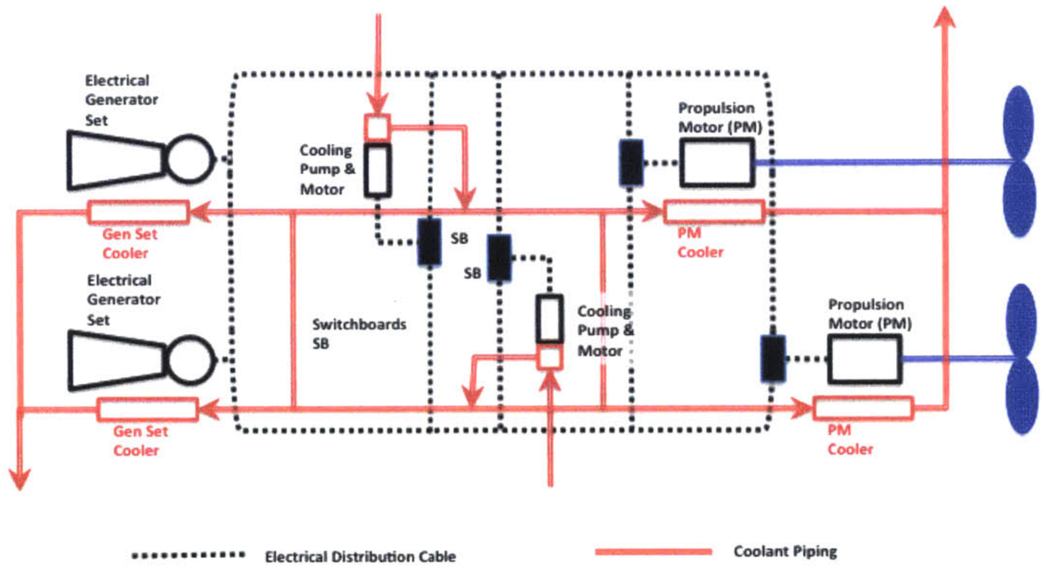


Figure 3-12: Shipboard Cooling Plant - Notional Arrangement

3.8.1 Cooling Piping Modeling

Like electrical cables, seawater piping in the cooling domain are optimized by "choosing" a minimum cost plant topology from many redundant candidate piping runs. Candidate piping runs should only be precluded from the input when they are not feasible or otherwise specifically undesirable. More candidate pipe runs may allow the solver to find a less expensive solution.

For the early-stage design process, in a small scale shipboard plant, it is assumed there are no fluid friction losses in the piping (similar to the no power loss assumption for electric plant). The capacity units are mass flow rate of seawater. If the designer desires to calculate pipe size following the optimization, simple equations relating flow rate, seawater velocity pipe area can be used:

$$
\begin{aligned}
Q_{sw} &= A_{pipe}\, V_{sw} \\
\dot{m}_{sw} &= \rho_{sw}\, A_{pipe}\, \vec{V}_{sw} \\
A_{pipe_{min}} &= \frac{\dot{m}_{sw}}{\rho_{sw}\, \vec{V}_{sw_{max}}}
\end{aligned}
\tag{3.25}
$$

where Q_{sw} is the volumetric flow rate through the pipe, A_{pipe} is the cross sectional internal area of the piping, $V_{sw_{max}}$ is the maximum seawater velocity in the piping, ρ_{sw} is the seawater density, and $\dot{m}$ is the mass flow rate through the pipe. One of the limiting factors of ship life is the corrosion and erosion wear of piping in cooling systems. Excessive velocity of the fluid in the cooling system can cause erosion of the protective oxide layer and accelerated corrosion of the piping. A rule of thumb for maximum fluid velocity in seawater cooling systems is $2.5 - 3.6$m/s [38]. The output of the solver will be mass flow capacity for each edge in the cooling plant. Cross sectional area of the pipe for each edge can be calculated using Equation 3.25.

3.8.2 Cooling System Valves

Normally, valves are used in fluid systems to reconfigure the system to survive casualties related to leaks, loss of piping, loss of cooling to a critical component, and to isolate portions of the system for maintenance. In this thesis, the formulation allows the system to reconfigure as necessary to survive casualties. The assumption is that there will be operator or automatic action taken to reconfigure and that is sufficient for this early-stage design method. There is no modeling of valves the action of valves in this work.

3.8.3 Cooling System Resistance Consideration

The cooling system presents flow resistance to the pumps based on the amount of surface area, the piping diameter and pressure (head) in the system. If the system is reconfigured, the flow resistance will change, and the mass flow rate of the fluid will decrease or, if mass flow rate is constant, an increase in pressure differential will need to be made. For the purpose of this thesis, changes in flow resistance in the system are neglected, assuming the change is relatively small and that the early-stage design does not require this level of detail.

3.8.4 Component Coolers

Electrical components such as synchronous machines (SMs), propulsion drives (PDs), and other large electrical power conversion equipment require cooling by heat transfer with fluid. Table (3.7) shows the derivation of the required flowrate of fluid (cooling water) through a component cooler to remove electrical heat loss. Figure 3-13 illustrates the result of the derivation.

Converter Physics

$$P_{out} = \eta_{conv} P_{in} \qquad \eta_{conv} \in \{0 \ldots 1\} \tag{3.26}$$

$$\dot{Q} = P_{in} - P_{out} \tag{3.27}$$

$$\dot{Q} = (1 - \eta_{conv}) P_{in} \tag{3.28}$$

Cooler Physics

$$\dot{Q} = \eta_{cool} \dot{m}\, c_p\, \Delta T \tag{3.29}$$

$$\dot{m} = \frac{\dot{Q}}{\eta_{cool}\, c_p\, \Delta T} \qquad \eta_{cool} \in \{0 \ldots 1\} \tag{3.30}$$

Combined Cooling Physics

$$\dot{m}_{reqd} = \frac{(1 - \eta_{conv}) P_{in}}{\eta_{cool} c_p\, \Delta T} \tag{3.31}$$

Table 3.7: Derivation of Component Cooling Physics

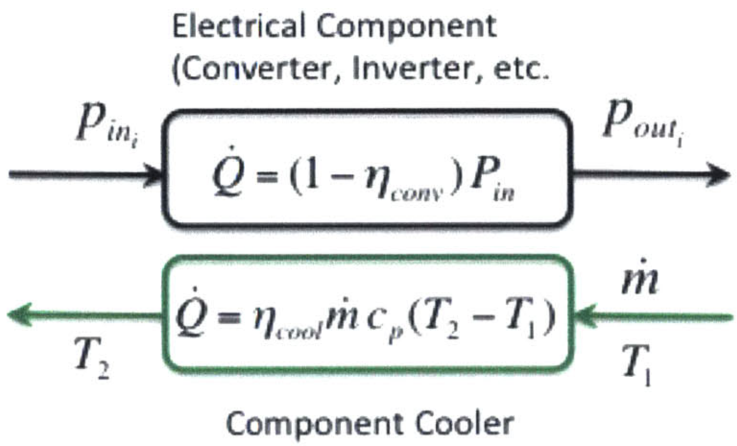
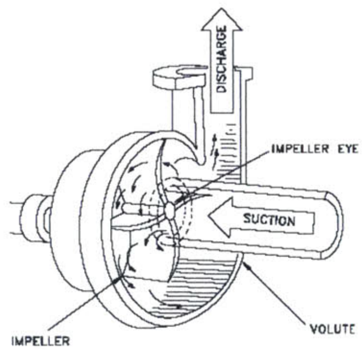


Figure 3-13: Electrical Component Cooler with Equations

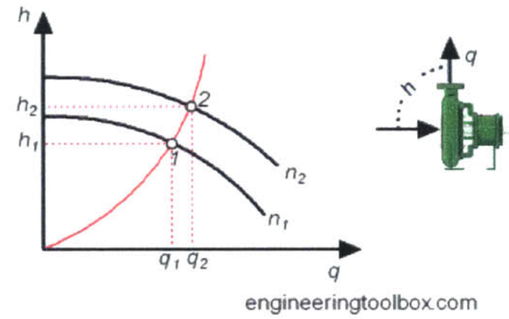
- P_{in} is the input power to the DC/DC converter (or other device).
- P_{out} is the output power of the device.
- η_{conv} is the efficiency of the device ($80 - 90\%$).
- $\dot{Q}$ is the electrical heat loss of the device.
- η_{cool} is the thermal efficiency of the device component cooler.
- $\dot{m}$ is the fluid mass flowrate through the cooler.
- c_p is the heat capacity of the cooling fluid.
- ΔT is the fluid temperature difference across the cooler.
- $\dot{m}_{reqd}$ is the fluid mass flowrate required to remove the heat generated by the device.

3.8.5 Cooling Pump Modeling

Centrifugal cooling pumps are common in shipboard cooling systems. They offer good flowrate and enough head pressure to supply multiple levels in the ship. Centrifugal pumps have well-understood physics and can be modeled in the non-simultaneous multicommodity flow (NSMCF) optimization problem. Figure 3-14 shows the pressure (h) vs. flowrate (q) curve for a standard centrifugal pump and Table 3.8 shows that the relationship between pump hydraulic power (P) is cubic with flowrate (q). The hydraulic power P is used also as the electrical power required for the pump motor (Equations 3.36 and 3.37).



(a) Centrifugal Pump (DOE-HDBK-1018/1-93)



(b) Centrifugal Pump Curve

Figure 3-14: Centrifugal Cooling Pump Modeling

$$q \propto n \tag{3.32}$$

$$h = \Delta p \propto n^2 \tag{3.33}$$

$$P \propto hq = n^2(n) = n^3 \tag{3.34}$$

$$P \propto q^3 \tag{3.35}$$

Table 3.8: Centrifugal Pump Affinity Laws

- n is the pump rotational speed (3.32)
- q is the volumetric flowrate of the pump (3.32)
- h is the pump head (pressure discharge - pressure suction) (3.33)
- P is the hydraulic power of the pump (head times flowrate) (3.35)

The pump power law relates the electrical power (P_{motor}) to the mass flow rate ($\dot{m}$) of the pump. The constant $\mathscr{K}$ is the system resistance coefficient and depends on piping size, hydraulic resistance, system elevation, and system configuration. See Section 3.8.4 for explanation of the thermodynamic terms in Equation 3.37.

Pump Power Law:

$$P_{motor} = \mathscr{K}\dot{m}^3 \tag{3.36}$$

$$P_{motor} = \mathscr{K}\left(\frac{(1-\eta_{conv})P_{in}}{\eta_{cool}c_p\,\Delta T}\right)^3 \tag{3.37}$$

3.8.6 Cubic to Linear Approximation

Since the solver requires all constraint relationships to be linear, the pump power curve cannot be implemented as a cubic function. Fortunately, because pump power vs. mass flow rate is a convex function, it is suitable for optimization. In order to implement the cubic function, a series of linear approximations is used. As shown in Figure 3-15, lines can provide a close approximation to the cubic. The equations of these linear approximations are derived as such:

$$\begin{aligned}
\dot{m}_{i\ldots n} &= \dot{m}_1,\ \dot{m}_2,\ \dot{m}_3,\ldots\dot{m}_{n-2},\ \dot{m}_{n-1},\ \dot{m}_n \\
P(\dot{m})_i &= P_{slope_i}\,\dot{m}_i + P_{yint_i} \\
P_{slope_i} &= 3\,\mathscr{K}\,\dot{m}_i^2 \\
P_{yint_i} &= -2\mathscr{K}\,\dot{m}_i^3
\end{aligned} \tag{3.38}$$

where $P(\dot{m})_i$ is the slope of the cubic at $\dot{m}_i$, and P_{yint_i} is the y-intercept of the line associated with $\dot{m}_i$ (see Appendix A). The solver is relatively insensitive to the number of linear approximations with regard to computation time. The designer can decide how many lines to use for the desired accuracy to the cubic curve.

When implemented in the formulation, the linear approximations are inequalities, signifying that the area above each is the feasible region:

$$
\begin{aligned}
P_1(\dot{m}) &\geq P_{slope_1}\,\dot{m}_1 + P_{yint_1}\\
P_2(\dot{m}) &\geq P_{slope_2}\,\dot{m}_2 + P_{yint_2}\\
P_3(\dot{m}) &\geq P_{slope_3}\,\dot{m}_3 + P_{yint_3}\\
&\vdots\\
P_{n-2}(\dot{m}) &\geq P_{slope_{n-2}}\,\dot{m}_{n-2} + P_{yint_{n-2}}\\
P_{n-1}(\dot{m}) &\geq P_{slope_{n-1}}\,\dot{m}_{n-1} + P_{yint_{n-1}}\\
P_n(\dot{m}) &\geq P_{slope_n}\,\dot{m}_n + P_{yint_n}
\end{aligned}
$$

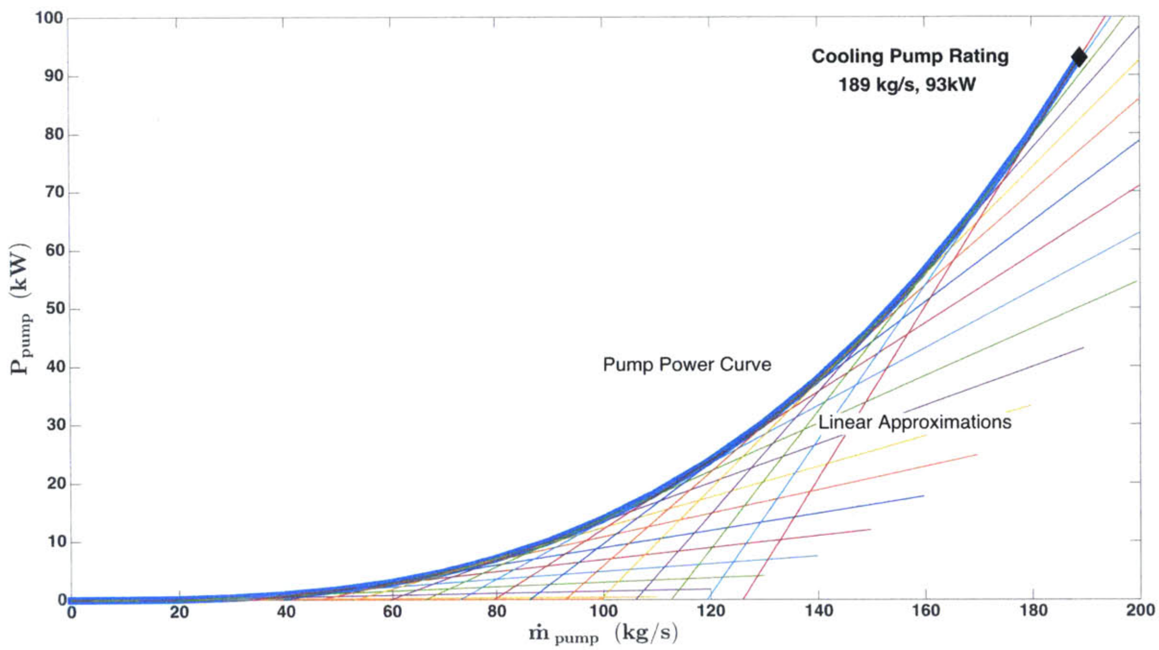


Figure 3-15: Example Pump Electrical Power vs. Mass Flow Rate

3.8.7 Sea Suction & Discharge

The seawater cooling plant is an open system to the sea that nominally includes two intakes and two discharges for redundancy. In the notional system demonstrated in Chapter 4, the suctions and discharges are offset fore and aft also for spatial separation.

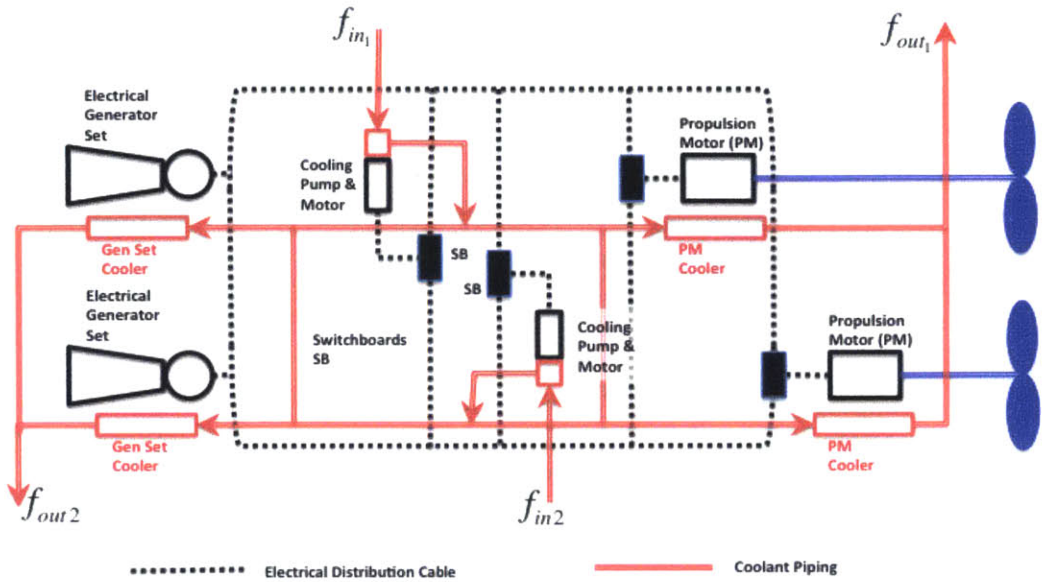


Figure 3-16: Seawater Suction & Discharge Modeling

$$f_{in_1} + f_{in_2} = f_{out_1} + f_{out_2} \tag{3.39}$$

Constraining the continuity of flow allows the solver to "share" the flow appropriately throughout the system. This gives the system the freedom to allow cooling where it would naturally flow but not constrain it to any particular branch of the system.

3.9 Casualty & Operating Conditions Modeling

One of the advantages of the proposed integrated engineering plant (IEP) design optimization method over current methods is that casualty and operating conditions are input "upfront" in the design process and the network is optimized with these unique flow conditions, ensuring a mathematical minimum network (within the accuracy of the model approximations). In other words, survivability is designed "into" the system. Casualties are plant conditions that occur as the result of unexpected consequences of physical damage to the plant or disruption of service due to other means (shock from explosion or electromagnetic pulse, etc.) Operating conditions are those plant conditions that are specified and desired by the operator. An example of an operating condition is the sharing of power generation such that the propulsion motors are drawing full power and the combat system is at minimum power. Conversely, the combat system could be at maximum power and the propulsion motors at low power. Casualty and operating conditions are both taken into account in the formulation to solve the optimization problem and minimize cost while meeting all the specifications. These casualty and operating conditions are formulated by the following methods:

- loss of electrical or cooling edge set edge flow variable unique to the casualty equal to zero ($f_{ij}^k = 0$)
- loss of electrical or cooling node set all edge flow variables unique to the casualty for all edges entering or leaving the lost node equal zero ($f_{ij}^k = 0$).
- special load conditions assignment of demand values to unique flow condition variables ($b_i^k = D$) where D is the unique demand value for that operating condition.

3.10 Conclusion

Applied mathematicians have and continue to develop solvers to handle large scale linear programming (LP) as well as mixed-integer linear programming (MILP) problems. The job of the designer is to utilize the formulation as a tool. To model a physical system in a linear programming solver requires creative thought in order to get the desired behavior from the solver. When a formulation is derived, a solver will provide the optimal solution with certification. The optimal solution is within the design assumptions and accuracy of the model. In Chapter 3, the following steps and techniques were used to obtain the desired solver behavior for a minimum capacity survivable integrated engineering plant (IEP):

- Maximum of the local flow variables "rollup" to the minimum capacity global variables.
- Variable cost modeling of cables and pipes in the design (material cost per unit capacity).

- Fixed cost modeling using binary variables and capacity zeroing constraints (cost of installation and other costs of edge existence).
- Generator rating limits and limits due to reduced cooling.
- Component redundancy relationships.
- Constitutive relationship between electrical motor power and pump fluid mass flow rate (linear approximation of cubic relationship).
- Constitutive relationship between cooler mass flow rate and electrical component heat loss.
- Stored energy management using power flow cost penalty in the objective.

The non-simultaneous multicommodity flow (NSMCF) formulation lends itself well to this early stage design method and in some respects can approach detail design potential. There are at least 3 approaches that can be used to allow more or less freedom of the solver to design the topology. The method proposed is superior to the present method of "trial and error" with respect to best value using indirect design methods.

Chapter 4

NSMCF Applied to a Notional IEP

4.1 Notional IEP Topology & Features

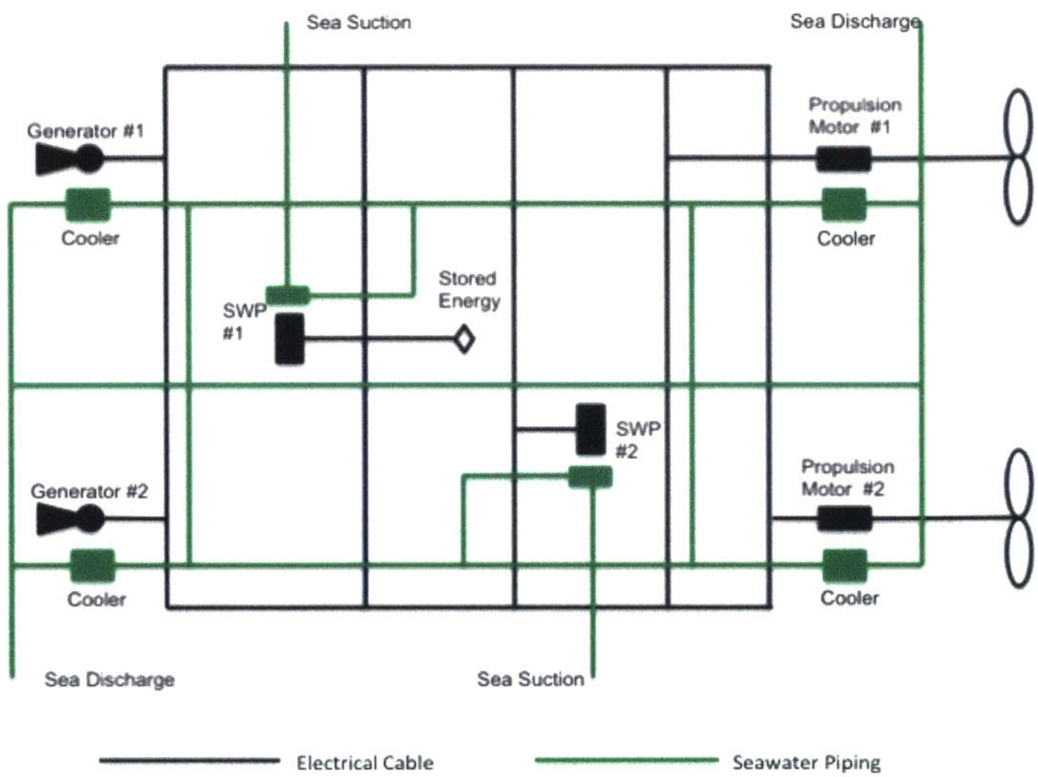


Figure 4-1: Notional IEP Topology

The integrated engineering plant (IEP) shown in figure 4-1 was developed to demonstrate the proposed modeling and design process. The Notional IEP is a dual domain system with electric generation and distribution plant with electric propulsion and a seawater cooling plant. The electric plant candidate topology is a ring bus with zonal electrical distribution (ZED) that offers alternate power supply for the loads from both port and starboard distribution busses. The cooling plant candidate topology has port and starboard supply headers with two (fore and aft) athwartship cross-connects and two discharge headers with one longitudinal cross-connect. The term "candidate" implies that some (or all) of the edges of the electric and cooling networks may be "deleted" by the solver if found unnecessary to meet survivability and operating condition specifications.

4.2 Notional Electrical Plant

The IEP has the following features in the electric plant: two independent electrical generators rated at 30MW each, two independent electric propulsion motors rated at 10MW each, two independent cooling pump motors rated at 40kW each and various distribution cables (edges) and distribution and load center switchboards (nodes). The electric plant also contains one electrical stored energy device (SED) that is connected via cable to the load center switchboard at the switchboard powering #1 cooling pump motor. This SED is intended to power the cooling pump motor in loss of normal power casualty and to demonstrate the ability of this method to aid in design of minimum stored energy.

No.	Feature
22	Electrical Nodes
2	Electrical Generators (SM)
2	Propulsion Motors (PM)
2	Seawater Pump Motors
1	Stored Energy Device (SED)
15	Distribution Nodes (switchboards / junctions)
24	Electrical Edges (cables)

Table 4.1: Notional Electric Plant Features

4.3 Notional Seawater Cooling Plant

The seawater cooling plant has the following features: two cooling pumps, two each sea suction and discharge hull openings, two suction headers with fore and aft (athwartship) cross-connecting pipes, two discharge headers with one longitudinal cross-connecting pipe, and four coolers; one for each of the electrical generators and propulsion motors.

