2011

On the Application of Mixed Integer Programming to the Facility Layout Problem: A Case Study

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ON THE APPLICATION OF MIXED INTEGER PROGRAMMING TO THE FACILITY LAYOUT PROBLEM: A CASE STUDY

by

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A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of

Master of Science
in
Industrial Engineering

September 2011

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

Date

Thesis Advisor

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

An undertaking such as this does not take place in a vacuum. I am indebted to the mentoring of two great advisors, Dr. Mikell Groover and Dr. Aurélie Thiele. Dr. Groover first planted the seed of using the facility layout problem as a thesis for my MS IE degree, he provided invaluable guidance during the shaping of the scope of the thesis. It was in Dr. Thiele's class that I became aware of the application of MIP to facility layout. Her guidance and mentoring saw me through the development and completion of the thesis. I also cannot understate the importance of my management in the Department of Defense, Dr. Richard Wittstruck, Ron Gibson and Michael Brunskill. They provided the time, and the motivation, to dedicate time to this project.

ABSTRACT

This thesis evaluates the use of mixed integer programming to solve the facility layout problem on three case studies that correspond to three real-life problems faced by the Department of Defense. Each of the case studies presents unique attributes to evaluate possible improvements to the MIP solution to the facility layout problem. We provide in-depth descriptions of the problems faced by the Department of Defense (while sanitizing sensitive data), discuss the issue of size and the impact of the proportionality ratio in solving the problem. The main contribution of the thesis to the facility layout literature is the analysis of the MIP approach for various military logistics problems, with a focus on tractability, when high-performance computing tools are used.

CHAPTER 1: Introduction and Background

Background and Concepts

History

Since the Industrial Revolution and the beginning of what is understood to be modern manufacturing techniques, engineers and scientists have strived to improve the layout of facilities. From the 1960's onward, there has been a large amount of research has been devoted to the facility layout problem (FLP) (Thompkins et. al., 2003). In 1963 the Computerized Relative Allocation of Facilities Technique (CRAFT) algorithm was introduced by Armour and Buffa (1963). In 1989/1990 BLOCPLAN was introduced by Donaghey and Pire (1990). Shortly after that in the early 1990's FLP's were formulated as mixed integer problems (MIP), one of the earliest sources is Montreuil's (1990) which will be used for the rest of this thesis.

Discrete Departments

One of the most important concepts is that the facility has to be divided up into discrete departments. For some situations, there are natural and logical divisions, such as restroom facilities, offices and teams as given in Case Study 1 of the present thesis. In other situations, there was a lot of effort put into creating departments and dividing responsibilities, such as in Case Study 3. In Case Study 1, the departments were well defined since it is a US Government office requiring a clear definition of roles; however, the constant debate between functional organization and team organization makes it possible that these roles will change in the future, which will call for re-optimization. At the current time, Integrated Product Teams (IPT) are the standard format.

From the Department of Defense Handbook (1998):

> *"An Integrated Product Team (IPT) is a multidisciplinary group of people who are collectively responsible for delivering a defined product or process. The IPT is composed of people who plan, execute, and implement life-cycle decisions for the system being acquired. It includes empowered representatives (stakeholders) from all of the functional areas involved with the product—all who have a stake in the success of the program, such as design, manufacturing, test and evaluation (T&E), and logistics personnel, and, especially, the customer."*

In Case Study 3, Company C is transitioning from a "Skunk Works" type research and development house to a production house to support future requirements.

Problem Categories

The facility layout problem can be broken down into two main categories, construction problems (where the facility or an addition to it is built from scratch) and improvement problems (where the manager must use a pre-existing facility). Intuitively, construction type problems will result in an equal or lower layout cost compared to the improvement problem due to unique constraints in the improvement problem. However construction may not always be an option due to fiscal requirements related to capital investment restrictions or it may not be an option due to social requirements with the building listed on the National Register of Historical Places.

Layout Cost

Regardless of problem categories both are evaluated based using the metric of layout cost. The layout cost may be defined as the total distance traveled during an item's trip through the plant or by a summation of "closeness ratings," which are described below. Layout cost can also be calculated from a weight-distance calculation, it is much easier to transport 100 1kg batteries over a distance of 100m (10,000 kg-m) than 100 1,000kg motors over a distance of 100m (10,000,000 kg-m), which under a simple distance calculation would be identical instead of a difference of three orders of magnitude.