No.	Feature
24	Thermal Nodes
2	Seawater Pumps (SWP)
2	Electrical Generator Coolers
2	Propulsion Motor Coolers
18	Distribution Nodes (pipe junctions)
27	Thermal Edges
2	Sea Suctions
2	Sea Discharges
23	Distribution Edges (pipes)

Table 4.2: Notional Thermal Plant Features

4.4 Redundancy

It is useful for the designer to offer as much redundancy in the candidate plant as possible to allow the biggest possible design space. Redundancy allows the integrated engineering plant (IEP) to meet load power flow demands via two or more independent paths and two or more independent components. If there is no redundancy offered in the candidate topology, a single casualty that removes the sole source of power to a required load will result in an infeasible solution. The infeasible solution would be appropriate if in fact the offending casualty were a required survivability condition. To clearly demonstrate the non-simultaneous multicommodity flow (NSMCF) design optimization method, the Notional IEP shown in Figure 4-1 has sufficient redundancy to allow M-1 survivability (loss of all edges, any one at a time), yet the system is simple enough be able to show some intuitive results so the reader can visualize the mechanics of the method.

4.5 Topology

The IEP as shown in figure 4-1 has been modeled with a larger than necessary number of distinct nodes and arcs. For example, the electrical edge 2, marked with a diamond between nodes 2 and 3 could be combined with adjacent edge 3 and used in the formulation as a single edge. Modeling loss of edge 2 by setting flow equal to zero effectively models loss of edge 3 also since the two edges are continuous in their connection and there is no other edge connected at the node. However, the use of two distinct edges can have advantages. One advantage is that the edges can be used to distinguish cables spatially throughout the ship for casualty modeling or simply for more accurate cost estimating. For the formulation, additional nodes and edges at the scale being demonstrated do not affect the computation time significantly. See Appendix A for more discussion regarding scalability and effects on computation time. The plant studied in this chapter is practically the simplest meaningful integrated engineering plant (IEP) that can be studied, containing redundancy in the generation of electrical power, the supply of cooling water (seawater) and the availability of propulsion motors.

4.6 Notional IEP M-1 Minimum Cost Solution

The solution to the Notional IEP M-1 minimum cost problem is shown graphically in Figure 4-2. The values for capacity are shown in tabular form in Tables 4.3 and 4.4.

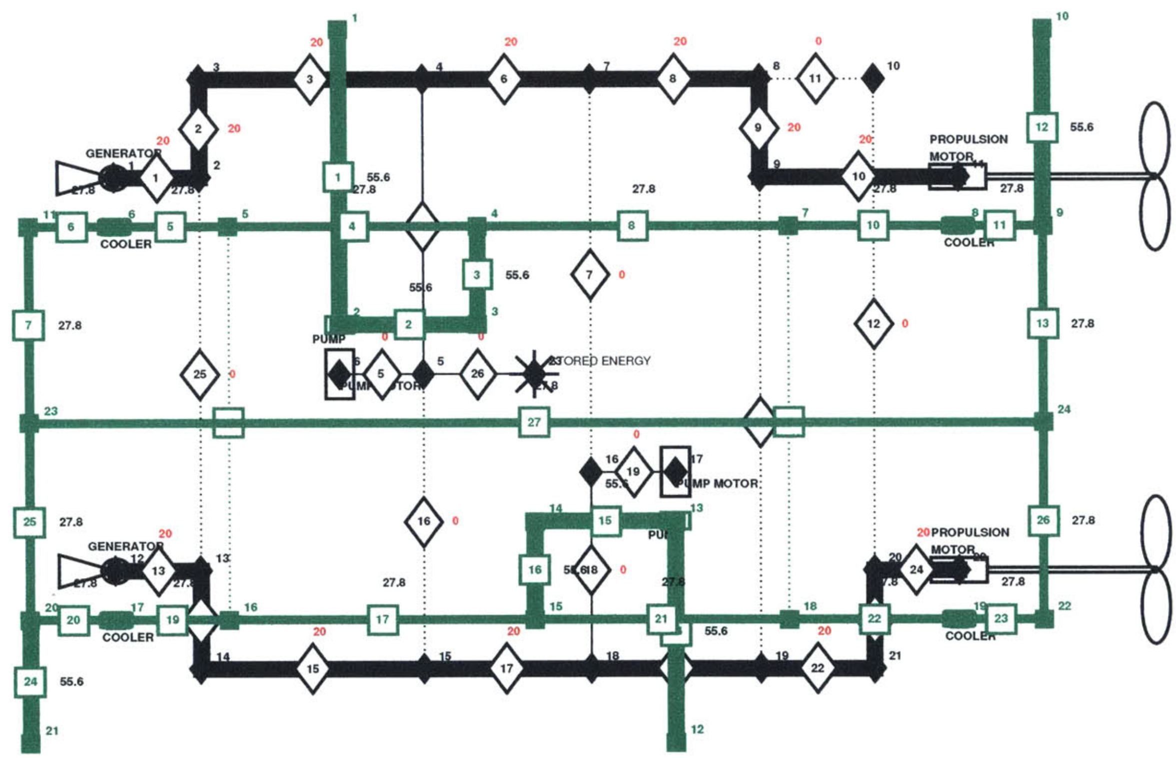


Figure 4-2: Notional IEP M-1 Solution Capacities

Edge #	Capacity (MW)	Edge #	Capacity (MW)	Edge #	Capacity (MW)
1	20.0023	10	20	19	0.0023
2	20.0023	11	-	20	20
3	20.0023	12	-	21	-
4	0.0023	13	20.0023	22	20
5	0.0023	14	20.0023	23	20
6	20	15	20.0023	24	20
7	-	16	-	25	-
8	20	17	20.0023	26	0.0016
9	20	18	0.0023		

Table 4.3: Notional IEP Electrical Edge M-1 Capacity Solution

Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)
1	55.6032	10	27.8000	19	27.8032
2	55.6032	11	27.8000	20	27.8032
3	55.6032	12	55.6032	21	27.8000
4	27.8032	13	27.8032	22	27.8000
5	27.8032	14	55.6032	23	27.8000
6	27.8032	15	55.6032	24	55.6032
7	27.8032	16	55.6032	25	27.8000
8	27.8000	17	27.8032	26	27.8000
9	-	18	-	27	27.8032

Table 4.4: Notional IEP Thermal Edge M-1 Capacity Solution

4.7 Notional IEP Model Parameters

The following tables contain the parameters for the nodes and edges of the electrical and seawater plants that make up the Notional IEP. The columns of the node parameters table contain the node numbers, the x and y coordinates of each node, the function name of the node and it's rating. The edge parameter table columns contain the edge number, the start and end node of the edge, the direction (Dir) of the edge, the fixed cost (FC) and the variable cost (VC) of each edge.

Node #	X (m)	Y (m)	Name	Rating (MW)	Node #	X (m)	Y (m)	Name	Rating (MW)
1	5	24	SM	30	13	8	8	-	-
2	8	24	-	-	14	8	4	-	-
3	8	28	-	-	15	16	4	-	-
4	16	28	-	-	16	22	12	-	-
5	16	16	-	-	17	25	12	SWP	.04
6	13	16	SWP	.04	18	22	4	-	-
7	22	28	-	-	19	28	4	-	-
8	28	28	-	-	20	32	8	-	-
9	28	24	-	-	21	32	4	-	-
10	32	28	-	-	22	35	8	PM	10
11	35	24	PM	10	23	20	16	SED	-
12	5	8	SM	30					

Table 4.5: Notional IEP Electrical System Nodes

Node #	X (m)	Y (m)	Name	Rating (kg/s)	Node #	X (m)	Y (m)	Name	Rating (kg/s)
1	13	30	-	60	13	25	10	SWP	60
2	13	18	SWP	-	14	20	10	-	-
3	18	18	-	-	15	20	6	-	-
4	18	22	-	-	16	9	6	-	-
5	9	22	-	-	17	5	6	CLR	-
6	5	22	CLR	-	18	29	6	-	-
7	29	22	-	-	19	35	6	CLR	-
8	35	22	CLR	-	20	2	6	-	-
9	38	22	-	-	21	2	1	-	-
10	38	30	-	-	22	38	6	-	-
11	2	22	-	-	23	2	14	-	-
12	25	1	-	-	24	38	14	-	-

Table 4.6: Notional IEP Thermal System Nodes

Edge #	Start Node	End Node	Dir	FC ($)	VC ($/MW)	Edge #	Start Node	End Node	Dir	FC ($)	VC ($/MW)
1	1	→	2	500	0.230	14	13	→	14	500	0.307
2	2	→	3	500	0.307	15	14	→	15	1000	0.614
3	3	→	4	1000	0.614	16	5	↔	15	500	0.921
4	4	↔	5	500	0.921	17	15	↔	18	1000	0.460
5	5	→	6	500	0.230	18	16	↔	18	500	0.614
6	4	↔	7	1000	0.460	19	16	→	17	500	0.230
7	7	↔	16	500	1.228	20	18	↔	19	1000	0.460
8	7	↔	8	1000	0.460	21	9	↔	19	500	1.535
9	8	↔	9	500	0.307	22	19	↔	21	1000	0.307
10	9	→	11	1000	0.537	23	20	↔	21	500	0.307
11	8	↔	10	1000	0.307	24	20	→	22	500	0.230
12	10	↔	20	500	1.535	25	2	↔	13	500	1.228
13	12	→	13	500	0.230	26	5	↔	23	500	0.307

Table 4.7: Notional IEP Electrical Arcs

Edge #	Start Node	Dir	End Node	FC ($)	VC ($ s/kg)	Edge #	Start Node	Dir	End Node	FC ($)	VC ($ s/kg)
1	1	→	2	2000	3.386	15	13	→	14	2000	1.411
2	2	→	3	2000	1.411	16	14	→	15	2000	1.129
3	3	→	4	2000	1.129	17	15	↔	16	4000	3.104
4	4	↔	5	4000	2.540	18	16	↔	5	2000	4.515
5	5	→	6	4000	1.129	19	16	→	17	2000	1.129
6	6	→	11	2000	0.847	20	17	→	20	2000	0.847
7	11	→	23	2000	2.257	21	15	↔	18	4000	2.540
8	4	↔	7	4000	3.104	22	18	→	19	4000	1.693
9	7	↔	18	2000	4.515	23	19	→	22	2000	0.847
10	7	→	8	4000	1.693	24	20	→	21	2000	1.411
11	8	→	9	2000	0.847	25	20	↔	23	2000	2.257
12	9	→	10	2000	2.257	26	22	↔	24	2000	2.257
13	9	↔	24	2000	2.257	27	23	↔	24	8000	10.159
14	12	→	13	2000	2.540						

Table 4.8: Notional IEP Thermal Arcs

4.8 Solution Flow Variables

The visualization of the solution variables is interesting and can lend insight into possible reconfigurations of the integrated engineering plant (IEP) for casualties and to validate the formulation is correct. However, conclusions cannot be drawn from these solutions regarding the best way for the plant to be reconfigured for a specific casualty. This is because the flows are part of an optimization to minimize overall capacity, not to optimize reconfiguration flows. What can be said regarding the values assigned to solution flow variables is that they support the minimum overall capacity (and hence the minimum objective) for the formulation. For example, refer to figure 4-3 for the following discussion. This visualization of the flow is for casualty "0" where there is no loss of any edge or node in the system. The flow may seem to indicate the minimum cost flow to reconfigure the IEP, but this cannot be assumed because it is not individual flow variables that are being minimized by the solver. The flow shown in the solution meets all the requirements of the formulation (all the constraints are satisfied). The propulsion motors' total power flow is 20 MW (PM #1 is assuming all the propulsion electrical load) as required by constraint (See Equation 3.8). There could possibly be other values for the flow variables for casualty 0 that satisfy all the constraints of the formulation but yet do not affect the objective (to decrease or increase it). The values of flow in this case would be called a degenerate solution. A degenerate solution is a unique solution that does not further reduce the objective, so it is inconsequential. This is the point being made; that no conclusion regarding the flow for any casualty situation can be assumed to be an ideal or optimal reconfiguration of the IEP when flow is not being directly minimized.

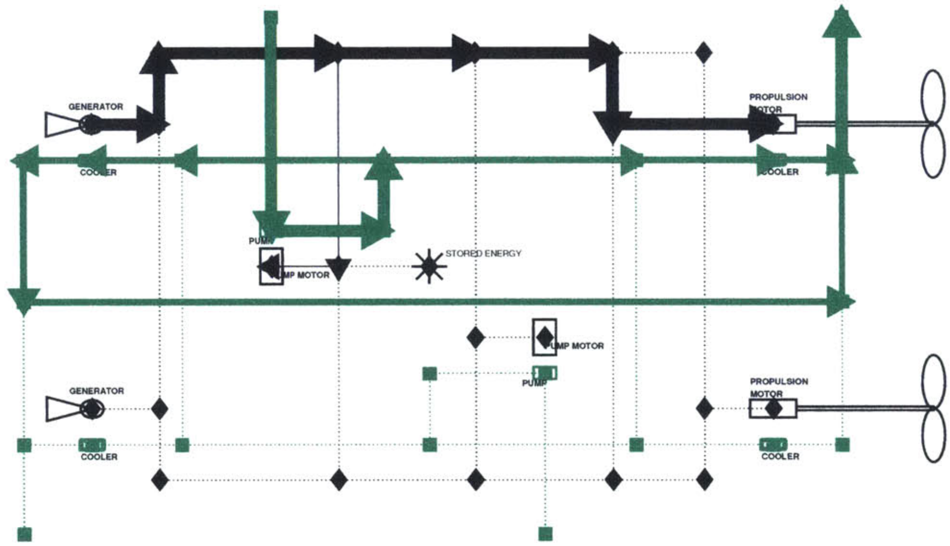
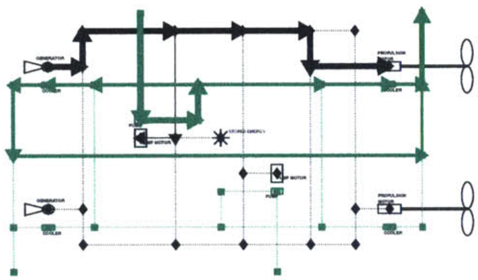


Figure 4-3: Notional IEP Solution Flow - No Casualty

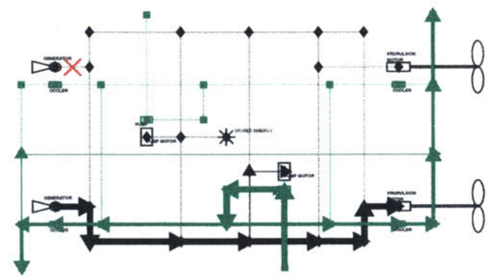
4.9 Visual Display of Solution Flow Variables

As discussed in Chapter 3, the solver is searching the design space and determining the minimum overall capacity of the dual domain integrated engineering plant (IEP). The formulation is made up of unique sets of flow variables modeling the electrical power and cooling mass flow physics in the presence of casualty and operating conditions. In the process of finding the minimum possible objective value, the solver stores the values of the flow variables for every casualty and operating condition. These flow values satisfy the physics constraints of the formulation for continuity and supply of the required loads throughout the system. Together, they also represent values that support the minimum objective, but as individual sets of values, they do not necessarily represent optimal flow solutions. There is, however, some benefit to studying them, as an audit of them will confirm the minimum capacity solution and they can show possible (although not necessarily optimal) plant reconfigurations in the presence of casualties.

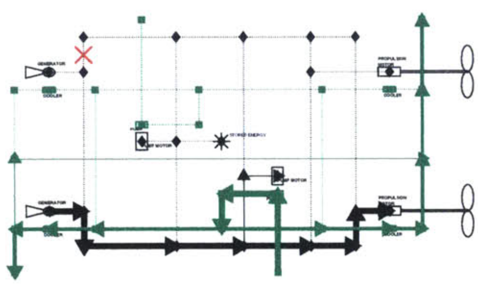
In Figures 4-4 through 4-10, several flow conditions are shown with the flow variables illustrated with line thickness proportional to flow and arrows to show the direction of flow. Each diagram shows which edge was lost by placement of a red "X." The final diagram shows the loss of normal power to the #1 cooling pump motor and the activation of the ESD. The value of power flow for the stored energy device (SED) is that needed to supply the emergency load. In conjunction with the designer input for how long a load must be sustained by survivability specifications, the designer can calculate the minimum energy required in the design for that device.



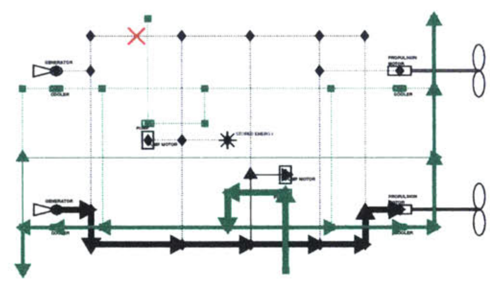
(a) #0 No Loss



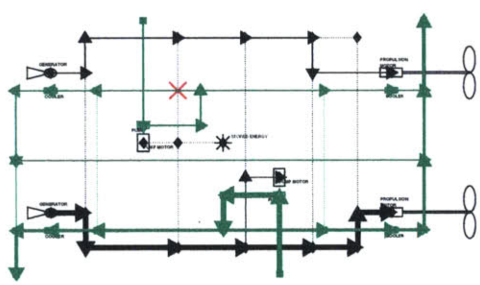
(b) #1 Loss of Electrical Edge 1



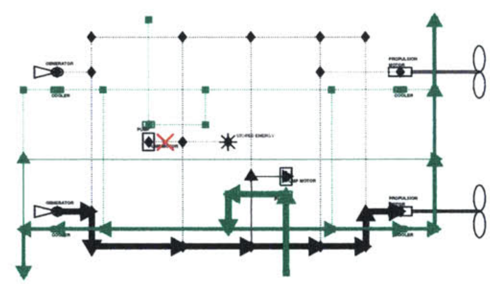
(c) #2 Loss of Electrical Edge 2



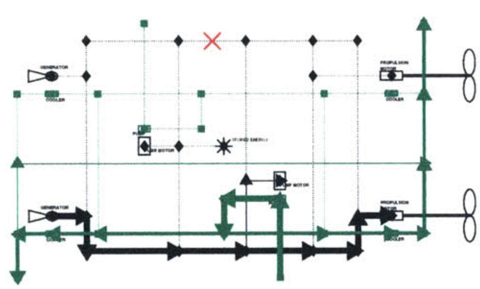
(d) #3 Loss of Electrical Edge 3



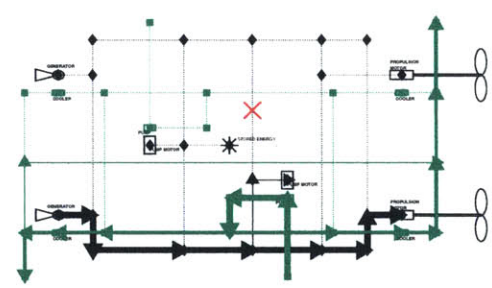
(e) #4 Loss of Electrical Edge 4



(f) #5 Loss of Electrical Edge 5

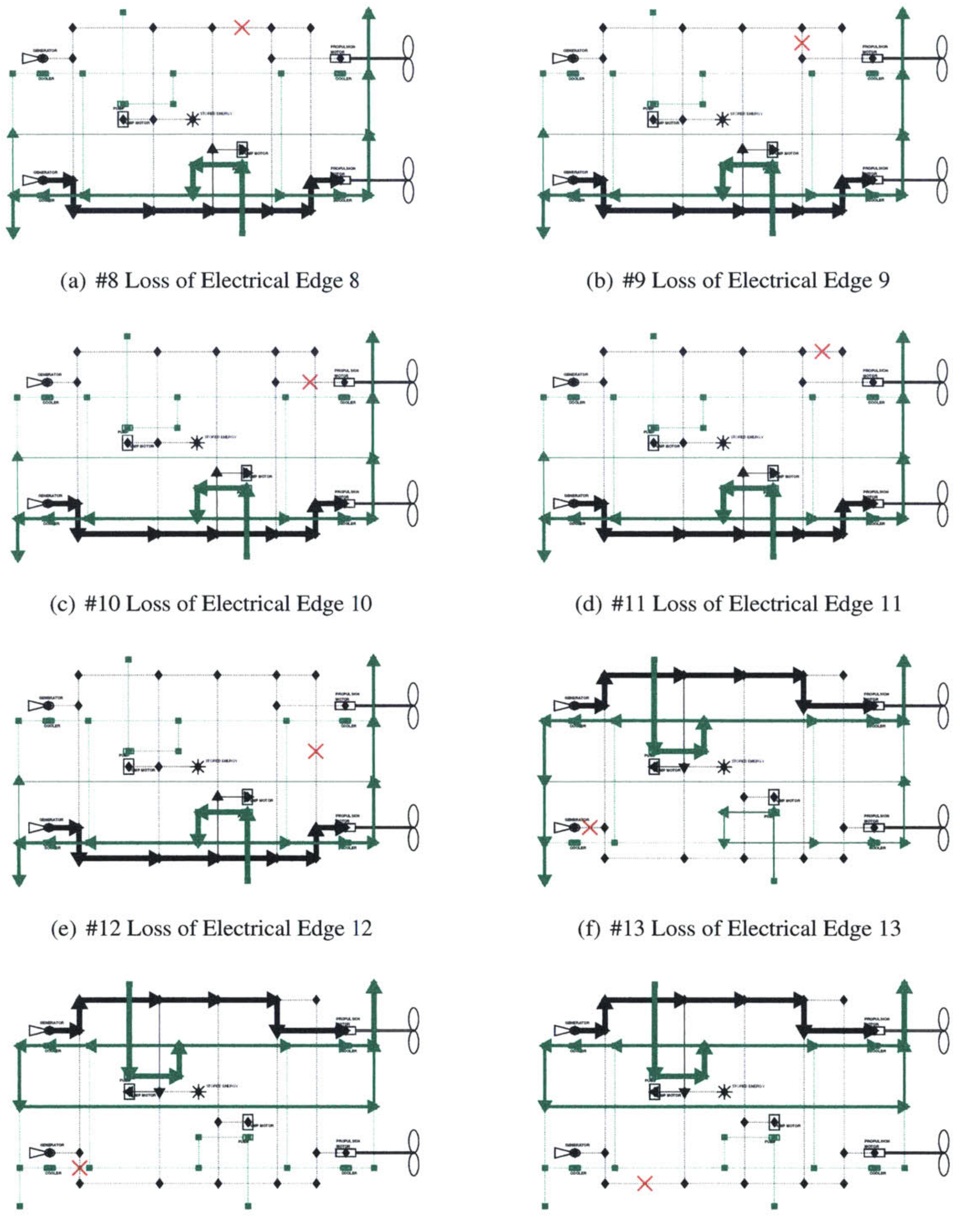


(g) #6 Loss of Electrical Edge 6



(h) #7 Loss of Electrical Edge 7

Figure 4-4: Notional IEP Solution Flows Casualties #0 - #7



(a) #8 Loss of Electrical Edge 8

(b) #9 Loss of Electrical Edge 9

(c) #10 Loss of Electrical Edge 10

(d) #11 Loss of Electrical Edge 11

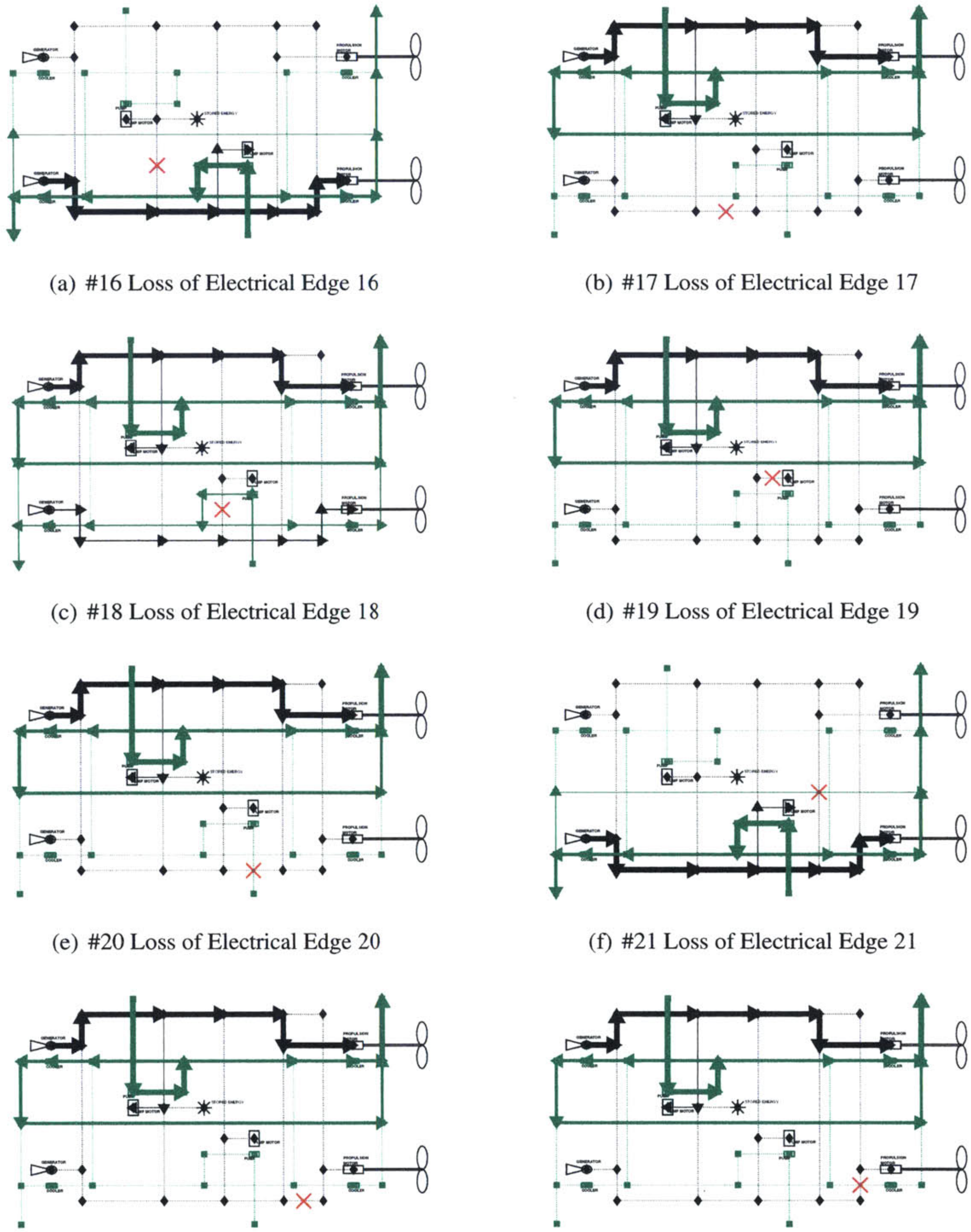
(e) #12 Loss of Electrical Edge 12

(f) #13 Loss of Electrical Edge 13

(g) #14 Loss of Electrical Edge 14

(h) #15 Loss of Electrical Edge 15

Figure 4-5: Notional IEP Solution Flows Casualties #8 - #15



(a) #16 Loss of Electrical Edge 16

(b) #17 Loss of Electrical Edge 17

(c) #18 Loss of Electrical Edge 18

(d) #19 Loss of Electrical Edge 19

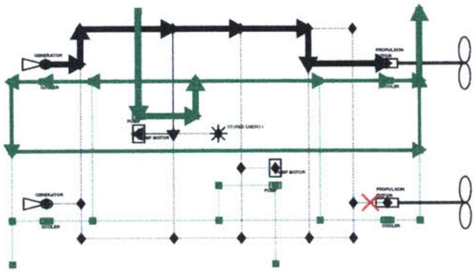
(e) #20 Loss of Electrical Edge 20

(f) #21 Loss of Electrical Edge 21

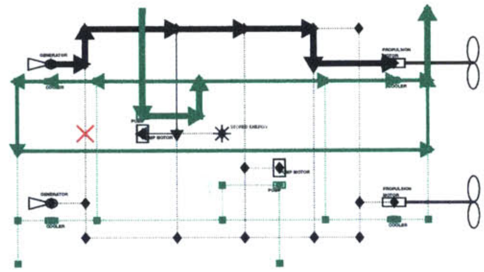
(g) #22 Loss of Electrical Edge 22

(h) #23 Loss of Electrical Edge 23

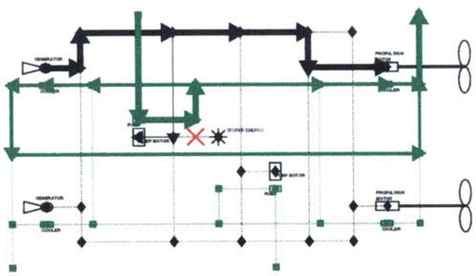
Figure 4-6: Notional IEP Solution Flows Casualties #16 - #23



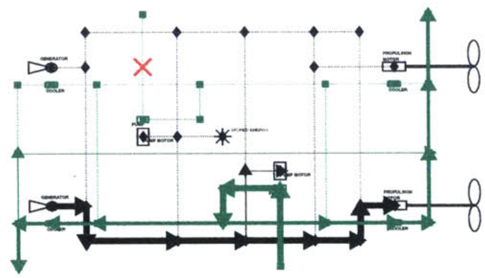
(a) #24 Loss of Electrical Edge 24



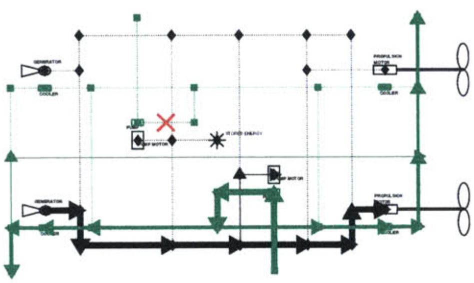
(b) #25 Loss of Electrical Edge 25



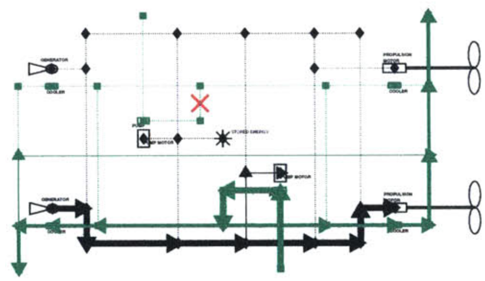
(c) #26 Loss of Electrical Edge 26



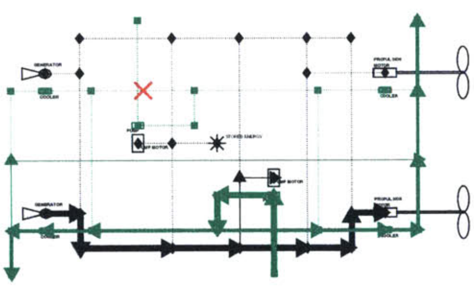
(d) #27 Loss of Cooling Edge 1



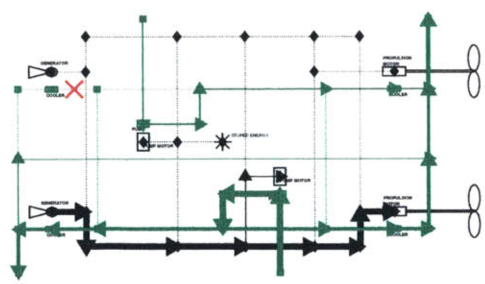
(e) #28 Loss of Cooling Edge 2



(f) #29 Loss of Cooling Edge 3

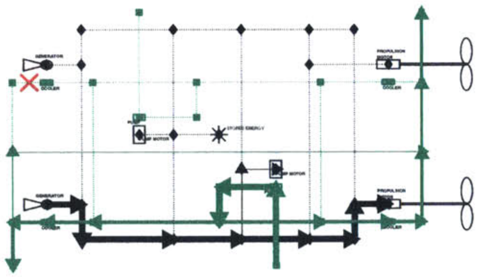


(g) #30 Loss of Cooling Edge 4

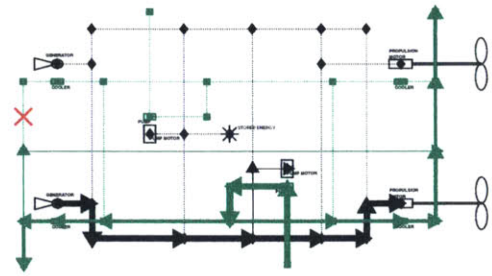


(h) #31 Loss of Cooling Edge 5

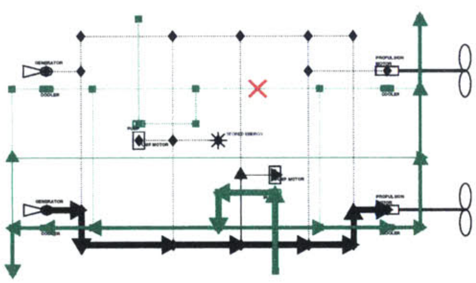
Figure 4-7: Notional IEP Solution Flows Casualties #24 - #31



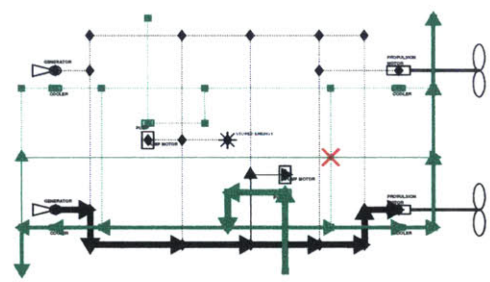
(a) #32 Loss of Cooling Edge 6



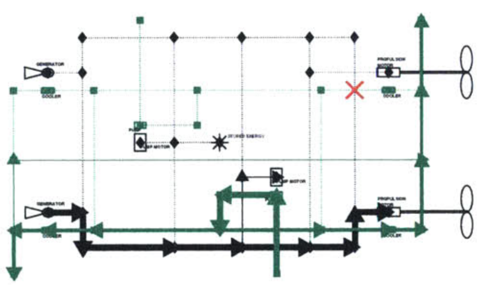
(b) #33 Loss of Cooling Edge 7



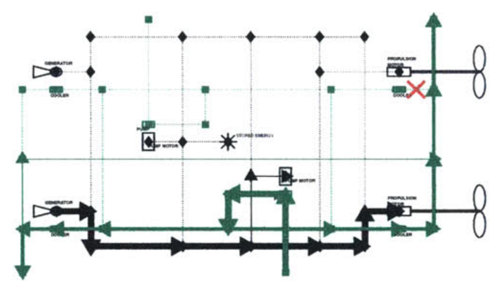
(c) #34 Loss of Cooling Edge 8



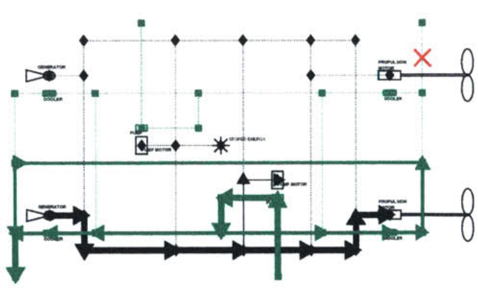
(d) #35 Loss of Cooling Edge 9



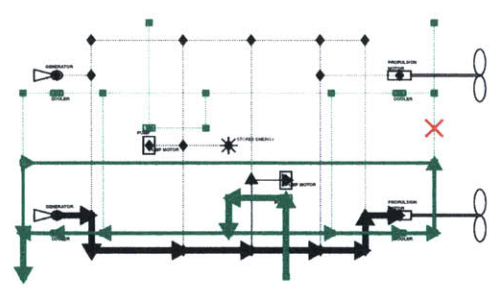
(e) #36 Loss of Cooling Edge 10



(f) #37 Loss of Cooling Edge 11

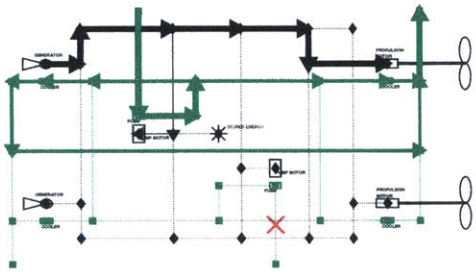


(g) #38 Loss of Cooling Edge 12

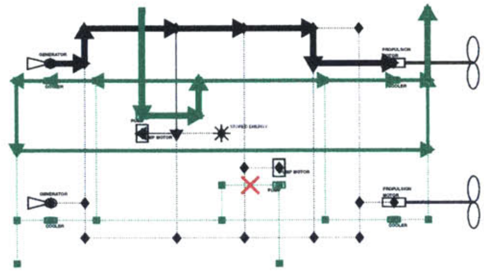


(h) #39 Loss of Cooling Edge 13

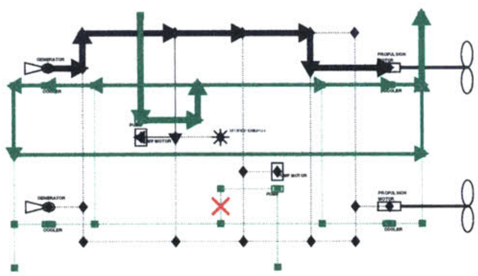
Figure 4-8: Notional IEP Solution Flows Casualties #32 - #39



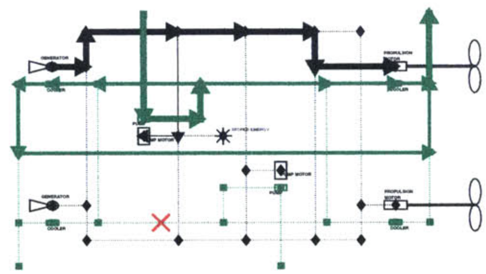
(a) #40 Loss of Cooling 14



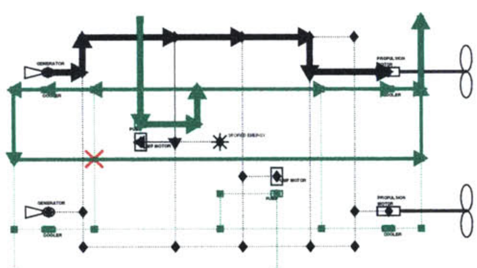
(b) #41 Loss of Cooling Edge 15



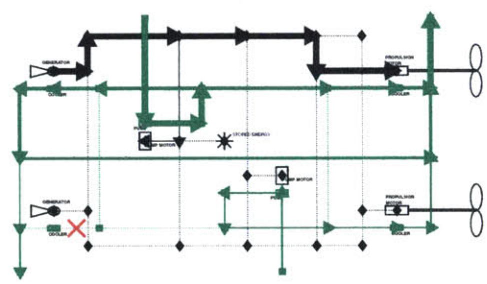
(c) #42 Loss of Cooling Edge 16



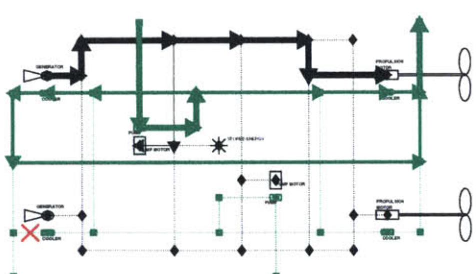
(d) #43 Loss of Cooling Edge 17



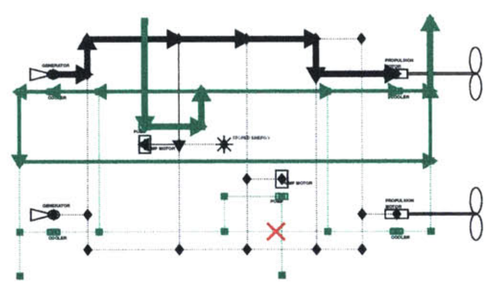
(e) #44 Loss of Cooling Edge 18



(f) #45 Loss of Cooling Edge 19

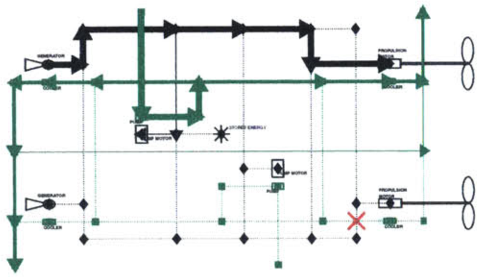


(g) #46 Loss of Cooling Edge 20

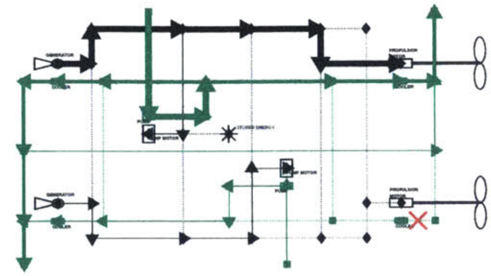


(h) #47 Loss of Cooling Edge 21

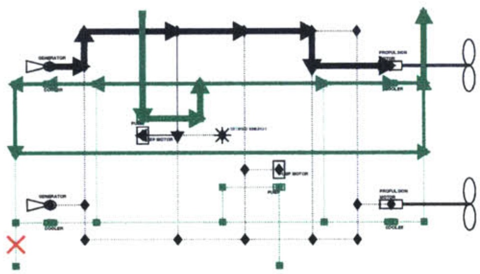
Figure 4-9: Notional IEP Solution Flows Casualties #40 - #47



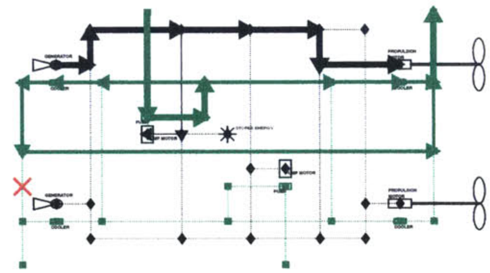
(a) #48 Loss of Cooling Edge 22



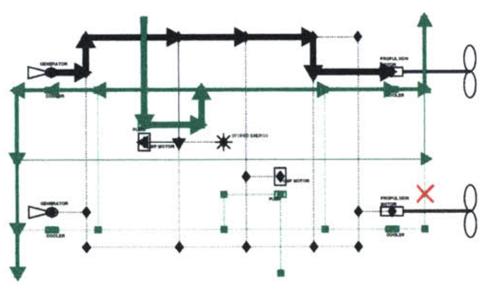
(b) #49 Loss of Cooling Edge 23



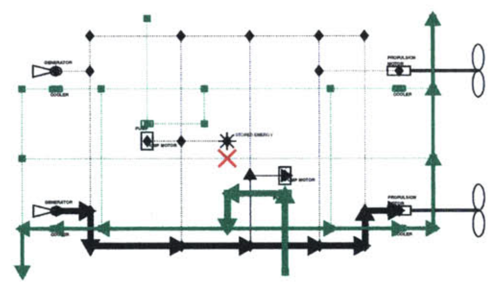
(c) #50 Loss of Cooling Edge 24



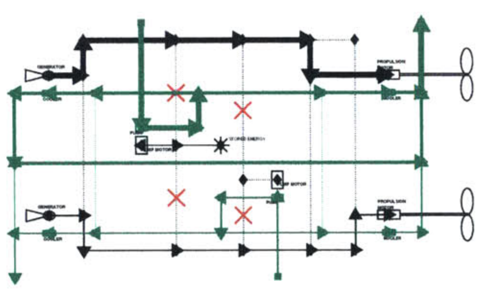
(d) #51 Loss of Cooling Edge 25



(e) #52 Loss of Cooling Edge 26



(f) #53 Loss of Cooling Edge 27



(g) #54 Loss of Normal Power to Cooling Pump 1

Figure 4-10: Notional IEP Solution Flows Casualties #48 - #54

4.10 Conclusions

The Notional IEP is used in this work to demonstrate the proposed method for design of a survivable minimum cost IEP. Table 4.9 shows the savings of the plant from the optimization method. The savings shown are that of the solution vs. the input (candidate) plant. The purpose of the method is not to save capacity or cost over the candidate plant, however. The purpose is to find the minimum cost IEP for the survivability and operating condition specifications given. The data in Table 4.9 shows that the solver is reducing the topology and capacity of the IEP and the solver certificates validate that the solution is the minimum cost.

	Electrical	**Seawater**
Possible Edges	26	27
Actual Edges	20	25
Edge Savings	**23.1%**	**7.4%**
Possible Cost	$ 17,617	$ 75,914
Actual Cost	$ 14,117	$ 71,914
Cost Savings	**19.9%**	**5.3%**

Table 4.9: Edge and Cost Savings M-1 Survivability Over Candidate Topology

In Figure 4-2 it can be seen that all the electrical and thermal cross-connections were deleted from the candidate plant for the minimum cost solution. This is due to the fact that the plant has at least two redundancy features. First, the electrical and cooling plants are zonal distribution, which allows supply from both port and starboard distribution busses. Second, the components are redundant. Each SM can supply the entire load, each seawater pump can supply the entire cooling load, and each PM can supply the propulsion load. Therefore, for M-1 survivability the cross-connects are not needed. If the survivability specification were more robust, requiring more of the plants to be disabled or large sections disabled, the IEP solution would become more redundant and could require the cross-connects.

Chapter 5

NSMCF Applied to the Naval Combat Survivability (NCST) IEP Testbed

5.1 Description of the NCST

The Naval Combat Survivability Testbed (NCST) is located at Purdue University and is funded by the Electric Ship Research and Development Consortium (ESRDC) for the advance of integrated power systems and survivability studies. The NCST is a small scale land-based prototype system designed to test dynamic behavior of an integrated power system. It is used to study reliability, survivability and quality of power of a ring-bus zonal electrical distribution (ZED) medium voltage DC (MVDC) system (note: the name of the NCST has recently been changed to Purdue's Reduced Scale Naval DC Microgrid).

The NCST relies on air cooling of its electrical components. However, for the purpose of study of interdependent system concerns, a virtual cooling system has been derived and the integrated engineering plant (IEP) (actual electrical system plus virtual cooling system) is the subject of several published works, including [18], [16], [13] among others. In [16], linear programming is used to simulate the reconfiguration and survivability of the IEP in the presence of combat damage.

5.2 Modeling Naval Combat Survivability Testbed (NCST)

The NCST plant is the topic of other literature so only a brief explanation follows here. A good description of the plant can be found in work by Cramer [16]. The first step in modeling the system to apply the non-simultaneous multicommodity flow method of optimization is to number the nodes. This allows the definition of unique flow variables. It can be useful to number the nodes in an organized way, but it is not necessary. The nodes can be numbered in any arbitrary way and the numbering of the edges of the system then be manual or automated. A common numbering convention for shipboard application is to number equipment (generators, propulsion motors, other nodes) increasing from forward to aft and centerline to outboard, with normal convention being even number nodes on the port side and odd numbers on the starboard side. The numbering of the electrical, seawater and freshwater systems is shown in Tables 5.1 through 5.6. In the tables for edges in the system, the direction (Dir) of the flow is shown as $\leftarrow$, $\leftrightarrow$, or $\rightarrow$. The $\leftarrow$ denotes flow is positive and limited to flow from the end node to the start node. The $\leftrightarrow$ denotes the flow is bidirectional, and $\rightarrow$ denotes flow is positive and limited to flow from start node to end node. This is used for convention as well as prohibiting the formulation from violating the laws of physics for the problem. The fixed and variable cost for each edge is shown in the tables. The fixed cost (FC) is associated with installation or lifecycle cost for the edge, whereas the variable cost (VC) is the material cost. Installation cost is generally driven by the number of bulkheads that are crossed by the edge, but can include any known costs associated with the existence of an edge. Fixed cost is in \$ and variable cost is in ¢ per kW (capacity) for the electrical system and ¢ per kg/s (capacity) for the cooling systems.

5.2.1 NCST Electric Plant

The NCST electric plant is shown in Figure 5-2. There are several unique features of the NCST compared to the notional plant discussed in Chapter 4. The NCST plant has several electrical power conversion devices - power supplies (PSs), which rectify and filter the output of the generators (synchronous machines SMs). The SMs have a 69 kW rating each and are designed to provide full power to the ship if only one SM is available. The prime movers (PMs) are not modeled for this application. The propulsion drives (PDs) which power the propellors, have 60 kW rating each. The converter modules (CMs) convert distribution DC voltage to zonal supply DC voltage. Finally, inverter modules (IMs) convert DC to AC to power electrical loads, such as the seawater and freshwater pump motors. The models for the conversion devices simulate approximately 90% efficiency [53], so there is a loss of 10% electrical power passing through the devices. This 10% lost power is also simulated as being removed as heat by the associated cooling system. For the purpose of this early stage design application, the electrical losses are approximated as varying linearly with power input.

5.2.2 NCST Seawater Cooling System

The NCST seawater system is shown in Figure 5-3. The seawater cooling system has three pumps, all of which have power laws modeled as in Chapter 4; pump motor power is cubic with mass flow rate. The cooling loads on the system are the 2 synchronous machines (SMs), the 2 propulsion motors (PMs), and the seawater-to-freshwater heat exchangers (FHXs). As shown in Figure 5-3, the component heat exchangers (CHXs) are labeled, numbered and assigned to each major cooler. The seawater pumps are modeled as FFG-7 seawater circulating pumps with rating 18.6 kW, 740 gpm. The FHXs are assumed to have 90% efficiency. Branch numbers (SWBs) are shown on the schematic in Figure 5-3.

5.2.3 NCST Freshwater Cooling System

The NCST freshwater system is shown in Figure 5-4. There are three freshwater loops shown (FWLS 1, 2 & 3). The freshwater loads are defined by constitutive relationships as discussed in Chapter 3. The cumulative cooling required by all the freshwater loads in each loop becomes the demand on the freshwater pump in that loop. Although there is no redundancy in the freshwater system, redundancy is accomplished by the vital loads in the three electrical zones. The FHXs are modeled both as a heat exchanger and pump combination. There are two constitutive relations governing each. The first is the thermal relationship between the freshwater and seawater:

$$Q_{sw} = \eta_{cool}\, Q_{fw}$$
$$Q_{fw} = \dot{m} c_p \Delta T$$

c_p is the specific heat capacity of seawater, η_{cool} is the efficiency of the cooler, taking into account the incomplete mixing of fluid, and ΔT is the design temperature difference across the outlet to inlet of the seawater side of the heat exchanger.

The second constitutive relationship is electrical pump loads, governed by pump power laws. The required seawater mass flow rate through the cooler is modeled as described in Section 3.8.4 and the pump curve linear approximation is modeled as described in Section 3.8.5.