Closeness Rating

The closeness rating is a value which attempts to quantify the relationship between two departments. It can be based on product flow between the departments, or such negatives as fumes from a painting department or undesirable odors from sanitary facilities. The closeness rating is not quantitatively derived, although quantitative data, along with subjective input can be used to create them (Thompkins et. al. 2003).

Facility Layout Algorithms

The current most popular algorithmic approaches are pairwise comparison of departments such as CRAFT and BLOCPLAN and guillotine cuts such as LOGIC (Tam 1991). Pairwise comparison is based on the change to the layout cost, the minimization of which represents the objective of the optimization problem. CRAFT for instance is an improvement algorithm which requires an existing layout. While an in-depth discussion of these other algorithms is out of the scope of this thesis, we will mention that CRAFT works by examining the benefit to switching departments; specifically, it chooses the one that gives the largest benefits to layout cost and then repeats until switching will no longer provide a benefit to the layout cost. BLOCPLAN similarly uses the pairwise comparison but also forces the departments into bands which flow parallel to each other.

Conceptual Optimization Problem

A very basic layout algorithm can be thought of as a set of short cylinders connected to each other by rubber bands through the center point of the top of the cylinders. The strength of the rubber band corresponds to the attractiveness between the cylinders. The optimal solution can be defined as the solution which has the lowest energy level. Rubber bands approximately follow Hooke's Law $F=k*x$, where the force is equal to spring constant multiplied by the amount of displacement.

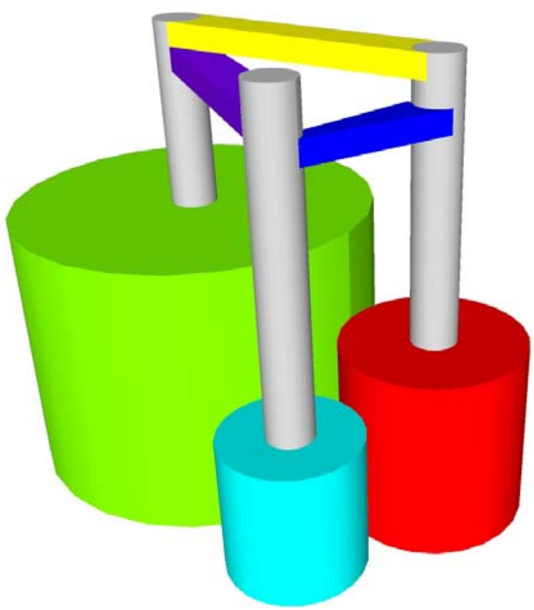

Figure 1 Cylinder Conceptual Representation

In terms of the facility layout problem, the force can be thought of as the function to be minimized while *k* is representative of the closeness rating between two departments. A basic conceptual problem is as follows:

$$Minimize\ Z = \sum_{i=1}^{n}\sum_{j=1}^{n} \mathrm{D_{ij}}\ \mathrm{v_{ij}}$$

$$D_{ij=}\ =\ \sqrt{\sum_{k=1}^{2}(d_{ijk})^2}\ \forall i,j$$

$$r_i + r_j\ \leq D_{i,j}\ \forall i,j$$

$$r_i = \frac{\sqrt{A_i}}{\pi}\ \forall i$$

$$d_{ijk} = \left|\ c_{ik} -\ c_{jk}\right|\ \forall\ i,j,k$$

The goal is to minimize the layout cost, *Z*, which is calculated by the summation of the product of the distance (D_{ij}) between *n* departments and the closeness rating (v_{ij}) for those departments. The variable D_{ij} is defined as the distance from department *i* to department *j*, which is calculated as an Euclidian distance between centroids, i.e., the square root of the summation of the square of d_{ijk} for all *k*, i.e., the distance from the centroid c_{ik} to centroid c_{jk}. The centroid contains the x coordinate for *k=1* while the y coordinate is represented by *k=2*. The variable v_{ij} is defined as the closeness rating between department *i* and department *j*. Both the closeness rating and the area of the individual departments (A_i) are fixed inputs to the problem. The variable r_i is the radius of department A_i. Assuming A_i is always greater than 0 will prevent r_i from ever becoming negative, therefore a positive bound on the latter is not required. In order to enforce perimeter integrity, that is, prevent physical overlap between departments, a constraint must be created which will force the departments to remain separate (distinct) from each other. Incorporating rectangular rather than point-like departments adds a substantial layer of complexity to the model, both in constraining departments from overlapping, and measuring centroid to centroid differences. In the present setting, forcing the distance between the two departments to be greater than the sum of the radii of the departments will prevent the departments from overlapping.