Table 5.1: NCST Electrical System Nodes

Node #	X (m)	Y (m)	Z (m)	Component Rating (kW)	Node #	X (m)	Y (m)	Z (m)	Component Rating (kW)
1	44.5	-3.66	4.11	SM 1 (69)	39	111.03	4.57	3.04	CM 6 (10)
2	44.5	-3.66	4.72	-	40	111.03	4.57	5.495	-
3	44.5	-4.08	4.72	-	41	39.84	-4.57	9.21	-
4	82.91	-4.08	4.72	PD 1 (60)	42	39.84	0.00	9.21	-
5	44.5	-3.66	2.46	-	43	38.60	0.00	9.21	-
6	44.5	0.00	2.46	-	44	39.84	4.57	9.21	-
7	41.45	0.00	2.46	PS 1 (30)	45	39.84	0.00	9.21	-
8	92.96	-0.61	5.79	SM 2 (69)	46	36.12	0.00	13.72	IM 1 (10)
9	92.96	-0.61	4.72	-	47	36.12	0.00	9.21	-
10	92.96	4.08	4.72	-	48	64.60	-4.57	8.25	-
11	82.91	4.08	5.79	PD 2 (60)	49	64.60	0.00	8.25	-
12	92.96	-0.61	5.56	-	50	64.34	0.00	8.25	-
13	92.96	0.00	5.56	-	51	64.60	4.57	8.25	-
14	91.82	0.00	5.56	PS 2 (30)	52	64.60	0.00	8.25	-
15	39.84	-7.32	5.49	-	53	63.81	0.00	10.86	IM 2 (10)
16	50.60	-7.32	5.49	-	54	63.81	0.00	8.25	-
17	88.09	-7.32	5.49	-	55	111.03	-4.57	8.25	-
18	111.03	-7.32	5.49	-	56	111.03	0.00	8.25	-
19	39.84	7.32	5.49	-	57	110.57	0.00	8.25	-
20	50.60	7.32	5.49	-	58	111.03	4.57	8.25	-
21	88.09	7.32	5.49	-	59	111.03	0.00	8.25	-
22	111.03	7.32	5.49	-	60	109.65	0.00	10.86	IM 3 (10)
23	41.45	0.00	5.49	-	61	109.65	0.00	8.25	-
24	41.45	-7.32	5.49	-	62	36.12	0.00	2.47	-
25	39.84	-4.57	10.86	CM 1 (10)	63	50.29	0.00	2.47	SWP 1 (10)

(Electrical system nodes continued on next page)

Table 5.1: NCST Electrical System Nodes (continued)

Node #	X (m)	Y (m)	Z (m)	Component Rating (kW)	Node #	X (m)	Y (m)	Z (m)	Component Rating (kW)
26	39.84	-4.57	5.49	-	64	63.81	0.00	2.47	-
27	64.60	-4.57	10.86	CM 2 (10)	65	77.11	0.00	2.47	SWP 2 (10)
28	64.60	-4.57	5.49	-	66	109.65	0.00	2.47	-
29	64.60	-7.32	5.49	-	67	88.39	0.00	2.47	SWP 3 (10)
30	111.03	-4.57	10.86	CM 3 (10)	68	36.12	0.00	2.46	-
31	111.03	-4.57	5.49	-	69	36.12	-0.11	2.46	-
32	91.82	0.00	5.49	-	70	39.82	-0.11	2.46	FHX 1 (10)
33	91.82	7.32	5.49	-	71	63.81	0.00	3.04	-
34	39.84	4.57	3.04	CM 4 (10)	72	63.81	0.08	3.04	-
35	39.84	4.57	5.49	-	73	64.30	0.08	3.04	FHX 2 (10)
36	64.60	4.57	3.0	CM 5 (10)	74	109.65	0.00	3.04	-
37	64.60	4.57	5.49	-	75	105.89	0.00	3.04	FHX 3 (10)
38	64.60	7.32	5.49	-					

Table 5.2: NCST Electrical System Edges

Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)	Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)
SM 1 to PD 1						CM 1 to ZDCB 1					
1	1	2	↔	500	9.36	39	25	41	↔	500	25.3
2	2	3	↔	500	6.45	40	41	42	↔	500	70.1
3	3	4	↔	4500	589	41	42	43	↔	500	19.0
SM 1 to PS 1						CM 4 to ZDCB 1					
4	1	5	↔	500	25.3	42	15	18	↔	500	94.7
5	5	6	↔	500	56.2	43	16	18	↔	500	70.1
6	6	7	↔	500	46.8	44	16	17	↔	500	19.0
SM 2 to PD 2						IM 1 to ZDCB 1					
7	8	9	↔	500	16.4	45	18	19	↔	500	69.2
8	9	10	↔	500	72.0	46	9	19	↔	500	38.1
9	10	11	↔	1500	154	CM 2 to ZDCB 2					
SM 2 to PS 2						47	27	48	↔	500	40.1
10	8	12	↔	500	3.53	48	20	21	↔	500	70.1
11	12	13	↔	500	9.36	49	20	22	↔	500	3.99
12	13	14	↔	500	17.5	CM 5 to ZDCB 2					
PDCB 1 to Zone 1						50	36	51	↔	500	80.0
13	15	24	↔	500	24.7	51	51	52	↔	500	70.1
14	16	24	↔	1500	140	52	52	50	↔	500	3.99
PDCB 1 to Zone 2						IM 2 to ZDCB 2					
15	16	29	↔	1500	215	53	53	54	↔	500	40.1
16	17	29	↔	2500	361	54	50	54	↔	500	8.13
PDCB 1 to Zone 3						CM 3 to ZDCB 3					
17	17	18	↔	2500	352	55	30	55	↔	500	40.1
PDCB 2 to Zone 1						56	55	56	↔	500	70.1

(Electrical system edges continued on next page)

Table 5.2: NCST Electrical System Edges (continued)

Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)	Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)
18	19	20	↔	1500	165	57	56	57	↔	500	7.06
PDCB 2 to Zone 2						CM 6 to ZDCB 3					
19	20	38	↔	1500	214	58	39	58	↔	500	80.0
20	21	38	↔	2500	361	59	58	59	↔	500	70.1
PDCB 2 to Zone 3						60	57	59	↔	500	7.06
21	21	33	↔	500	57.2	IM 3 to ZDCB 3					
22	22	23	↔	2500	295	61	60	61	↔	500	40.1
PS 1 to PDCB 1						62	57	59	↔	500	14.1
23	7	23	↔	500	46.5	IM 1 to SWP 1					
24	23	24	↔	1500	112	63	46	62	↔	1500	173
PS 1 to PDCB 1						64	62	63	↔	1500	217
25	25	26	↔	500	82.4	IM 2 to SWP 2					
26	15	26	↔	500	42.2	65	53	64	↔	1500	129
CM 2 to PDCB 1						66	64	65	↔	1500	204
27	27	28	↔	500	82.4	IM 3 to SWP 3					
28	28	29	↔	500	42.2	67	60	66	↔	1500	129
CM 3 to PDCB 1						68	66	67	↔	2500	326
29	30	31	↔	500	82.4	IM 1 to FHX 1					
30	18	31	↔	500	42.2	69	46	68	↔	500	173
PS 2 to PDCB 2						70	68	69	↔	500	1.69
31	14	32	↔	500	1.07	71	69	70	↔	500	56.8
32	32	33	↔	500	112	IM 2 to FHX 2					
CM 4 to PDCB 2						72	53	71	↔	1500	120
33	34	35	↔	500	37.6	73	71	72	↔	500	1.23
34	19	35	↔	500	42.2	74	72	73	↔	500	7.52

(Electrical system edges continued on next page)

Table 5.2: NCST Electrical System Edges (continued)

Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)	Edge #	Start Node	End Node	Dir	FC ($)	VC (¢/kW)
CM 5 to PDCB 2						IM 3 to FHX 3					
35	36	37	↔	500	37.6	75	60	74	↔	500	120
36	37	38	↔	500	42.2	76	74	75	↔	500	57.7
CM 6 to PDCB 2											
37	39	40	↔	500	37.6						
38	22	40	↔	500	42.2						

Table 5.3: NCST Seawater System Nodes

Node #	X (m)	Y (m)	Z (m)	SW Compt/ Cooled	Node #	X (m)	Y (m)	Z (m)	SW Compt/ Cooled
1	38.40	0.00	2.47	-	20	106.68	-4.57	2.47	-
2	38.40	4.57	2.47	-	21	38.40	0.00	2.46	-
3	50.29	4.57	2.47	-	22	38.40	-0.11	2.46	-
4	65.23	4.57	2.47	-	23	39.82	-0.11	2.46	FHX 1
5	77.11	4.57	2.47	-	24	65.23	4.57	4.72	-
6	88.39	4.57	2.47	-	25	65.23	4.08	4.72	-
7	106.68	4.57	2.47	-	26	82.91	4.08	4.72	CHX 3/PD 2
8	106.68	0.00	2.47	-	27	65.23	0.30	3.04	-
9	38.40	-3.66	2.47	-	28	65.23	0.08	3.04	-
10	50.29	0.00	2.47	SWP 1	29	64.30	0.08	3.04	FHX 2
11	65.23	0.30	2.47	-	30	65.23	-4.57	4.72	-
12	77.11	0.00	2.47	SWP 2	31	65.23	-4.08	4.72	-
13	88.39	0.00	2.47	SWP 3	32	82.91	-4.08	4.72	CHX 2/PD 1
14	106.68	-0.61	2.47	-	33	106.68	0.00	3.04	-

(Seawater system nodes continued on next page)

Table 5.3: NCST Seawater System Nodes (continued)

Node #	X (m)	Y (m)	Z (m)	SW Compt/ Cooled	Node #	X (m)	Y (m)	Z (m)	SW Compt/ Cooled
15	50.29	-4.57	2.47	-	34	105.89	0.00	3.04	FHX 3
16	65.23	-4.57	2.47	-	35	106.68	-0.61	5.79	-
17	77.11	-4.57	2.47	-	36	92.96	-0.61	5.79	CHX 4/SM 2
18	88.39	-4.57	2.47	-	37	38.40	-3.66	4.11	-
19	38.40	-4.57	2.47	-	38	44.50	-3.66	4.11	CHX 1/SM 1

Table 5.4: NCST Seawater System Edges

Edge #	Start Node	End Node	Dir	FC (k\$)	VC ($\$ s/kg$)	Edge #	Start Node	End Node	Dir	FC (k\$)	VC ($\$ s/kg$)
	SWB 1						SWB 17				
1	1	2	$\leftrightarrow$	2	1.29	20	15	16	$\leftrightarrow$	4	4.22
2	2	3	$\leftrightarrow$	4	3.36		SWB 18				
	SWB 2					21	16	17	$\leftrightarrow$	4	3.35
3	3	4	$\leftrightarrow$	8	4.22		SWB 19				
	SWB 3					22	17	18	$\leftrightarrow$	4	3.18
4	4	5	$\leftrightarrow$	4	3.35		SWB 20				
	SWB 4					23	18	20	$\leftrightarrow$	8	5.16
5	5	6	$\leftrightarrow$	4	3.18	24	14	20	$\leftrightarrow$	2	1.12
	SWB 5						SWB L1				
6	6	7	$\leftrightarrow$	4	5.16	25	1	21	$\rightarrow$	2	0.003
7	7	8	$\leftrightarrow$	8	1.29	26	21	22	$\rightarrow$	2	0.031
	SWB 6					27	22	23	$\rightarrow$	2	0.401
8	1	9	$\leftrightarrow$	2	1.03		SWB L2				
	SWB 7					28	4	24	$\rightarrow$	2	0.635

(Seawater system edges continued on next page)

Table 5.4: NCST Seawater System Edges (continued)

Edge #	Start Node	End Node	Dir	FC (k\$)	VC (\$ s/kg)	Edge #	Start Node	End Node	Dir	FC (k\$)	VC (\$ s/kg)
9	3	10	↔	2	1.29	29	24	25	→	2	0.138
	SWB 8					30	25	26	→	8	4.99
10	4	11	↔	2	1.20		SWB L3				
	SWB 9					31	11	27	→	2	0.161
11	5	12	↔	2	1.29	32	27	28	→	2	0.062
	SWB 10					33	28	29	→	2	0.262
12	6	13	↔	2	1.29		SWB L4				
	SWB 11					34	16	30	→	2	0.635
13	8	14	↔	2	0.172	35	30	31	→	2	0.138
	SWB 12					36	31	328	→	8	4.99
14	10	15	↔	2	1.29		SWB L5				
	SWB 13					37	8	33	→	2	0.161
15	11	16	↔	2	1.37	38	33	34	→	2	0.223
	SWB 14						SWB L6				
16	12	17	↔	2	1.29	39	14	35	→	2	0.937
	SWB 15					40	35	36	→	4	3.87
17	13	18	↔	2	1.29		SWB L7				
	SWB 16					41	9	37	→	2	0.463
18	9	19	↔	2	.257	42	37	38	→	2	1.72
19	15	19	↔	4	3.36						

Table 5.5: NCST Freshwater System Nodes

Node #	X (m)	Y (m)	Z (m)	Name	Elec Edge	Node #	X (m)	Y (m)	Z (m)	Name	Elec Edge
1	39.82	-0.11	2.46	FHX	-	16	64.60	-4.57	10.86	FWC	47
2	39.82	0.00	2.46	-	-	17	64.30	4.57	3.04	-	-
3	41.45	0.00	2.46	FWC	23	18	64.60	4.57	3.04	FWC	35
4	39.82	-0.11	10.86	-	-	19	64.30	0.00	10.86	-	-
5	39.82	-4.57	10.86	-	-	20	63.81	0.00	10.86	FWC	65
6	39.84	-4.57	10.86	FWC	39	21	105.89	0.00	3.04	FHX	-
7	39.82	-0.11	3.04	-	-	22	105.89	0.00	5.56	-	-
8	39.82	4.57	3.04	-	-	23	91.82	0.00	5.56	FWC	31
9	39.84	4.57	3.04	FWC	33	24	105.89	0.00	10.86	-	-
10	39.82	-0.11	13.72	-	-	25	105.89	-4.57	10.86	-	-
11	39.82	0.00	13.72	-	-	26	111.03	-4.57	10.86	FWC	29
12	36.12	0.00	13.72	FWC	63	27	105.89	4.57	3.04	-	-
13	64.30	0.08	3.04	FHX	-	28	111.03	4.57	3.04	-	-
14	64.30	0.08	10.86	-	-	29	109.65	0.00	10.86	FWC	67
15	64.30	-4.57	10.86	-	-						

Table 5.6: NCST Freshwater System Edges

Edge #	Start Node	End Node	Dir	FC (k$)	VC ($ s/kg)	Edge #	Start Node	End Node	Dir	FC (k$)	VC ($ s/kg)
FHX 1 to PS 1						FHX 2 to IM 2					
1	1	2	→	2	.031	17	13	14	→	2	2.21
2	2	3	→	2	.460	18	14	19	→	2	0.023
FHX 1 to CM 1						19	19	20	→	2	0.138
3	1	4	→	4	2.37	FHX 3 to PS 2					
4	4	5	→	2	1.26	20	21	22	→	2	0.711
5	5	6	→	2	.006	21	22	23	→	4	3.97
FHX 1 to CM 4						FHX 3 to CM 3					
6	1	7	→	2	0.164	22	21	24	→	4	2.21
7	7	8	→	2	1.32	23	24	25	→	2	1.29
8	8	9	→	2	0.056	24	25	26	→	2	1.45
FHX 1 to IM 1						FHX 3 to CM 6					
9	1	10	→	2	3.18	25	21	27	→	2	1.29
10	10	11	→	2	0.031	26	27	28	→	2	1.45
11	11	12	→	2	1.044	FHX 3 to IM 3					
FHX 2 to CM 2						27	21	24	→	4	2.21
12	13	14	→	4	2.21	28	24	29	→	2	1.06
13	14	15	→	2	1.31						
14	15	16	→	2	0.085						
FHX 2 to CM 5											
15	13	17	→	4	2.21						
16	17	18	→	2	0.023						

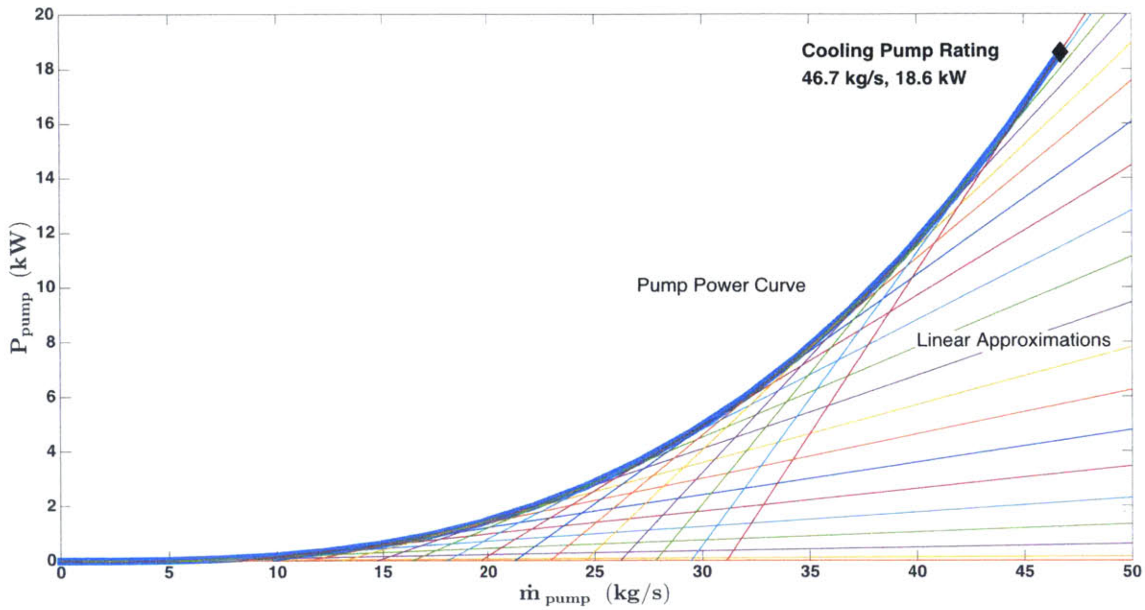


Figure 5-1: Pump Electrical Power vs. Mass Flow Rate

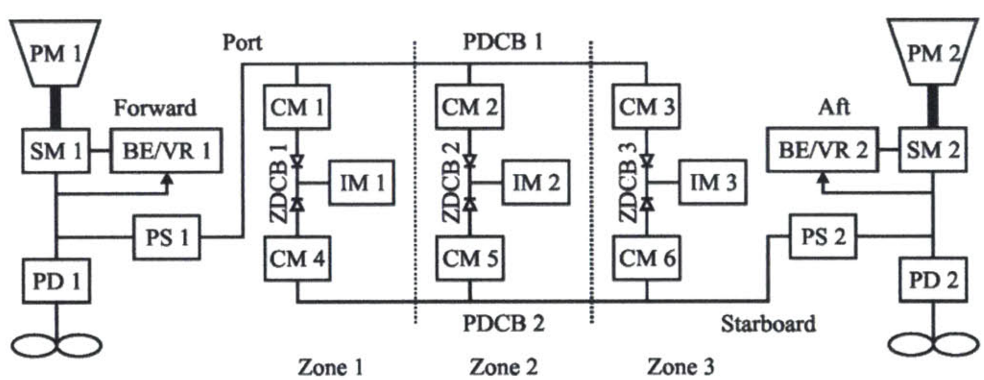


Figure 5-2: NCST Electrical System [16]

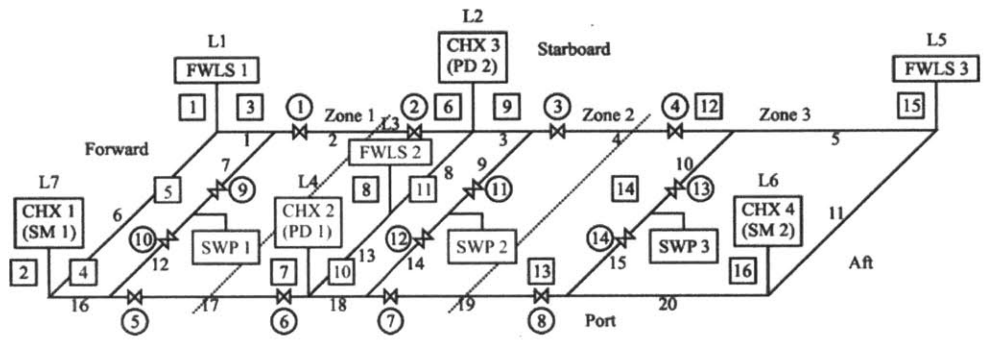


Figure 5-3: NCST Seawater System [16]

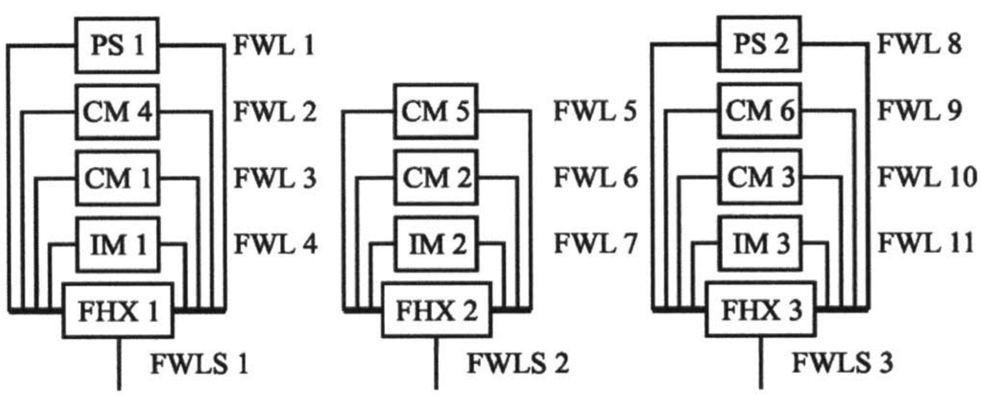


Figure 5-4: NCST Freshwater System [16]

5.3 Modeling Casualties & Mission Operating Conditions

The casualty set for this example is M-1 survivability. There are 146 total edges in the system (76 electrical, 42 seawater and 28 freshwater edges). The casualties in Table 5.7 shows the 71 individual casualties that simulates M-1 survivability. All 146 casualties are unnecessary since the 71 listed cover the loss of every connection between nodes in the integrated system.

5.4 Results & Conclusions

The purpose of modeling the Naval Combat Survivability Testbed (NCST) is to demonstrate that the proposed method will work on a more complex plant that includes a third domain (freshwater cooling). The NCST is also modeled slightly different than the notional plant in Chapter 4. The seawater and freshwater cooling systems dead-end at their respective loads; for the seawater system there is no sea suction or discharge modeling and the freshwater system has no mass flow return. These details are at the discretion of the designer.

For M-1 survivability, the solver deleted 42 of the 76 candidate electrical edges. The solver also deleted 15 of 42 seawater cooling edges and 14 of 28 freshwater cooling edges. Savings are shown in tabular form in Table 5.11.

5.4.1 Edge and Cost Savings

For the M-1 casualty set, Table 5.11 shows the savings over the candidate topology. These savings are significant, however, the intention here is not to claim large savings. The M-1 casualty specification (plant able to survive the loss of all edges any one at a time) is not particularly challenging for a zonal electrical distribution (ZED) architecture and it is shown that ZED is over-redundant for such a specification. The intention here is to show that the solver is working to delete unnecessary edges for the casualty set given.

Cas Op #	Cas Op Condition	Lost Function	Cas Op #	Cas Op Condition	Lost Function
1	$p_1, p_2, p_3 = 0$	SM 1 to PD 1	37	$q_5 = 0$	SWB 4
2	$p_4, p_5, p_6 = 0$	SM 1 to PS 1	38	$q_6, q_7 = 0$	SWB 5
3	$p_7, p_8, p_9 = 0$	SM 2 to PD 2	39	$q_8 = 0$	SWB 6
4	$p_{10}, p_{11}, p_{12} = 0$	SM 2 to PS 2	40	$q_9 = 0$	SWB 7
5	$p_{13}, p_{14} = 0$	PDCB 1 to Zone 1	41	$q_{10} = 0$	SWB 8
6	$p_{15}, p_{16} = 0$	PDCB 1 to Zone 2	42	$q_{11} = 0$	SWB 9
7	$p_{17} = 0$	PDCB 1 to Zone 3	43	$q_{12} = 0$	SWB 10
8	$p_{18} = 0$	PDCB 2 to Zone 1	44	$q_{13} = 0$	SWB 11
9	$p_{19}, p_{20} = 0$	PDCB 2 to Zone 2	45	$q_{14} = 0$	SWB 12
10	$p_{21}, p_{22} = 0$	PDCB 2 to Zone 3	46	$q_{15} = 0$	SWB 13
11	$p_{23}, p_{24} = 0$	PS 1 to PDCB 1	47	$q_{16} = 0$	SWB 14
12	$p_{25}, p_{26} = 0$	PDCB 1 to CM 1	48	$q_{17} = 0$	SWB 15
13	$p_{27}, p_{28} = 0$	PDCB 1 to CM 2	49	$q_{18}, q_{19} = 0$	SWB 16
14	$p_{29}, p_{30} = 0$	PDCB 1 to CM 3	50	$q_{20} = 0$	SWB 17
15	$p_{31}, p_{32} = 0$	PS 2 to PDCB 2	51	$q_{21} = 0$	SWB 18
16	$p_{33}, p_{34} = 0$	PDCB 2 to CM 4	52	$q_{22} = 0$	SWB 19
17	$p_{35}, p_{36} = 0$	PDCB 2 to CM 5	53	$q_{23}, q_{24} = 0$	SWB 20
18	$p_{37}, p_{38} = 0$	PDCB 2 to CM 6	54	$q_{25}, q_{26}, q_{27} = 0$	SWB L1
19	$p_{39}, p_{40}, p_{41} = 0$	CM 1 to ZDCB 1	55	$q_{28}, q_{29}, q_{30} = 0$	SWB L1
20	$p_{42}, p_{43}, p_{44} = 0$	CM 4 to ZDCB 1	56	$q_{31}, q_{32}, q_{33} = 0$	SWB L2
21	$p_{45}, p_{46} = 0$	ZDCB 1 to IM 1	57	$q_{34}, q_{35}, q_{36} = 0$	SWB L3
22	$p_{47}, p_{48}, p_{49} = 0$	CM 2 to ZDCB 2	58	$q_{37}, q_{38} = 0$	SWB L4
23	$p_{50}, p_{51}, p_{52} = 0$	CM 5 to ZDCB 2	59	$q_{39}, q_{40} = 0$	SWB L5
24	$p_{53}, p_{54} = 0$	ZDCB 2 to IM 2	60	$q_{41}, q_{42} = 0$	SWB L6
25	$p_{55}, p_{56}, p_{57} = 0$	CM 3 to ZDCB 3	61	$r_1, r_2 = 0$	FHX 1 to PS 1
26	$p_{58}, p_{59}, p_{60} = 0$	CM 6 to ZDCB 3	62	$r_3, r_4, r_5 = 0$	FHX 1 to CM 1
27	$p_{61}, p_{62} = 0$	ZDCB 3 to IM 3	63	$r_6, r_7, r_8 = 0$	FHX 1 to CM 4
28	$p_{63}, p_{64} = 0$	IM 1 to SWP 1	64	$r_9, r_{10}, r_{11} = 0$	FHX 1 to IM 1
29	$p_{65}, p_{66} = 0$	IM 2 to SWP 2	65	$r_{12}, r_{13}, r_{14} = 0$	FHX 2 to CM 2
30	$p_{67}, p_{68} = 0$	IM 3 to SWP 3	66	$r_{15}, r_{16} = 0$	FHX 2 to CM 5
31	$p_{69}, p_{70}, p_{71} = 0$	IM 1 to FHX 1	67	$r_{17}, r_{18}, r_{19} = 0$	FHX 2 to IM 2
32	$p_{72}, p_{73}, p_{74} = 0$	IM 2 to FHX 2	68	$r_{20}, r_{21} = 0$	FHX 3 to PS 2
33	$p_{75}, p_{76} = 0$	IM 3 to FHX 3	69	$r_{22}, r_{23}, r_{24} = 0$	FHX 3 to CM 3
34	$q_1, q_2 = 0$	SWB 1	70	$r_{25}, r_{26} = 0$	FHX 3 to CM 6
35	$q_3 = 0$	SWB 2	71	$r_{27}, r_{28} = 0$	FHX 3 to IM 3
36	$q_4 = 0$	SWB 3			

Table 5.7: NCST M-1 Survivability Casualty & Operating Conditions

Edge #	Capacity (kW)	Edge #	Capacity (kW)	Edge #	Capacity (kW)
1	60	27	-	53	-
2	60	28	-	54	-
3	60	29	-	55	-
4	5.00002	30	-	56	-
5	5.00002	31	5.00002	57	-
6	5.00002	32	5.00002	58	5.00002
7	60	33	-	59	5.00002
8	60	34	-	60	5.00002
9	60	35	-	61	5.00002
10	5.00002	36	-	62	5.00002
11	5.00002	37	5.00002	63	2e-5
12	5.00002	38	5.00002	64	2e-5
13	5.00002	39	-	65	-
14	-	40	5.00002	66	-
15	-	41	5.00002	67	2e-5
16	-	42	-	68	-
17	-	43	-	69	-
18	-	44	-	70	-
19	-	45	5.00002	71	-
20	-	46	5.00002	72	-
21	-	47	-	73	-
22	5.00002	48	-	74	-
23	5.00002	49	-	75	-
24	5.00002	50	-	76	-
25	5.00002	51	-		
26	5.00002	52	-		

Table 5.8: NCST M-1 Survivability Solution Electrical Capacities

Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)
1	-	15	-	29	0.0833
2	-	16	-	30	0.0833
3	-	17	0.1134	31	-
4	0.0833	18	0.1134	32	-
5	0.0833	19	0.1134	33	-
6	-	20	0.1134	34	0.0833
7	-	21	-	35	0.0833
8	0.0231	22	-	36	0.0833
9	-	23	0.1134	37	0.0231
10	-	24	0.1134	38	0.0231
11	-	25	0.0231	39	0.0903
12	0.0833	26	0.0231	40	0.0903
13	0.0231	27	0.0231	41	0.0903
14	0.1967	28	0.0833	42	0.0903

Table 5.9: NCST M-1 Survivability Solution Seawater Capacities

Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)	Edge #	Capacity (kg/s)
1	6.9e-3	11	6.9e-3	21	6.9e-3
2	6.9e-3	12	-	22	6.9e-3
3	6.9e-3	13	-	23	-
4	6.9e-3	14	-	24	-
5	6.9e-3	15	-	25	6.9e-3
6	-	16	-	26	6.9e-3
7	-	17	-	27	-
8	-	18	-	28	6.9e-3
9	6.9e-3	19	-		
10	6.9e-3	20	6.9e-3		

Table 5.10: NCST M-1 Survivability Solution Freshwater Capacities

	Electrical	**Seawater**	**Freshwater**
Possible Edges	76	42	28
Actual Edges	34	27	14
Edge Savings	**55.3%**	**35.7%**	**50.0%**
Possible Cost	$ 123,643	$ 132,004	$ 68,000
Actual Cost	$ 85,643	$ 82,004	$ 34,000
Cost Savings	**30.7%**	**37.9%**	**50%**

Table 5.11: Edge and Cost Savings M-1 Survivability Over Candidate Topology

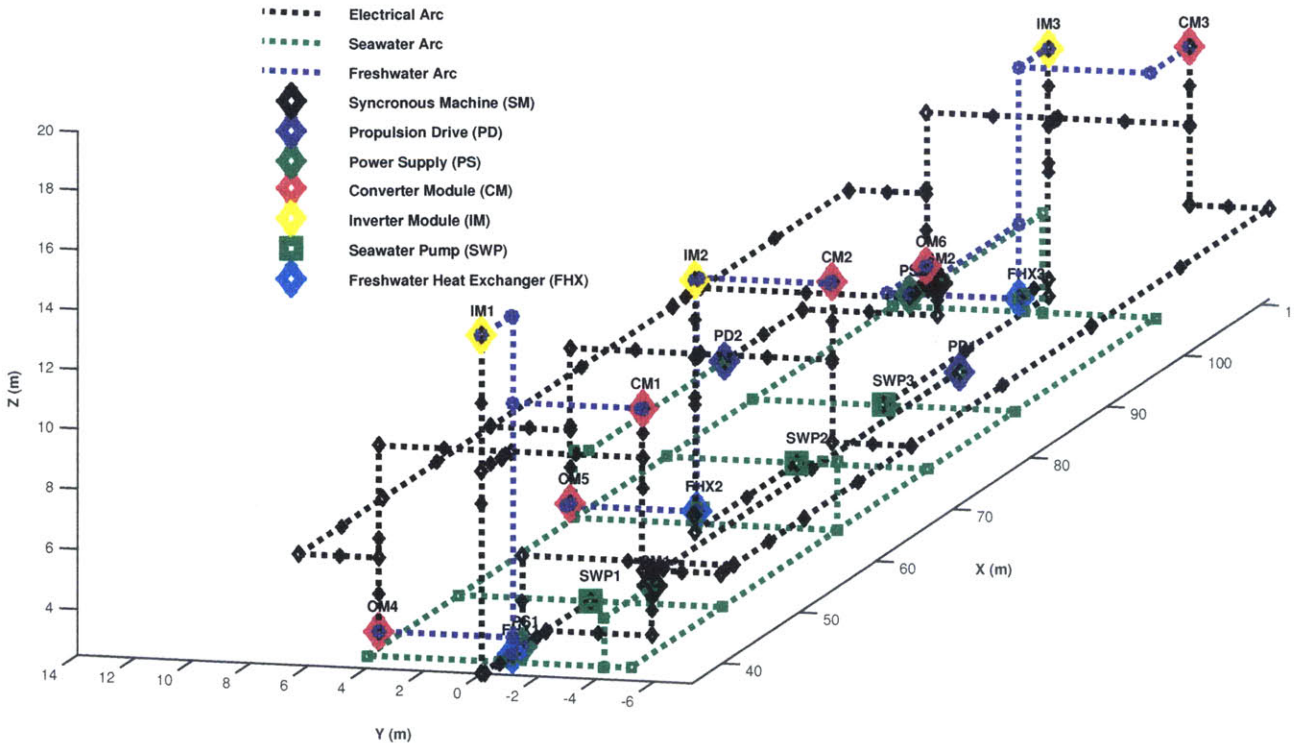


Figure 5-5: NCST IEP Topology

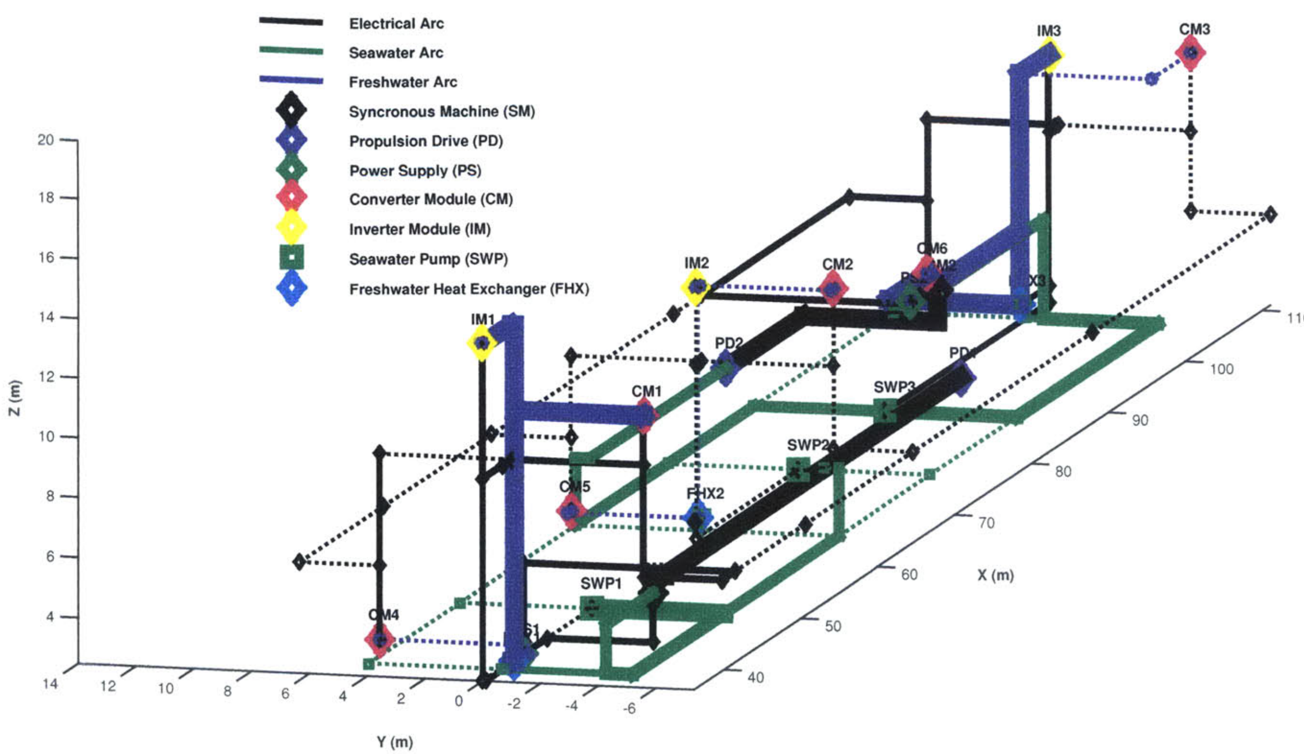
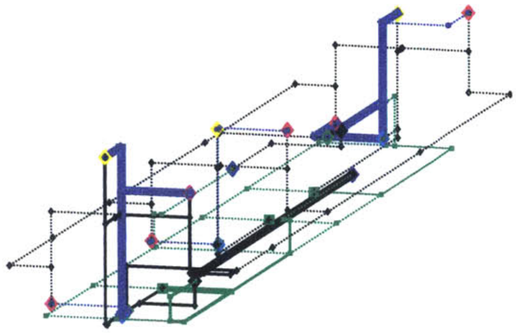
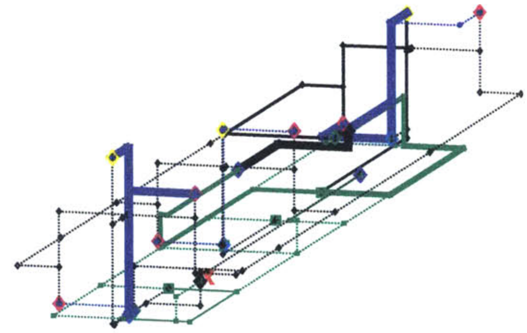


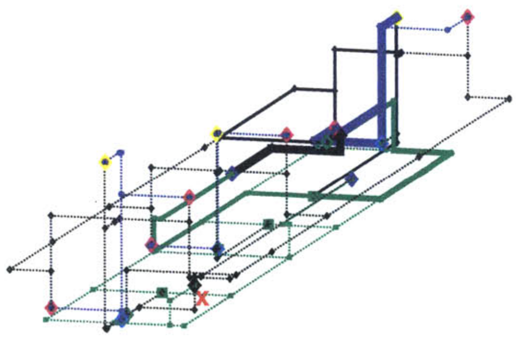
Figure 5-6: NCST Optimization Solution



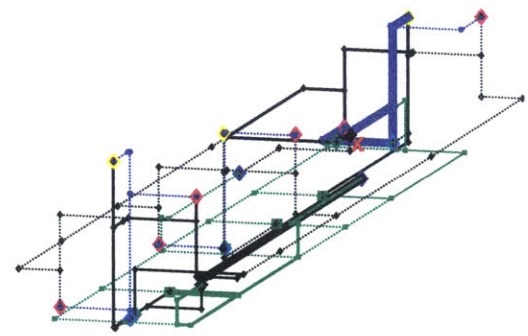
(a) #0 No Loss



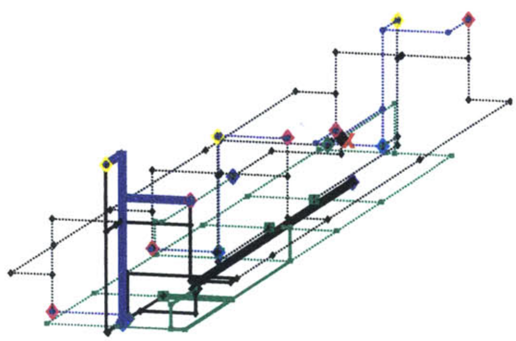
(b) #1 Loss of Electrical Edges 1, 2, 3



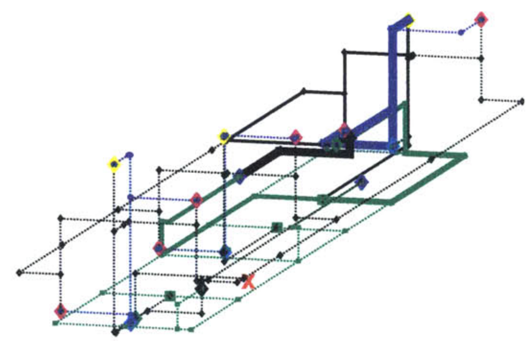
(c) #2 Loss of Electrical Edges 4, 5, 6



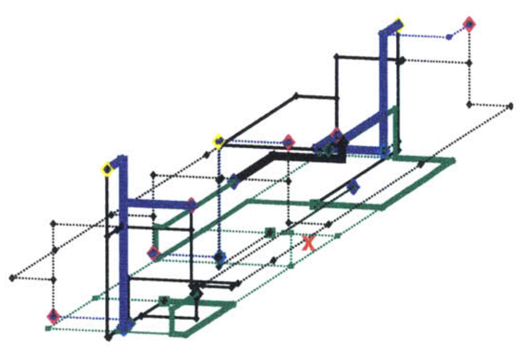
(d) #3 Loss of Electrical Edges 7, 8, 9



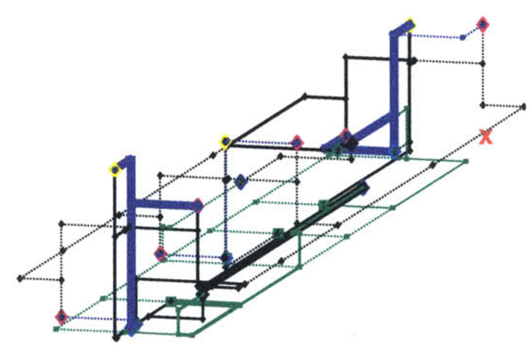
(e) #4 Loss of Electrical Edges 10, 11, 12



(f) #5 Loss of Electrical Edges 13, 14

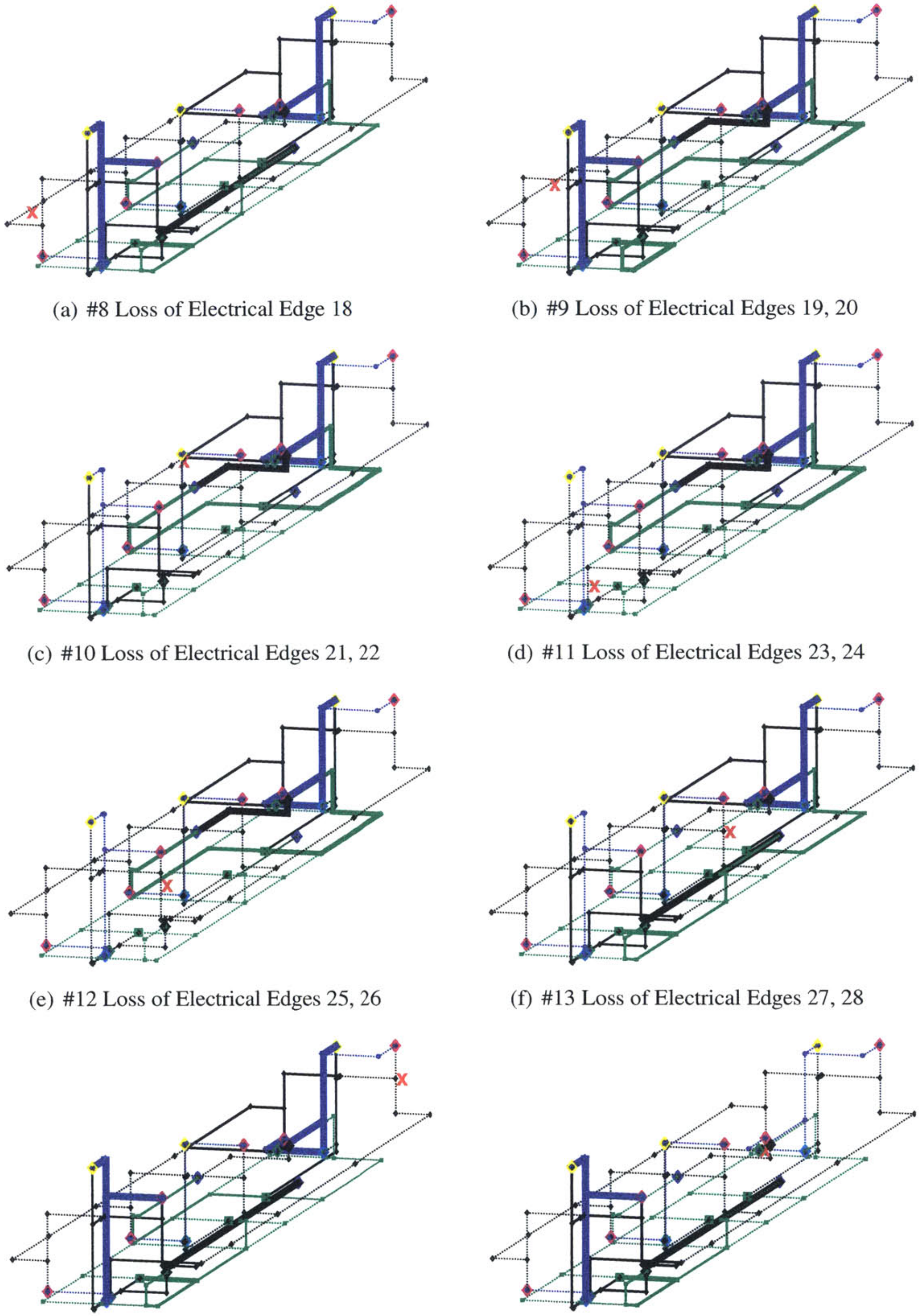


(g) #6 Loss of Electrical Edges 15, 16



(h) #7 Loss of Electrical Edge 17

Figure 5-7: NCST IEP Solution Flows Casualties #0 - #7



(a) #8 Loss of Electrical Edge 18

(b) #9 Loss of Electrical Edges 19, 20

(c) #10 Loss of Electrical Edges 21, 22

(d) #11 Loss of Electrical Edges 23, 24

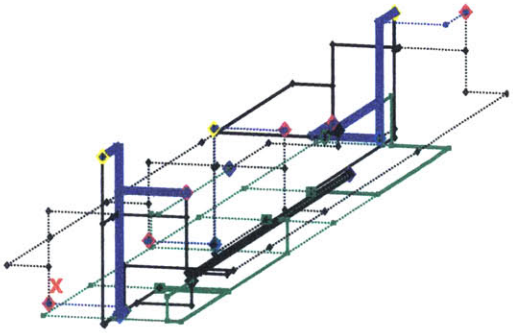
(e) #12 Loss of Electrical Edges 25, 26

(f) #13 Loss of Electrical Edges 27, 28

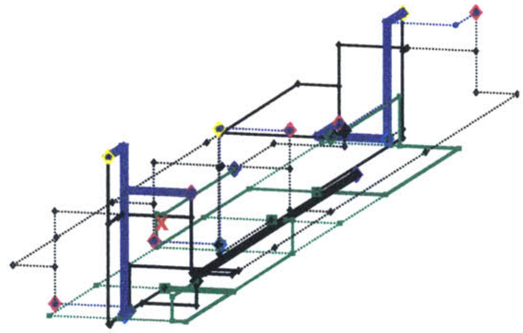
(g) #14 Loss of Electrical Edges 29, 30

(h) #15 Loss of Electrical Edges 31, 32

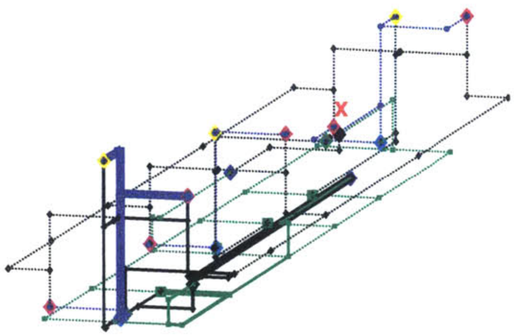
Figure 5-8: NCST IEP Solution Flows Casualties #8 - #15



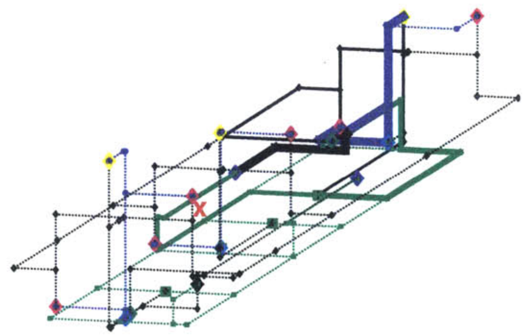
(a) #16 Loss of Electrical Edges 33, 34



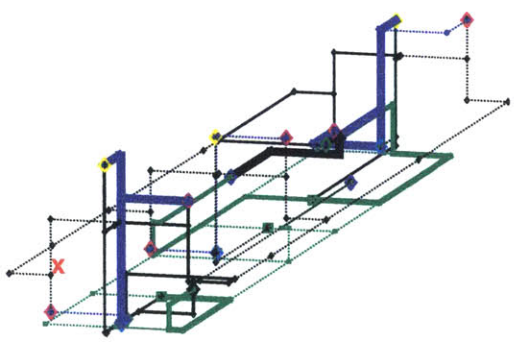
(b) #17 Loss of Electrical Edges 35, 36



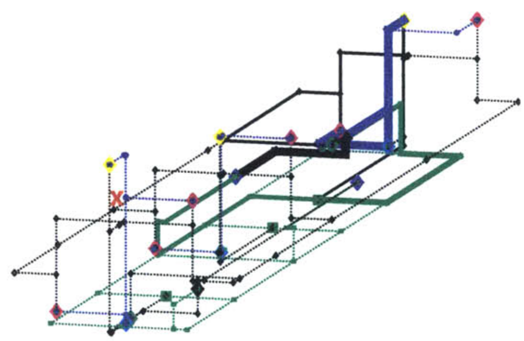
(c) #18 Loss of Electrical Edges 37, 38



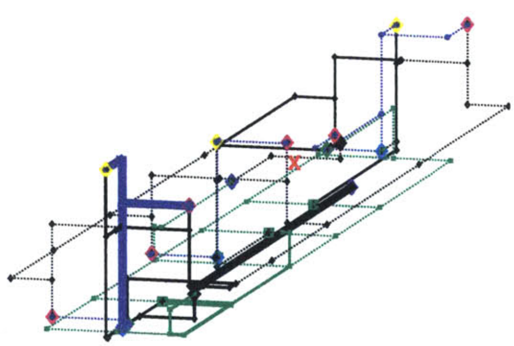
(d) #19 Loss of Electrical Edges 39, 40, 41



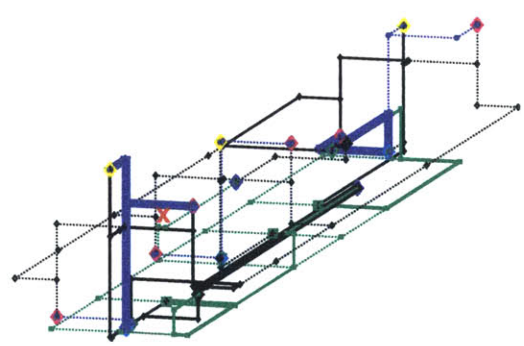
(e) #20 Loss of Electrical Edges 42, 43, 44



(f) #21 Loss of Electrical Edges 45, 46

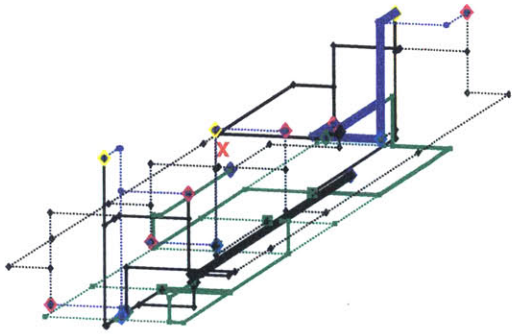


(g) #22 Loss of Electrical Edges 47, 48, 49

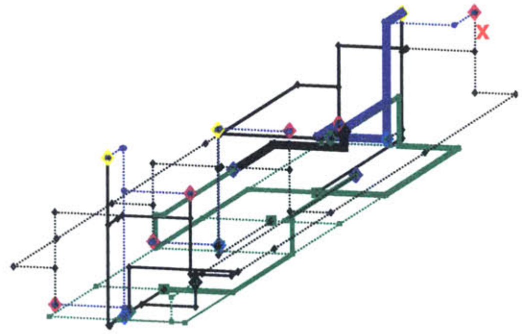


(h) #23 Loss of Electrical Edges 50, 51, 52

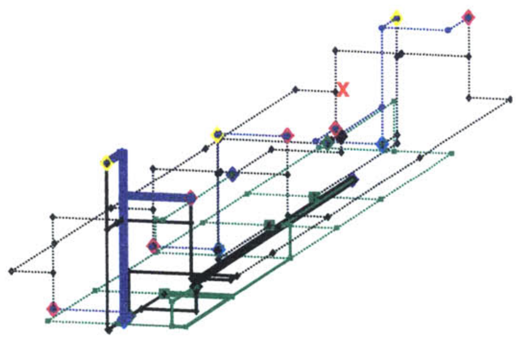
Figure 5-9: NCST IEP Solution Flows Casualties #16 - #23



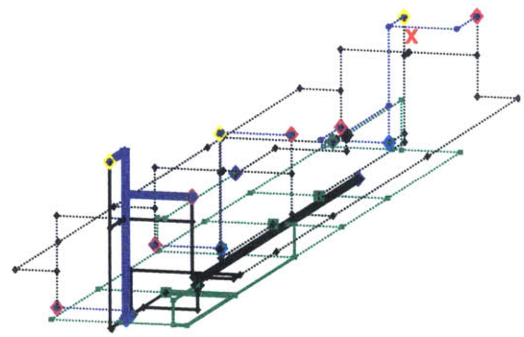
(a) #24 Loss of Electrical Edges 53, 54



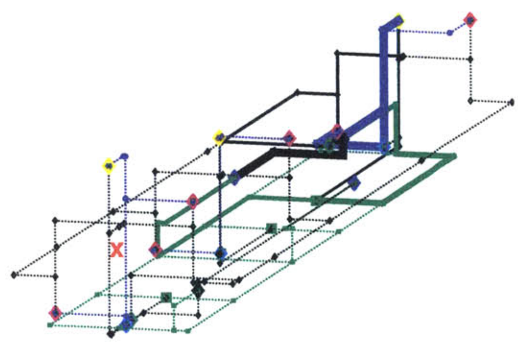
(b) #25 Loss of Electrical Edges 55, 56, 57



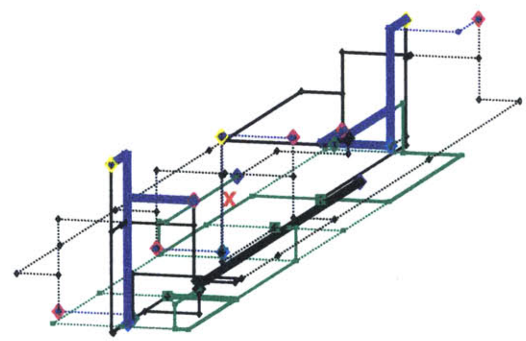
(c) #26 Loss of Electrical Edges 58, 59, 60



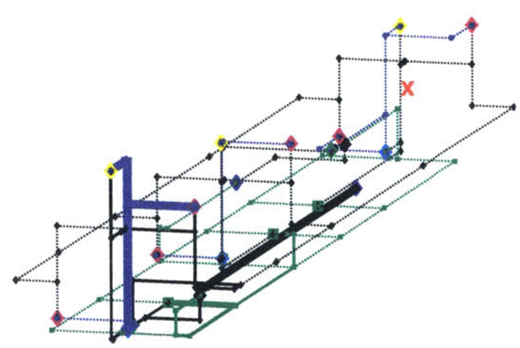
(d) #27 Loss of Electrical Edges 61, 62



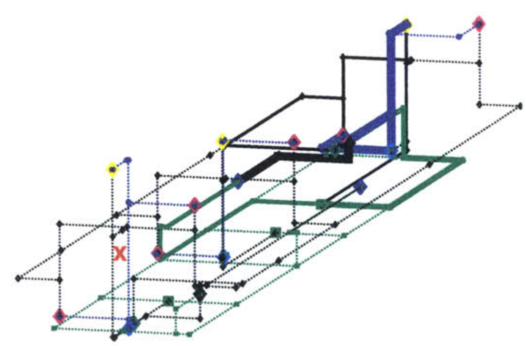
(e) #28 Loss of Electrical Edges 63, 64



(f) #29 Loss of Electrical Edges 65, 66

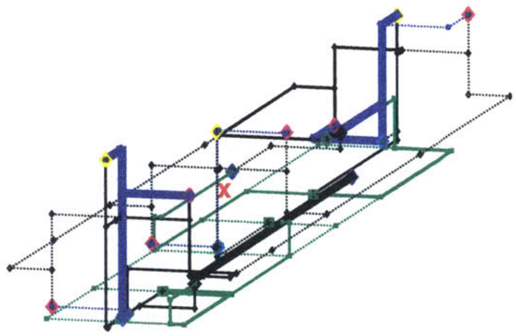


(g) #30 Loss of Electrical Edges 67, 68

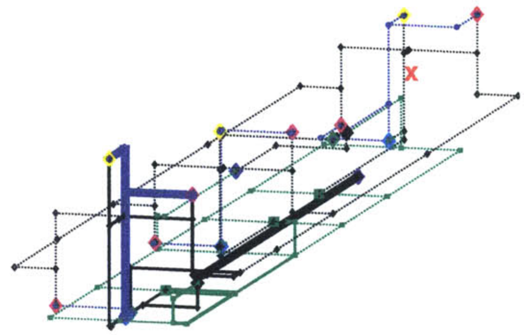


(h) #31 Loss of Electrical Edges 69, 70, 71

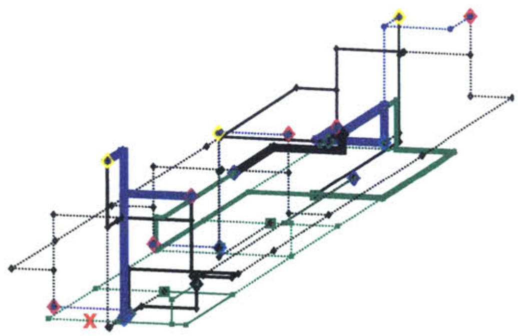
Figure 5-10: NCST IEP Solution Flows Casualties #24 - #31



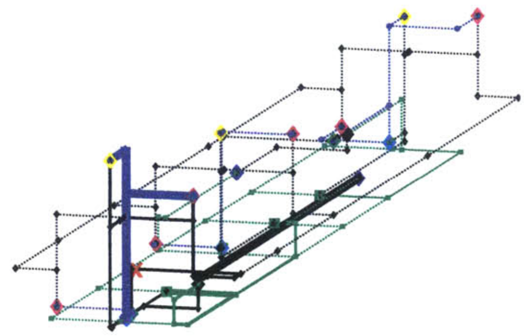
(a) #32 Loss of Electrical Edges 72, 73, 74



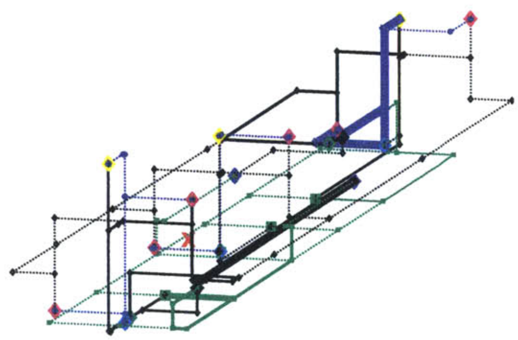
(b) #33 Loss of Electrical Edges 75, 76



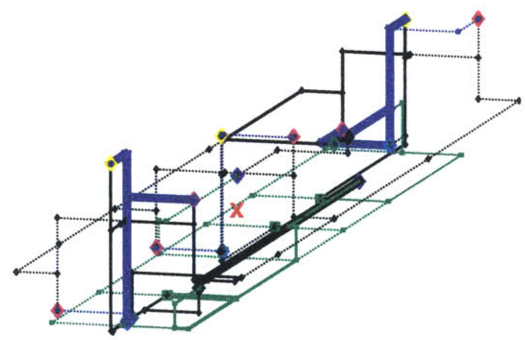
(c) #34 Loss of Seawater Edges 1, 2



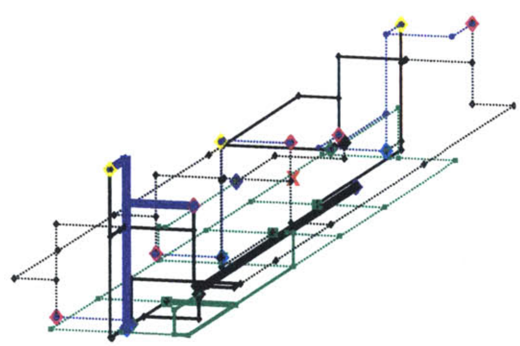
(d) #35 Loss of Seawater Edge 3



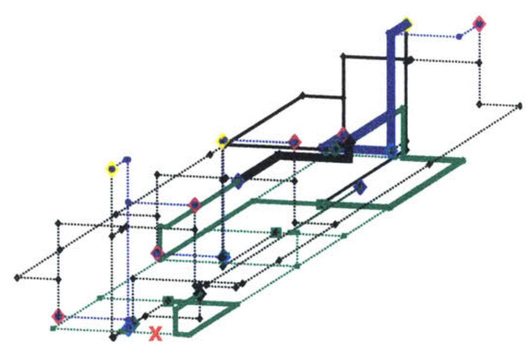
(e) #36 Loss of Seawater Edge 4



(f) #37 Loss of Seawater Edge 5

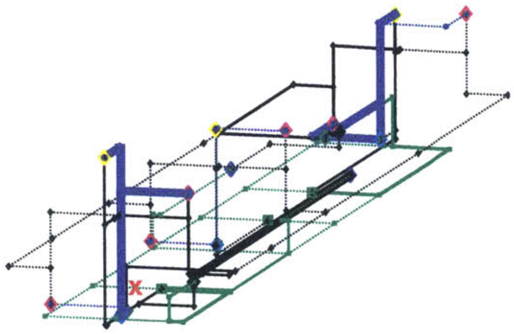


(g) #38 Loss of Seawater Edges 6, 7

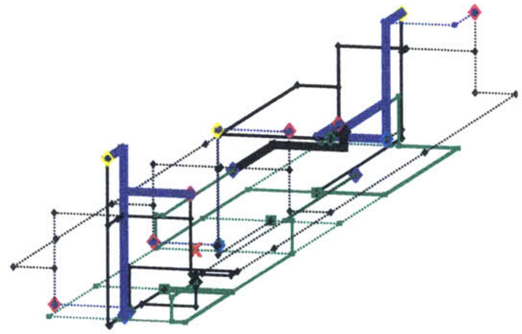


(h) #39 Loss of Seawater Edge 8

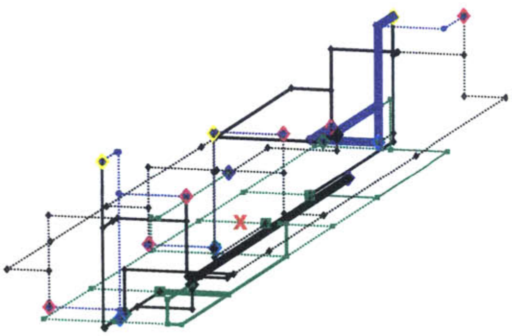
Figure 5-11: NCST IEP Solution Flows Casualties #32 - #39



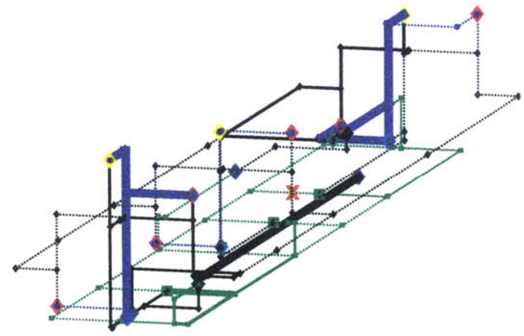
(a) #40 Loss of Seawater Edge 9



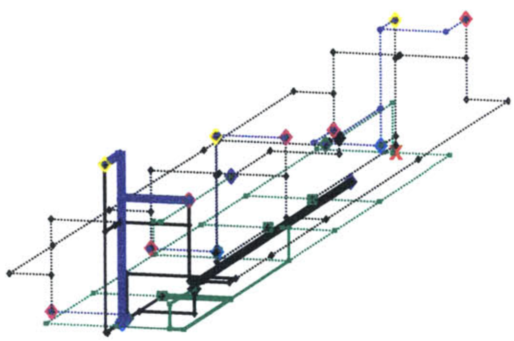
(b) #41 Loss of Seawater Edge 10



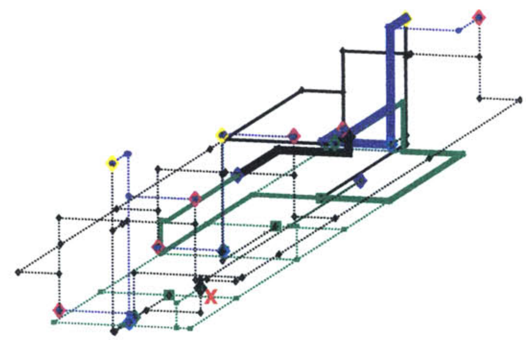
(c) #42 Loss of Seawater Edge 11



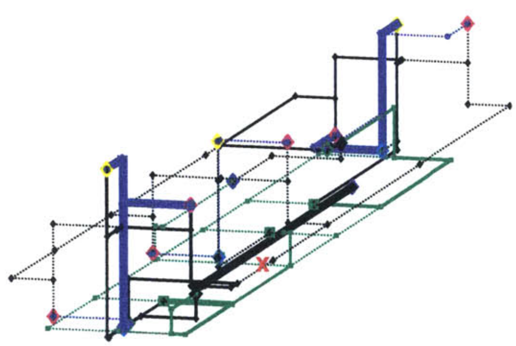
(d) #43 Loss of Seawater Edge 12



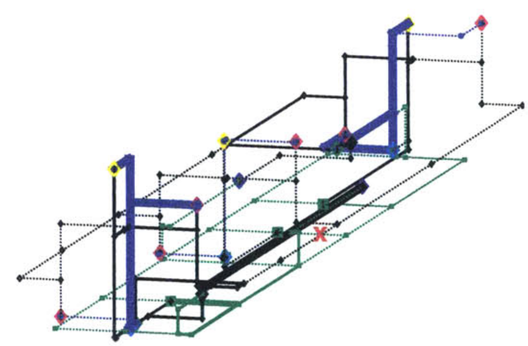
(e) #44 Loss of Seawater Edge 13



(f) #45 Loss of Seawater Edge 14

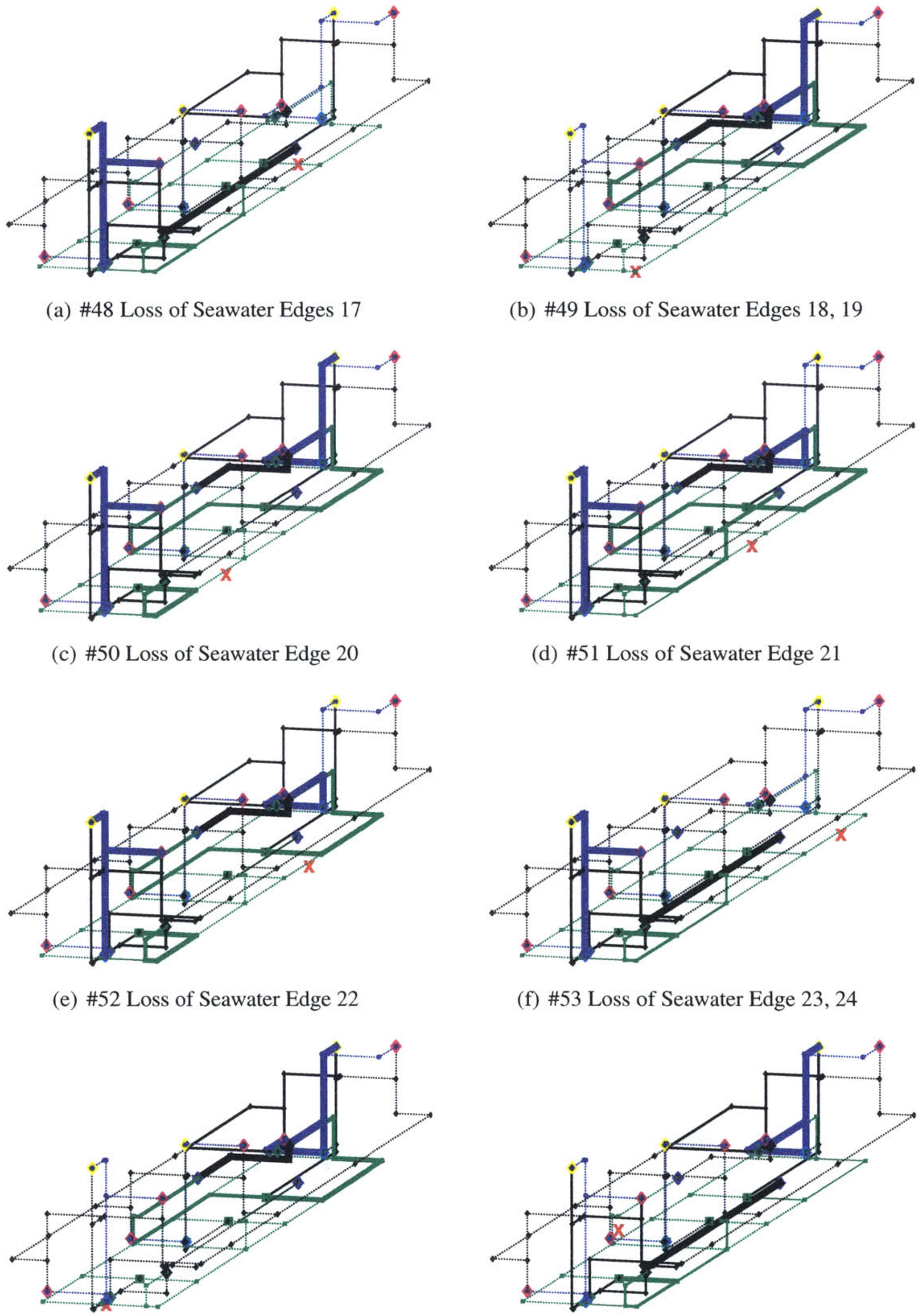


(g) #46 Loss of Seawater Edge 15



(h) #47 Loss of Seawater Edge 16

Figure 5-12: NCST IEP Solution Flows Casualties #40 - #47



(a) #48 Loss of Seawater Edges 17

(b) #49 Loss of Seawater Edges 18, 19

(c) #50 Loss of Seawater Edge 20

(d) #51 Loss of Seawater Edge 21

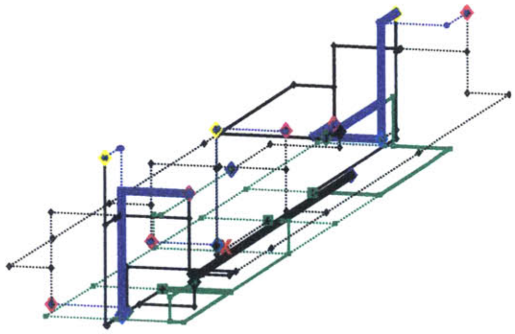
(e) #52 Loss of Seawater Edge 22

(f) #53 Loss of Seawater Edge 23, 24

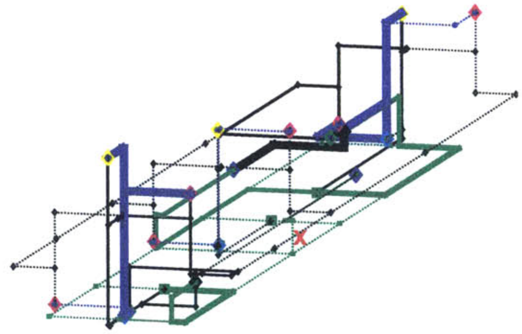
(g) #54 Loss of Seawater Edges 25, 26, 27

(h) #55 Loss of Seawater Edges 28, 29, 30

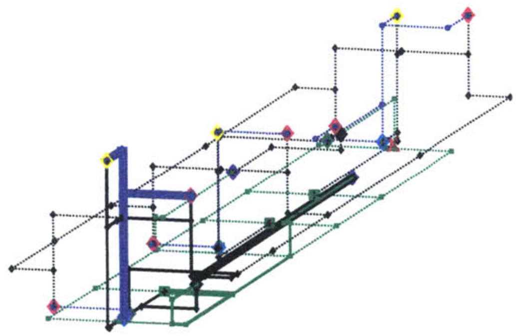
Figure 5-13: NCST IEP Solution Flows Casualties #48 - #55



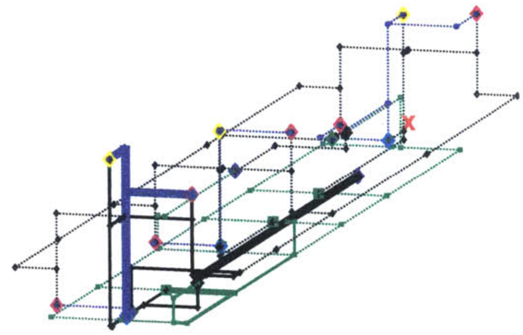
(a) #56 Loss of Seawater Edges 31, 32, 33



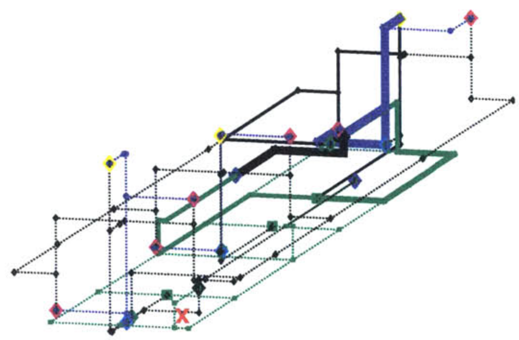
(b) #57 Loss of Seawater Edges 34, 35, 36



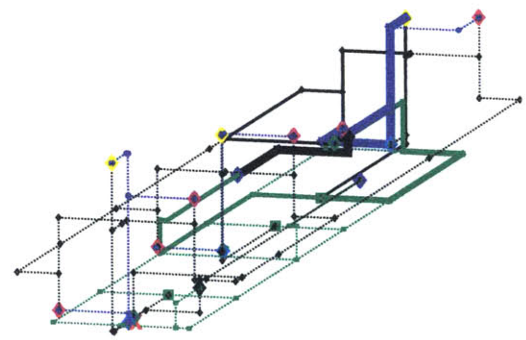
(c) #58 Loss of Seawater Edges 37, 38



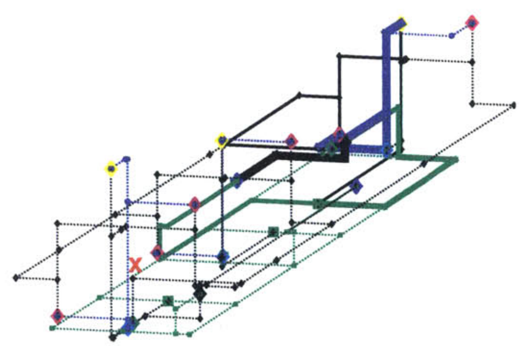
(d) #59 Loss of Seawater Edges 39, 40



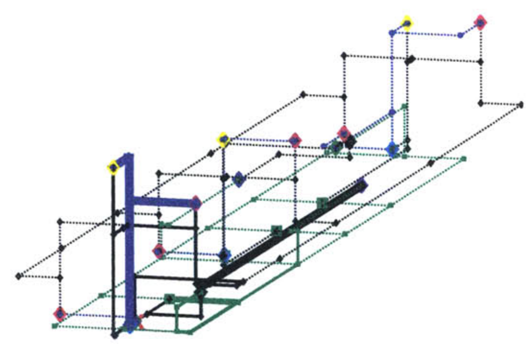
(e) #60 Loss of Seawater Edges 41, 42



(f) #61 Loss of Freshwater Edges 1, 2

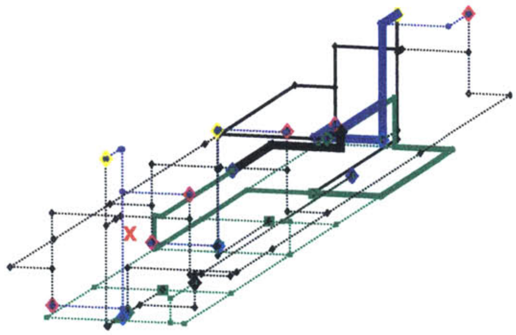


(g) #62 Loss of Freshwater Edges 3, 4, 5

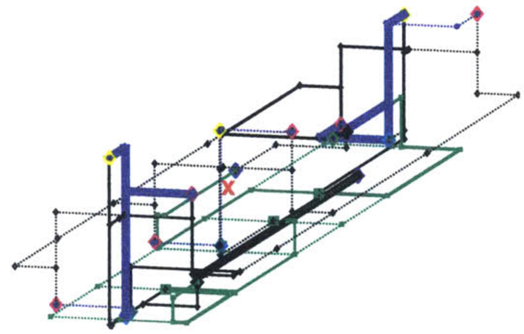


(h) #63 Loss of Freshwater Edges 6, 7, 8

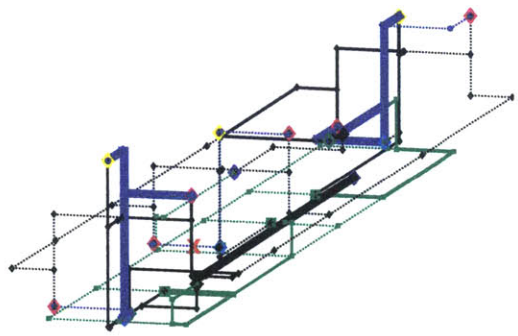
Figure 5-14: NCST IEP Solution Flows Casualties #56 - #63



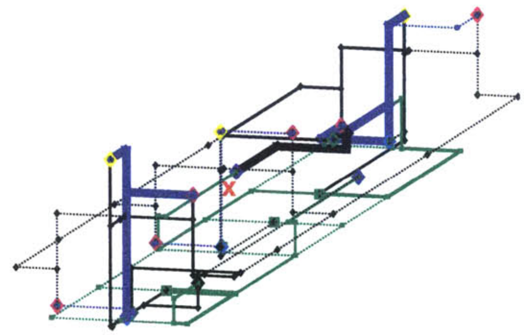
(a) #64 Loss of Freshwater Edges 9, 10, 11



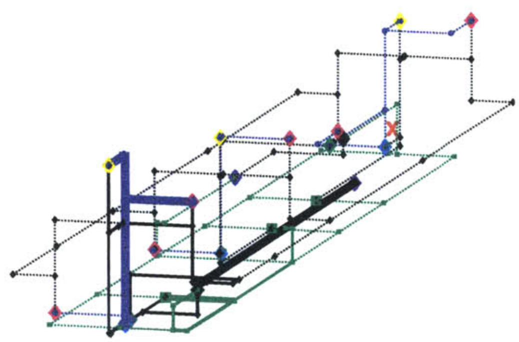
(b) #65 Loss of Freshwater Edges 12, 13, 14



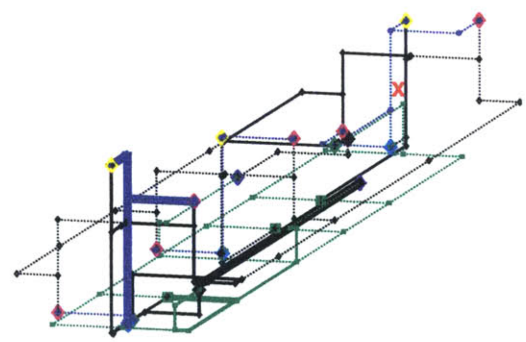
(c) #66 Loss of Freshwater Edges 15, 16



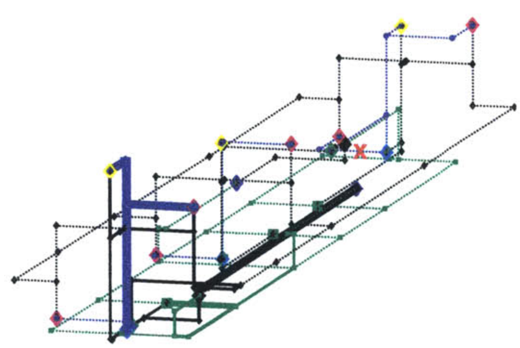
(d) #67 Loss of Freshwater Edges 17, 18, 19



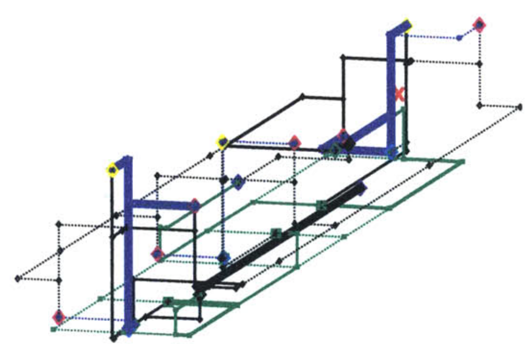
(e) #68 Loss of Freshwater Edges 20, 21



(f) #69 Loss of Freshwater Edges 22, 23, 24



(g) #70 Loss of Freshwater Edges 25, 26



(h) #71 Loss of Freshwater Edges 27, 28

Figure 5-15: NCST IEP Solution Flows Casualties #64 - #71

Chapter 6

Conclusions & Recommendations

6.1 Conclusions

In this thesis a new method has been demonstrated for integrated engineering plant (IEP) cost minimization in early stage design. The method uses non-simultaneous multicommodity flow (NSMCF), a class of linear programming (LP) network flow optimization. This offers certain advantages over the current indirect survivable design methods. With NSMCF, survivability can be designed into the plant by including the survivable conditions in the formulation. Also, this can be done in the early stage design phase when changes to the design are least expensive and cost savings for the acquisition process can be maximized.

6.1.1 Acquisition Savings

Fixed costs dominate the IEP design due to costs associated with the installation and maintenance of edges in the electrical and cooling systems. The ability to take into account fixed costs and therefore prioritize the reduction of edges is a great advantage of this method. The examples given in this thesis, first of the notional IEP in Chapter 4 and the Naval Combat Survivability Testbed (NCST) in Chapter 5, shows that for a M-1 casualty set (the loss of all edges, any one at a time), the solver reduced the cost by the amount shown in Table 6.1 over standard ring bus zonal electrical distribution (ZED) topology. This is due to the ability of the solver to delete edges in the system that are deemed unnecessary. Although

	Notional IEP	NCST
Possible Edges	53	146
Actual Edges	45	75
Edge Savings	**15.1%**	**48.6%**
Possible Cost	$ 93,531	$ 323,647
Actual Cost	$ 86,031	$ 201,648
Cost Savings	**8.0%**	**37.7%**
No. Constraints	~16k	~68k
Computation Time	0.72 sec	2 hr 9 min

Table 6.1: Edge and Cost Savings M-1 Survivability Over Candidate Topology

M-1 is not a robust survivability specification (it is used here for demonstration purposes), the method ensures that the output of the solver is the minimum cost IEP topology.

6.1.2 Pareto Optimal Variants

Cost-as-an-independent variable (CAIV) policy requires a knowledge of the lower bound for cost in concept designs. This method allows the designer to determine the minimum cost design for the performance specification given. The pareto optimal (non-dominated) solutions with respect to cost can be found and used to give program managers confidence that they are using true cost minimized variants.

6.1.3 Stored Energy Design

The method also allows the designer to determine the minimum stored energy throughout the ship to meet survivability and resiliency specifications.

6.2 Recommendations for Future Work

There are several areas in which this method has potential to be made more useful and also to be used in the detailed design phase. For detailed design capability, it would be useful to have the solver limited to only standard edge sizes (cables and piping). This would ensure optimality under those circumstances and would give the designer greater control of the output. The formulation could also be modified to account for inefficiencies in the edges (electrical power flow and hydraulic friction losses). Furthermore, a capability to have the formulation do more of the design work of routing cables in optimal locations and a spatial layer to allow the input of damage scenarios at locations and magnitudes could be added.

6.2.1 Standard Edge Components

There are several areas in which this method has potential to be made more useful and also to be used in the detailed design phase. The method as presented does provides the dollar value of the IEP as an output, including the capacities of all edges. The designer then would have to determine what is the appropriate component to use for each edge. Assuming that non-standard electrical cables and piping is significantly more expensive than standard sizes, the designer will prefer to select standard components. In order to do this, the designer will need to "round-up" to the component that is larger than the capacity solution. This practice could result in a significant deviation from optimality. It is possible to upgrade the formulation to only allow standard cable and pipe sizes. This would ensure that optimality would be reached, taking into account the discrete component sizes.

6.2.2 Accounting for Inefficiency

It could be possible to account for electrical power flow and hydraulic friction losses in the formulation assuming that the power flow losses are convex (proportional to I^2 where I is the current in a cable of given length) and mass flow losses are convex (linear with mass flow rate ($\dot{m}$) for a given pipe length.

6.2.3 Optimal Edge Routing

Since the NSMCF method will reduce any candidate topology to the minimum capacity (for a given casualty and operating condition set), the formulation could be set up to allow a large number of alternate cables serving the same function, but each with a slightly different routing through the ship. When the damage scenarios are input, the solver may choose the edge (assuming the edge is necessary and not deleted anyway) that would survive. The solver would choose the least expensive surviving edge and would provide the designer the optimally routed cable.

6.2.4 Spatial Layer

In order to facilitate traditional casualty modeling, a spatial layer could be added to the formulation. This way, the subject matter experts in survivability could enter specific hit locations and spheres of destruction. The formulation would take care of interpreting these inputs into losses of specific edges and nodes in the system.

6.2.5 Increased Design Freedom

Assuming the electrical loads are given, more electrical generation of different ratings and more stored energy devices at different locations can be installed as candidates. The solver can return to the designer the optimal generation and stored energy for the given plant loads and casualty and operating conditions.

6.2.6 Hydrodynamic Layer

The demonstration in this thesis includes operating conditions specifying the power level of the propulsion motors (PMs). An upgrade to the method could contain a hydrodynamic layer that would be implemented similarly to other layers in the formulation through constitutive relationships. For a standard displacement ship, such as a destroyer, the propulsion power varies as a cubic of ship speed. The power curve is convex so it can be used for optimization and linear approximations can be used to remain in the linear programming formulation. The designer can then enter ship speed for various operating conditions. The solver will find the minimum power necessary from the PMs to achieve the speed required and this will make the formulation inputs more intuitive.

6.2.7 Sensitivity Analysis

In mathematical optimization, the formulation can be reconfigured as the dual problem. The dual problem is the derivative of the objective function with respect to the generalized constraint resources. For the proposed method, the formulation constraint resources are analogous to the load demands. The dual problem can be analyzed to determine the cost per unit resource, which in this case is the cost per unit load demand and can be generalized to the cost per casualty and operating condition. A careful study could reveal the cost per unit capability of a particular IEP candidate.

Appendix A

Scalability and Effect on Computation Time

A.1 Introduction

All types of computation methods have scalability limitations. The goal of this section is to demonstrate the scalability of the proposed NSMCF formulation applied to cost minimization of survivable, mission configurable IEPs. A limited number of experiments have been run in the following 4 areas of scalability and the associated effect on computation cost:

1. Number of nodes (generators, distribution and load centers, stored energy, power converters, loads, cooling pumps, coolers and distribution connections)
2. Number of candidate edges (electrical distribution cables and seawater and freshwater piping)
3. Number of interdependent layers (constitutive relationships) between domains (cooling flow required to remove heat from electric loads, electric power required to produce cooling flow, seawater to freshwater heat exchangers)
4. Number of casualties and operating conditions

How much computational expense is unacceptable is the prerogative of the user. The level of computation time needs to be balanced by the fact that this method is an early stage design tool that can provide an exact (within accuracy of the model) mathematical minimum cost IEP. Cost savings and knowledge in the early stage can result in great savings. Perhaps even several days of computation on an IEP design with a favorable level of detail would be worth the time.

A.2 Model Detail vs. Computation Cost

In network flow modeling of a shipboard IEP, the nodes represent the generators, distribution and load center switchboards, motors, heaters, etc. The concept design can represent whatever level of detail necessary. For example, the model could include generation and distribution down to the load center switchboards, the load switchboards, or the loads themselves. The level of detail desired could significantly affect the computational cost of the optimization and may affect whether the method could be useful at all or if the model would need to be simplified. In the example below, the minimum number of nodes used is 6 electrical and 6 thermal. This represents a system with 2 generators, 2 propulsion motors 2 cooling pumps/motors, and 4 coolers. Having pairs of all electrical components ensures the plant is redundant and the solver has choices for casualty reconfiguration. Although the NSMCF method for IEP optimization is not intended to be a plant reconfiguration algorithm, it can show for every casualty, a possible reconfiguration of both domain plants. When looking at the values of power and mass flow in the respective plants for a specific casualty (loss of a line or pipe, for example), it cannot be said that those values represent the minimum flow topology for that casualty. What can be said is that reconfiguration supports the overall minimum capacity IEP for the overall candidate topology and in consideration of the entire casualty set.

A.3 Computer Equipment

For this thesis and these experiments, the equipment used is shown in Table A.1. This is a standard desktop machine that is almost 4 years old. For early stage ship design more advanced hardware could certainly be acquired and some improvement can be made in computation time.

Make	Apple ®
Model	iMac 27in, mid 2011
Processors	1 Intel Core i5
No. Cores	4
Speed	2.7 GHz
Memory	16GB SDRAM
OS	Yosemite 10.10.2
Optimizer	IBM CPLEX ®
Version	Studio 124 64 bit

Table A.1: Processor and Software Data

A.4 Results & Conclusions

Results of the experiments are shown in Table A.2. The results of the experiments can be used to assess:

1. Whether the proposed method is scalable and useful for a particular application
2. In what respect the network flow model would need to be simplified, if possible
3. What scaling effect on computation cost to expect

The computation time of the solver is most directly affected by the size of the formulation (number of constraints). The number of constraints is defined by the number of nodes and edges which relates to the percent connected of the plant. The size of the formulation is also affected by the number of casualty and operating conditions.

A.4.1 Effect of Plant Percent Connection

Comparing Test 3 with Test 12 in Table A.2 shows the sensitivity of solver computation time to the percent connection of the plant. Test 3 represents a complete graph (in which every node is connected to every other node). The complete graph has the maximum interconnection and therefore the continuity equations contain the maximum number of terms possible. Every node continuity equation contains common terms with every other node continuity equation. The node-incidence matrix in this case would be fully populated. The solver will naturally take longer to perform operations on a system with more interdependencies. Test 12 has more nodes and more edges, but it is only 50% connected. This means it has only half of the possible connections (50% of the connections of a complete graph). The solver takes 3044 seconds for Test 3 while it only takes 49 seconds for Test 12, a larger plant. This is only 1.6% of the computation time as Test 3. The encouraging conclusion is that most plants (even candidate plants, where extra edges may be included for design freedom) are much less connected than the plant in Test 12 (50%). The Naval Combat Survivability Testbed, for example, is only 3% connected for the electrical plant and 6% and 7% connected for the seawater and freshwater plants, respectively. Test "NCST", due to plant size and number of casualty and operating conditions ("Cas Op") the time was approximately double Test 3. Test NCST had almost 5 times the number of constraints as Test 3, however. The effect of percent connected can also be seen in Tests 5 through 8.

A.4.2 Effect of Number of Casualty and Operating Conditions

In the non-simultaneous multicommodity flow (NSMCF) formulation, the size (number of constraints) and the dimension (number of unique variables) of the formulation increases linearly with the number of casualty and operating conditions. The number of conditions is defined by the designer. There are a limited number of casualty and operating conditions that define the problem objective and many of the conditions will not impact the solver algorithm. Therefore the size of the casualty and operating condition set will not necessarily correlate to the computation time. In Table A.2, a comparison of Tests 4 and 12 shows that the plant percent connected is strongly correlated to computation time and the size of the casualty and operating condition set is not strongly correlated. Tests 4 and 12 have roughly the same number of casualty and operating conditions (50 and 47 respectively) and number of constraints (18,396 and 16,822 respectively) but the computation time varies greatly: 6,709 versus 49 seconds. This appears to be due to the 100% versus 50% connected plants, respectively.

Test #	Nodes Elec/SW/FW	Edges Elec/SW/FW	# Cas Op	% Connected	Con-straints	Solver Time (s)
Complete Graph Candidate Topology, M-1 Survivability						
1	6/6/0	15/15/0	31	100%	7746	204
2	6/7/0	15/21/0	37	100%	10615	960
3	7/7/0	21/21/0	43	100%	13971	3044
4	7/8/0	21/28/0	50	100%	18396	6709
6/6 Reduced Graph Candidate Topology, M-1 Survivability						
5	6/6/0	11/11/0	42	75%	4642	4
6	6/6/0	12/12/0	25	80%	5346	19
7	6/6/0	13/13/0	25	85%	6098	36
8	6/6/0	14/14/0	29	90%	6896	119
60% Connected Small Graph Candidate Topology, M-1 Survivability						
9	8/8/0	17/17/0	35	60%	9796	19
10	9/9/0	22/22/0	45	60%	15431	3642
50% Connected Large Graph Candidate Topology, M-1 Survivability						
11	9/9/0	18/18/0	37	50%	10911	21
12	10/10/0	23/23/0	47	50%	16822	49
13	11/11/0	28/28/0	57	50%	23993	340
14	12/12/0	33/33/0	67	50%	32424	622
15	13/13/0	39/39/0	79	50%	44157	1993
16	14/14/0	46/46/0	93	50%	60074	5718
Notional IEP & NCST Trials, Reduced M-1 Survivability						
Notional	23/24/0	26/27/0	54	9/10%	~16000	0.72
NCST	75/38/29	76/42/28	71	3/6/7%	~68000	7740

Table A.2: Scalability Testing Results

A.4.3 Effect of Number of Binary Variables

The experimental results shown in Table A.2 include the use of binary variables for the fixed cost feature as discussed throughout this thesis. Solvers for mixed-integer linear programming (MILP) have more complex algorithms and have generally been slower than those used for pure linear programming. The experimental data in Table A.2 shows that the solver is not nearly as sensitive to the number of binary variables as it is to the connected percent of the IEP. Take, for example Test 10 in which the IEP contains 22 electrical and 22 seawater edges (44 binary variables). The solver takes approximately 64% of the computation time as in Test 16 which has over twice the binary variables. The computation seems to scale somewhat less sensitively to the number of binary variables.

Appendix B

Optimization Solver Numerical Stability

The software used in this research is IBM CPLEX®, a commercial product that is a state-of-the-art optimization solver. There were numerical stability problems experienced with the solver and the problems seem to be common in any computer software that deals with large matrices and has machine precision limitations.

B.1 Nature of Stability Problem

Although a full treatment of the problem is not provided in this thesis, it is desired to give the reader a sufficient warning of stability problems while using optimization solvers. The issue of numerical stability in this work manifested in the precision of binary variables. In the IBM CPLEX® solver, binary variables are declared in the linear programming file format as shown in Table B.1.

The variables in Table B.1 represent on/off variables for each edge in the system. The variables that begin with "a" represent the 15 edges in the electric plant and the variables starting with "b" are the 15 edges in the cooling plant (for example). These variables also appear in the objective (see Table 3.2) and have coefficients that represent the fixed cost of each edge. The fixed (installation or life-cycle) costs of edges in the plant are generally much larger compared with the variable (material) costs of the edges. The optimization formulation is set up to allow the solver to delete edges by assigning 0 to the binary variables if possible, greatly minimizing the plant cost. Thus, it is critically important for the binary

⋮
Binaries

a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15
b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	b15

⋮
End

Table B.1: Example of Binary Variable Declaration in IBM CPLEX®

variables to be precisely 1 or 0 as expected. Consider, for example that the fixed cost of a electrical edge #5 is $100,000, and the variable cost is $500. The solver "intends" to delete the edge, but due to numerical instability, instead of $a5$ equalling zero, $a5 = 0.0001$. The first problem that results from this is that the designer is misled that edge #5 must exist for plant survivability and edge #5 becomes an unnecessary element of the design. The second problem is that the cost of the objective is misleading. Where edge #5 was supposed to be deleted, the cost associated with it would be zero. In the example given, the cost is incorrectly calculated as: $100,000 (0.0001) = $10. In any case, the more significant error is the incorrect existence of the edge in the solution.

B.2 Conditions for Numerical Instability

There are certain conditions under which the solver demonstrates numerical instability. This is the subject of much discussion among engineers and applied mathematicians. One such discussion board is located at http://orinanobworld.blogspot.com/2010/08/ill-conditioned-bases-and-numerical.html. The problem appears to be related to at least two conditions: (1) the use of integer variables and (2) matrix condition number. Since the fixed cost feature of the proposed optimization method demonstrated in this thesis has great advantage, there is no desire to attempt to stray from using binary variables. It is beyond the scope of this thesis to study the condition number of matrices and how they relate to the formulation method used. However, the problem of numerical instability seems to manifest itself when very large or very small numbers are used for coefficients in the formulation. An attempt should be made to as much as practicable keep the quantities near the order of magnitude of the binary variables. This can be done by carefully choosing units. For example, very large fixed cost coefficients should be avoided. If they are in the thousands of dollars, their units should be in $k, etc. to keep their magnitude close to the magnitude of the binaries. In some cases, the magnitude of the coefficients or the span of magnitude across the formulation cannot be controlled. The designer should then look to solutions in the conditioning of the matrices, which is beyond the scope of this thesis.

B.3 Example of Numerical Instability

To demonstrate the numerical instability discussed above, take for example a notional integrated engineering plant (IEP) with 6 electrical nodes and 6 cooling nodes. There are two electrical generators and two electrical loads. The cooling plant has 4 coolers, one for each generator and load. There are 2 cooling distribution nodes. Each candidate domain includes a complete graph; 15 edges each in which every node is connected to every other node in the domain. The casualty set is M-1; losing every edge any one at a time. The size of the casualty set is 30. First use a fixed cost for every edge of $1,000, then use a fixed cost of $1,000,000 and compare binary variable values.

As can be seen in Table B.2, the value of b5 for fixed cost $10M/Capacity is not exactly 0 or 1. Likewise the variables b6, b7 and b8 for fixed cost $10B/Capacity are not equal to 0 or 1. The numerical instability of the solver seems to be related to the magnitude of fixed cost coefficients in the formulation.

B.4 Recommendation

This problem does not seem to be well understood in the field, as evidenced from the lack of information about it and the existence of the problem in a large-scale commercial solver such as CPLEX®. There is some discussion regarding numerical instability at http://www.gams.com/solvers/cpxindic.htm. The problem is related to the condition num-

Binary	Fixed Cost ($/Capacity)		
Names	10^3	10^6	10^9
a1	1	1	0
a2	0	1	1
a3	0	0	0
a4	0	0	0
a5	1	0	1
a6	1	0	0
a7	1	0	1
a8	0	0	0
a9	1	0	1
a10	1	0	1
a11	0	0	0
a12	0	1	0
a13	0	1	0
a14	0	1	0
a15	0	0	0
b1	1	1	0
b2	0	0	1
b3	0	0	0
b4	1	0	0
b5	0	0.000010	1
b6	0	0	0.000003
b7	0	0	0.000003
b8	0	0	0.000003
b9	1	1	0.000003
b10	0	0	0
b11	1	1	1
b12	1	1	0
b13	0	1	0
b14	0	0	0
b15	0	0	1

Table B.2: Binary Variable Values for Various Fixed Cost ber of the matrices but it is not clear how to minimize the problem through structuring the formulation. The designer should be careful to use units that minimize the significant digits of the numerical values in the formulation. The designer should also carefully examine the solution variables to ensure that the binary variables have in fact taken on binary values.

Appendix C

Notional Plant CPLEX® Input File

The following is an abbreviated file of an example CPLEX® input file for the notional plant optimization. This purpose is to show the format of the file and to allow reproducing results and facilitating use of the method. The actual input file is over 60,000 lines long. The code below is abbreviated by attempting to show the minimum amount to detect the pattern and the use of ellipses to abbreviate. The full set of source code used to create this input is available from the author.

```
\ CPLEX Input File
\ LP File Format
\ File Name: elec_23_2_therm_24_2_nonlin_fixedcost
\ 23 Electrical Nodes 24 Thermal Nodes
\ 26 Electrical Edges 27 Thermal Edges
\ 2 Generators 2 Pumps
\ 1 Stored Energy

Minimize

 obj: + 1000 a1 + P1 + 1000 a2 + P2 + ... + 1000 a25 + P25 + 1000 a26 + P26
+ 10000 d23_0 + 10000 d23_1 + ... + 10000 d23_53 + 10000 d23_54
+ 1000 b1 + Q1 + 1000 b2 + Q2 + ... + 1000 b26 + Q26 + 1000 b27 + Q27

Subject To

\** Electrical Continuity Equations **
 - p1_0 + d1_0 = 0
 + p1_0 - p2_0 - p25_0 - d2_0 = 0
 + p2_0 - p3_0 - d3_0 = 0
```

```
+ p3_0 - p4_0 - p6_0 - d4_0 = 0
+ p4_0 - p5_0 - p16_0 - p26_0 - d5_0 = 0
+ p5_0 - d6_0 = 0
+ p6_0 - p7_0 - p8_0 - d7_0 = 0
+ p8_0 - p9_0 - p11_0 - d8_0 = 0
+ p9_0 - p10_0 - p21_0 - d9_0 = 0
+ p11_0 - p12_0 - d10_0 = 0
+ p10_0 - d11_0 = 0
- p13_0 + d12_0 = 0
+ p13_0 + p25_0 - p14_0 - d13_0 = 0
+ p14_0 - p15_0 - d14_0 = 0
+ p15_0 + p16_0 - p17_0 - d15_0 = 0
+ p7_0 - p18_0 - p19_0 - d16_0 = 0
+ p19_0 - d17_0 = 0
+ p17_0 + p18_0 - p20_0 - d18_0 = 0
+ p20_0 + p21_0 - p22_0 - d19_0 = 0
+ p12_0 - p23_0 - p24_0 - d20_0 = 0
+ p22_0 + p23_0 - d21_0 = 0
+ p24_0 - d22_0 = 0
+ p26_0 + d23_0 = 0

\** Thermal Continuity Equations **

\** Continuity with Sea **
- q1_0 - q14_0 + q12_0 + q24_0 = 0

\** Network Continuity **
+ q1_0 - q2_0 = 0
+ q2_0 - q3_0 = 0
+ q3_0 - q4_0 - q8_0 = 0
+ q4_0 + q18_0 - q5_0 = 0
+ q5_0 - q6_0 = 0
+ q8_0 - q9_0 - q10_0 = 0
+ q10_0 - q11_0 = 0
+ q11_0 - q12_0 - q13_0 = 0
+ q6_0 - q7_0 = 0
+ q14_0 - q15_0 = 0
+ q15_0 - q16_0 = 0
+ q16_0 - q17_0 - q21_0 = 0
+ q17_0 - q18_0 - q19_0 = 0
+ q19_0 - q20_0 = 0
+ q9_0 + q21_0 - q22_0 = 0
+ q22_0 - q23_0 = 0
+ q20_0 - q24_0 - q25_0 = 0
+ q23_0 - q26_0 = 0
```

```
 + q7_0 + q25_0 - q27_0 = 0
 + q13_0 + q26_0 + q27_0 = 0

\** Constitutive Relationships **

\ Cooling Load Relationships
 q6_0 -  0.10 d1_0 >= 0
 q11_0 -  0.10 d11_0 >= 0
 q20_0 -  0.10 d12_0 >= 0
 q23_0 -  0.10 d22_0 >= 0

 + d6_0 - 0.001 q2_0 >= 0.000
 + d6_0 - 0.015 q2_0 >= -0.010
 :
 :
 + d6_0 - 4.860 q2_0 >= -58.320
 + d6_0 - 5.415 q2_0 >= -68.590

 + d17_0 - 0.001 q15_0 >= 0.000
 + d17_0 - 0.015 q15_0 >= -0.010
 :
 :
 + d17_0 - 4.860 q15_0 >= -58.320
 + d17_0 - 5.415 q15_0 >= -68.590

\** Electrical Capacity Constraints **
 + p1_0 - P1 <= 0
 - p1_0 - P1 <= 0
 + p2_0 - P2 <= 0
 - p2_0 - P2 <= 0
 :
 :
 + p25_0 - P25 <= 0
 - p25_0 - P25 <= 0
 + p26_0 - P26 <= 0
 - p26_0 - P26 <= 0

\** Thermal Capacity Constraints **
 + q1_0 - Q1 <= 0
 - q1_0 - Q1 <= 0
 + q2_0 - Q2 <= 0
 - q2_0 - Q2 <= 0
 :
 :
 + q26_0 - Q26 <= 0
```

```
 - q26_0 - Q26 <= 0
 + q27_0 - Q27 <= 0
 - q27_0 - Q27 <= 0
         .
         .
         .
(Casualty Sets 1-53)
         .
         .
         .
\** Electrical Continuity Equations **
 - p1_54 + d1_54 = 0
 + p1_54 - p2_54 - p25_54 - d2_54 = 0
 + p2_54 - p3_54 - d3_54 = 0
 + p3_54 - p4_54 - p6_54 - d4_54 = 0
 + p4_54 - p5_54 - p16_54 - p26_54 - d5_54 = 0
 + p5_54 - d6_54 = 0
 + p6_54 - p7_54 - p8_54 - d7_54 = 0
 + p8_54 - p9_54 - p11_54 - d8_54 = 0
 + p9_54 - p10_54 - p21_54 - d9_54 = 0
 + p11_54 - p12_54 - d10_54 = 0
 + p10_54 - d11_54 = 0
 - p13_54 + d12_54 = 0
 + p13_54 + p25_54 - p14_54 - d13_54 = 0
 + p14_54 - p15_54 - d14_54 = 0
 + p15_54 + p16_54 - p17_54 - d15_54 = 0
 + p7_54 - p18_54 - p19_54 - d16_54 = 0
 + p19_54 - d17_54 = 0
 + p17_54 + p18_54 - p20_54 - d18_54 = 0
 + p20_54 + p21_54 - p22_54 - d19_54 = 0
 + p12_54 - p23_54 - p24_54 - d20_54 = 0
 + p22_54 + p23_54 - d21_54 = 0
 + p24_54 - d22_54 = 0
 + p26_54 + d23_54 = 0

\** Thermal Continuity Equations **

\** Continuity with Sea **
 - q1_54 - q14_54 + q12_54 + q24_54 = 0

\** Network Continuity **
 + q1_54 - q2_54 = 0
 + q2_54 - q3_54 = 0
 + q3_54 - q4_54 - q8_54 = 0
 + q4_54 + q18_54 - q5_54 = 0
```

```
 + q5_54 - q6_54 = 0
 + q8_54 - q9_54 - q10_54 = 0
 + q10_54 - q11_54 = 0
 + q11_54 - q12_54 - q13_54 = 0
 + q6_54 - q7_54 = 0
 + q14_54 - q15_54 = 0
 + q15_54 - q16_54 = 0
 + q16_54 - q17_54 - q21_54 = 0
 + q17_54 - q18_54 - q19_54 = 0
 + q19_54 - q20_54 = 0
 + q9_54 + q21_54 - q22_54 = 0
 + q22_54 - q23_54 = 0
 + q20_54 - q24_54 - q25_54 = 0
 + q23_54 - q26_54 = 0
 + q7_54 + q25_54 - q27_54 = 0
 + q13_54 + q26_54 + q27_54 = 0

\** Constitutive Relationships **

\ Cooling Load Relationships
 q6_54 -  0.10 d1_54 >= 0
 q11_54 -  0.10 d11_54 >= 0
 q20_54 -  0.10 d12_54 >= 0
 q23_54 -  0.10 d22_54 >= 0

 + d6_54 - 0.001 q2_54 >= 0.000
 + d6_54 - 0.015 q2_54 >= -0.010
 :
 :
 + d6_54 - 4.860 q2_54 >= -58.320
 + d6_54 - 5.415 q2_54 >= -68.590

 + d17_54 - 0.001 q15_54 >= 0.000
 + d17_54 - 0.015 q15_54 >= -0.010
 :
 :
 + d17_54 - 4.860 q15_54 >= -58.320
 + d17_54 - 5.415 q15_54 >= -68.590

\** Electrical Capacity Constraints **
 + p1_54 - P1 <= 0
 - p1_54 - P1 <= 0
 + p2_54 - P2 <= 0
 - p2_54 - P2 <= 0
 :
```

```
 :
 + p25_54 - P25 <= 0
 - p25_54 - P25 <= 0
 + p26_54 - P26 <= 0
 - p26_54 - P26 <= 0

\** Thermal Capacity Constraints **
 + q1_54 - Q1 <= 0
 - q1_54 - Q1 <= 0
 + q2_54 - Q2 <= 0
 - q2_54 - Q2 <= 0
 :
 :
 + q26_54 - Q26 <= 0
 - q26_54 - Q26 <= 0
 + q27_54 - Q27 <= 0
 - q27_54 - Q27 <= 0

\*Electrical Capacity Binary Switch Bounds
 P1 - 10000 a1 <= 0
 P2 - 10000 a2 <= 0
 :
 :
 P25 - 10000 a25 <= 0
 P26 - 10000 a26 <= 0

\*Thermal Capacity Binary Switch Bounds
 Q1 - 10000 b1 <= 0
 Q2 - 10000 b2 <= 0
 :
 :
 Q26 - 10000 b26 <= 0
 Q27 - 10000 b27 <= 0

\** Lower Bounds **
 d1_0 <= 30.00
 d1_0 >= 0
     .
     .
 d1_54 <= 30.00
 d1_54 >= 0


 d2_0 =  0.00
     .
```

.

d2_54 = 0.00

d3_0 = 0.00

.

.

d3_54 = 0.00

d4_0 = 0.00

.

.

d4_54 = 0.00

d5_0 = 0.00

d5_54 = 0.00

d6_0 <= 10.00

d6_0 >= 0

d6_54 <= 10.00

d6_54 >= 0

d7_0 = 0.00

d7_54 = 0.00

d8_0 = 0.00

d8_54 = 0.00

d9_0 = 0.00

d9_54 = 0.00

d10_0 = 0.00

d10_54 = 0.00

+ d11_0 + d22_0 = 20

+ d11_54 + d22_54 = 20

d12_0 <= 30.00

d12_0 >= 0

d12_54 <= 30.00

d12_54 >= 0

d13_0 = 0.00

d13_54 = 0.00

```
d14_0 =  0.00
d14_54 =  0.00

d15_0 =  0.00
d15_54 =  0.00

d16_0 =  0.00
d16_54 =  0.00

d17_0 <= 10.00
d17_0 >= 0
d17_54 <= 10.00
d17_54 >= 0

d18_0 =  0.00
d18_54 =  0.00

d19_0 =  0.00
d19_54 =  0.00

d20_0 =  0.00
d20_54 =  0.00

d21_0 =  0.00
d21_54 =  0.00

+ d11_0 + d22_0  = 20
+ d11_54 + d22_54  = 20

d23_0 >= 0
d23_54 >= 0

\** Casualty and Operating Conditions

p1_1 = 0  p2_2 = 0  p3_3 = 0  p4_4 = 0  p5_5 = 0  p6_6 = 0  p7_7 = 0  p8_8 = 0  p9_9 = 0
p10_10 = 0 p11_11 = 0  p12_12 = 0  p13_13 = 0  p14_14 = 0  p15_15 = 0  p16_16 = 0  p17_17 = 0
p18_18 = 0  p19_19 = 0 p20_20 = 0  p21_21 = 0  p22_22 = 0  p23_23 = 0  p24_24 = 0  p25_25 = 0
p26_26 = 0  p4_54 = 0  p16_54 = 0  p7_54 = 0  p18_54 = 0  q1_27 = 0  q2_28 = 0  q3_29 = 0
q4_30 = 0  q5_31 = 0  q6_32 = 0  q7_33 = 0 q8_34 = 0  q9_35 = 0  q10_36 = 0  q11_37 = 0
q12_38 = 0  q13_39 = 0 q14_40 = 0  q15_41 = 0  q16_42 = 0  q17_43 = 0  q18_44 = 0  q19_45 = 0
q20_46 = 0  q21_47 = 0  q22_48 = 0  q23_49 = 0  q24_50 = 0  q25_51 = 0  q26_52 = 0  q27_53 = 0

Bounds
```

```
\*Electrical Flow Variables
 p1_0 >= 0  p2_0 >= 0  p3_0 >= 0  p4_0 free  p5_0 >= 0  p6_0 free  p7_0 free  p8_0 free
 p9_0 free  p10_0 >= 0 p11_0 free  p12_0 free  p13_0 >= 0  p14_0 >= 0  p15_0 >= 0
 p16_0 free  p17_0 free  p18_0 free  p19_0 >= 0  p20_0 free  p21_0 free  p22_0 free
 p23_0 free  p24_0 >= 0  p25_0 free  p26_0 free

\*Thermal Flow Variables
 q1_0 >= 0  q2_0 >= 0  q3_0 >= 0  q4_0 free  q5_0 >= 0  q6_0 >= 0  q7_0 >= 0  q8_0 free
 q9_0 free  q10_0 >= 0  q11_0 >= 0  q12_0 >= 0  q13_0 free  q14_0 >= 0  q15_0 >= 0
 q16_0 >= 0  q17_0 free  q18_0 free  q19_0 >= 0  q20_0 >= 0  q21_0 free  q22_0 >= 0
 q23_0 >= 0  q24_0 >= 0  q25_0 free  q26_0 free  q27_0 free

 :
 :

\*Electrical Flow Variables
 p1_54 >= 0  p2_54 >= 0  p3_54 >= 0  p4_54 free  p5_54 >= 0  p6_54 free  p7_54 free
 p8_54 free  p9_54 free  p10_54 >= 0  p11_54 free  p12_54 free  p13_54 >= 0  p14_54 >= 0
 p15_54 >= 0  p16_54 free  p17_54 free  p18_54 free  p19_54 >= 0  p20_54 free  p21_54 free
 p22_54 free  p23_54 free  p24_54 >= 0  p25_54 free  p26_54 free

\*Thermal Flow Variables
 q1_54 >= 0  q2_54 >= 0  q3_54 >= 0  q4_54 free  q5_54 >= 0  q6_54 >= 0  q7_54 >= 0
 q8_54 free  q9_54 free  q10_54 >= 0  q11_54 >= 0  q12_54 >= 0  q13_54 free  q14_54 >= 0
 q15_54 >= 0  q16_54 >= 0  q17_54 free  q18_54 free  q19_54 >= 0  q20_54 >= 0  q21_54 free
 q22_54 >= 0  q23_54 >= 0  q24_54 >= 0  q25_54 free  q26_54 free  q27_54 free

\*Electrical Capacity Variables
 P1 >= 0  P2 >= 0 ... P25 >= 0  P26 >= 0

\*Thermal Capacity Variables
 Q1 >= 0  Q2 >= 0 ... Q26 >= 0  Q27 >= 0

Binaries

\*Electrical Binary Indices
 a1  a2 ... a25  a26

\*Thermal Binary Indices
 b1  b2 ... b26  b27

End
```

Bibliography

[1] NAVSEA DESIGN PRACTICE and CRITERIA MANUAL for SURFACE SHIP FRESHWATER SYSTEMS, CHAPTER 532. Washington, DC, 1987.

[2] NAVSEA DESIGN PRACTICE and CRITERIA MANUAL for ELECTRICAL SYSTEMS for SURFACE SHIPS, CHAPTER 300, NAVSEA T930U-AF-PRO-020, December 1992.

[3] Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for FY2015. Technical report, Office of the Chief of Naval Operations, Washington, DC, June 2014.

[4] Jeph Abara. Applying Integer Linear Programming to the Fleet Assignment Problem. Interfaces, 19(4):20–28, 1989.

[5] Dimitris Alevras, Martin Grotschel, and Roland Wessaly. Capacity and Survivability Models for Telecommunication Networks. Proceedings of EURO-INFORMS Joint International Meeting, pages 1–15, November 2007.

[6] Masoud Alimardani. Stochastic mixed-integer programming for financial planning problems using network flow structure. Master's thesis, University of Toronto, Toronto, Ontario, June 2014.

[7] Dimitris Bertsimas and John N Tsitsiklis. Introduction to Linear Optimization. Athena Scientific, Belmont, Mass., 1997.

[8] HU Bin, LI Fang, and ZHOU Hou-Shun. Robustness of Complex Networks under Attack and Repair. pages 1–4.

[9] Alan Brown and Juan Salcedo. Multiple-objective optimization in naval ship design. Naval Engineers Journal, 115(4):49–62, 2003.

[10] Alan Brown and LCDR Mark Thomas. Reengineering the Naval Ship Concept Design Process, From Research to Reality. In Ship Systems Engineering Symposium, ASNE. Citeseer, 1998.

[11] Karen Butler, NDR Sarma, and V Ragendra Prasad. Network Reconfiguration for Service Restoration in Shipboard Power Distribution Systems. IEEE TRANSACTIONS ON POWER SYSTEMS, 16(4):653–661, July 2001.

[12] Julie Steele Chalfant and Chryssostomos Chryssostomidis. Analysis of Various All-Electric-Ship Electrical Distribution System Topologies. In Electric Ship Technologies Symposium (ESTS), 2011 IEEE, pages 72–77. IEEE, 2011.

[13] R Chan, Scott D Sudhoff, Yonggon Lee, and Edwin L Zivi. A Linear Programming Approach to Shipboard Electrical System Modeling. In Electric Ship Technologies Symposium, 2009. ESTS 2009. IEEE, pages 261–269. IEEE, 2009.

[14] Chief of Naval Operations, Washington, DC. OPNAVINST 9070.1A: SURVIVABILITY POLICY AND STANDARDS FOR SURFACE SHIPS AND CRAFT OF THE U.S. NAVY, September 2012.

[15] ILOG CPLEX. 11.0 users manual. ILOG SA, Gentilly, France, 2007.

[16] Aaron M. Cramer. METRIC BASED DESIGN OF INTEGRATED ENGINEERING PLANTS FOR ROBUST PERFORMANCE DURING HOSTILE DISRUPTIONS. PhD thesis, Purdue University, West Lafayette, Indiana, July 2007.

[17] Aaron M. Cramer. Performance metrics for electric warship integrated engineering plant battle damage response. IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS, 47(1):634–646, January 2011.

[18] Aaron M Cramer, Scott D Sudhoff, and Edwin L Zivi. Evolutionary Algorithms for Minimax Problems in Robust Design. Evolutionary Computation, IEEE Transactions on, 13(2):444–453, 2009.

[19] Aaron M Cramer, Edwin L Zivi, and Scott D Sudhoff. Modeling and Simulation of an Electric Warship Integrated Engineering Plant for Battle Damage Response. In Proceedings of the 2011 Grand Challenges on Modeling and Simulation Conference, pages 230–237. Society for Modeling & Simulation International, 2011.

[20] Geir Dahl and Mechthild Stoer. A Cutting Plane Algorithm for Multicommodity Survivable Network Design Problems. INFORMS Journal on Computing, 10(1), January 1998.

[21] N Doerry and K. McCoy. Next generation integrated power system: NGIPS technology development roadmap. Technical report, Naval Sea Systems Command NAVSEA 05, Washington, DC, November 2007.

[22] N.H. Doerry and H. Fireman. Designing All Electric Ships. Proceedings of the Ninth International Marine Design Conference, 16-19 May 2006.

[23] Norbert Doerry. Zonal Ship Design. Naval Engineers Journal, 118(1):39–53, 2006.

[24] Norbert H. Doerry. Designing Electrical Power Systems for Survivability and Quality of Service. Naval Engineers Journal, 119(2):25–34, 2007.

[25] Norbert H Doerry and David H Clayton. Shipboard Electrical Power Quality of Service. In Electric Ship Technologies Symposium, 2005 IEEE, pages 274–279. IEEE, 2005.

[26] Ruixian Fang and et.al. Wei Jiang. System-level thermal modeling and co-simulation with hybrid power system for future all electric ship. In IEEE, pages 547–553, 2009.

[27] Ethan R Fiedel, Julie S Chalfant, and Chryssostomos Chryssostomidis. Cooling System Early-Stage Design Tool for Naval Applications. In Proceedings of the 2011 Grand Challenges on Modeling and Simulation Conference, pages 90–97. Society for Modeling & Simulation International, 2011.

[28] Bernard Gendron, Teodor Gabriel Crainic, and Antonio Frangioni. Multcommodity Capacitated Network Design. pages 1–29, January 2001.

[29] Wayne D. Grover and John Doucette. Topological Design of Survivable Mesh-Based Transport Networks. Annals of Operations Research, pages 79–125, May 2002.

[30] DOE Fundamentals Handbook. Thermodynamics, heat transfer and fluid flow. US Department of Energy, 1:53–96, 1992.

[31] C.R. Holsonback and T.M.Kiehne. Thermal aspects of a shipboard integrated electric power system. In Automation Science and Engineering (CASE), 2010 IEEE Conference on, pages 742–749. IEEE, August 2010.

[32] John Kuseian. Naval Power Systems Technology Development Roadmap. Technical report, Naval Sea Systems Command Electric Ships Office PMS 320, Washington, DC, April 2013.

[33] Martine Labbé, Rene Seguin, Patrick Soriano, and Christelle Wynants. Network Synthesis with Non-Simultaneous Multicommodity Flow Requirements: Bounds and Heuristics. pages 1–37, August 1999.

[34] M. Milošević Marden, P. Prempraneerach, J. L. Kirtley, G. Karniadakis, and C. Chryssostomidis. An End-to-End Simulator for the All-Electric Ship MVDC Integrated Power System. In Proceedings of the 2010 Conference on Grand Challenges in Modeling & Simulation, GCMS '10, pages 136–143, Vista, CA, 2010. Society for Modeling & Simulation International.

[35] Dimitri N Mavris and Daniel A DeLaurentis. Methodology for Examining the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies on Military Aircraft Design. 2000.

[36] Minoux. Network synthesis and optimum network design problems: Models, solution methods and applications. Networks, 19:313–360, 1989.

[37] Naval Sea Systems Command (NAVSEA). PEO Ships DDG Program Summary, January 2015.

[38] NAVSEA, Washington, DC. NAVSEA DESIGN PRACTICE and CRITERIA MANUAL for SURFACE SHIP SEAWATER SYSTEMS 0Y3-486, October 1990.

[39] Orlando Sentinel. http://articles.orlandosentinel.com/2013-04-25/business/os-southwest-airlines-earnings-20130425_1_airtran-flights-earlybird-check-in-southwest.

[40] Ronald O'Rourke. Navy littoral combat ship (LCS) program: Background, issues, and options for Congress. DIANE Publishing, 2011.

[41] Daniele Peri and Emilio F Campana. Multidisciplinary design optimization of a naval surface combatant. Journal of Ship Research, 47(1):1–12, 2003.

[42] Chester R. Petry and Jay W. Rumburg. Zonal electrical distribution systems: An affordable architecture for the future. Naval Engineers Journal, 105:45–51, May 1993.

[43] J P Powers. Construction Dewatering and Groundwater Control. John Wiley and Sons, 2007.

[44] DoD Regulation. 5000.2-R. Mandatory Procedures for Major Defense Acquisition Programs (MDAP), 1996.

[45] M. Rios, V. Marianov, and M. Gutierrez. Survivable capacitated network design problem: new formulation and Lagrangean relaxation. Journal of the Operational Research Society, pages 574–582, 2000.

[46] Benjamin C Rush. Cost as an Independent Variable: Concepts and Risks. Technical report, DTIC Document, 1997.

[47] Tom Schouwenaaars, Bart De Moor, Eric Feron, and Jonathon How. MIXED INTEGER PROGRAMMING FOR MULTI-VEHICLE PATH PLANNING. Proceedings for the European Control Conference, pages 2603–2608, May 2001.

[48] Mechthild Stoer and Geir Dahl. A polyhedral approach to multicommodity survivable network design. Numerische Mathematik, 68:149–167, February 1994.

[49] Joshua Adam Taylor. Conic Optimization of Electric Power Systems. PhD thesis, Massachusetts Institute of Technology (MIT), 2011.

[50] Patrick Rioux; Benjamin T. Smith; Krishnaiyan Thulasiramin. A Simplex Solution to the Minimum Cost Nonsimultaneous Multi-Commodity Flow Problem. Monograph 00841596, Transportation Research Board, Montreal H3C 3J7, Quebec, Canada, September 1994.

[51] Pamela H. Vance, Cynthia Barnhart, Ellis L. Johnson, and George L. Nemhauser. Airline crew scheduling: A new formulation and decomposition algorithm. Operations Research, 45(2):188–200, 1997.

[52] Clifford Alan Whitcomb. Composite System Analysis of Advanced Shipboard Electrical Power Distribution Systems. Master's thesis, Massachusetts Institute of Technology (MIT), Cambridge, MA, May 1992.

[53] W N White, Anil Pahwa, and Chris Cruz. Heat Loss from Electrical and Control Equipment in Industrial Plants: Part II - Results and Comparisons. In ASHRAE Transactions: Symposia 2004, pages 852–870.

[54] Isaac Woungang, Guangyan Ma, Mieso K Denko, Sudip Misra, Han-Chieh Chao, and Mohammad S Obaidat. Survivable ATM mesh networks: Techniques and performance evaluation. THE JOURNAL OF SYSTEM AND SOFTWARE, pages 1–10, November 2009.