Case Studies

Case Study 1

The first case study introduces the concepts of Department of Defense Acquisition policies and framework. This provides a background to understand the following two case studies which are of two different Army acquisition programs. Case Study 1 uses the impending move from Fort Monmouth, NJ to Aberdeen Proving Grounds, MD to demonstrate the MIP in an office environment. An office environment offers different constraints than a traditional manufacturing facility. Product "flow" is hard to define and effectiveness and interdependencies are not clear.

Case Study 2

The second case study examines a complete redesign of a factory which produces systems for the US Army. They experienced a large surge in orders and forecast a much larger surge in the future. The company plans to redesign to a single product due to the large number of committed orders.

Case Study 3

The last case study deals with a small research and development house converting into a production house. This posed unique challenges, specifically, how to bring the production framework to a primarily R&D type house and design for maximum efficiency.

Proprietary Information

Certain proprietary information has been removed or altered for confidentiality purposes. A high level description of the changes can be provided upon request.

CHAPTER 2: Facility Layout Problem

Optimization Function

This chapter shall develop the basic concepts from the "rubber band" thought experiment described earlier into a basic optimization problem based on the work of Montreuil (1990). The objective function once again seeks to minimize the cost multiplied by the distance between the departments. At this point of the paper, the distance equation is represented by d_{ij}, which will be developed in the "Centroid to Centroid Distance Calculation" section below. At a high level, the objective is defined by:

$$Minimize\ Z = \sum_{i=1}^{n} \sum_{j=1}^{n} \mathrm{D_{ij}}\ \mathrm{v_{ij}}$$

Point Definition

In order to define the positions, this problem makes an assumption that all departments are rectangular in shape and therefore the two points which define the west side of department *i* will share an x-coordinate (Xw_i) while the points that define the north side of department *i* will share a y-coordinate (Yn_i). The points which define each department are illustrated in Figure 2.

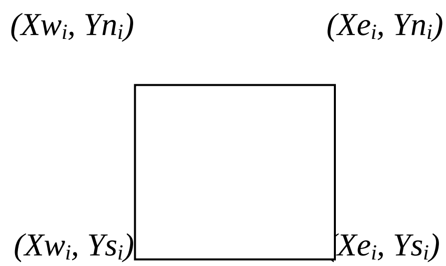

Figure 2 Coordinates of a department

We must add constraints to prevent overlap between departments. In the conceptual problem seen earlier, this was done by simply ensuring the distance between two centroids of the department was greater than the sums of their radii. The rectangle approach uses a similar logic. Forcing the distance between centroids to be at least equal to half the minimum distance for both department *i* and *j* will prevent departments from overlapping. It is possible for two departments to occupy a portion of same x coordinate or y coordinate, but not both at the same time. The distance between centroids, defined below, is greater than the sum of the distance from the centroid to the edge of the department. Binary variables are used to prevent the departments from overlapping, S_{ij}, Tx_{ij}, and Ty_{ij} are the binary variables. As both *i* and *j* range from 1 to n, the number of binary variables rapidly increases as the number of departments in the problem is increased.

$$Xc_j - Xc_i \geq 0.5 * \left(Xe_i - Xw_i + Xe_j - Xw_j\right) - Mx * \left(S_{ij}\right) - Mx * (1 - Tx_i)$$

$$Xc_i - Xc_j \geq 0.5 * \left(Xe_i - Xw_i + Xe_j - Xw_j\right) - Mx * \left(S_{ij}\right) - Mx * (1 - Tx_i)$$

$$Yc_j - Yc_i \geq 0.5 * \left(Yn_i - Ys_i + Yn_j - Ys_j\right) - My * \left(S_{ij}\right) - My * \left(1 - Ty_{ij}\right)$$

$$Yc_i - Yc_j \geq 0.5 * \left(Yn_i - Ys_i + Yn_j - Ys_j\right) - My * \left(S_{ij}\right) - My * \left(1 - Ty_{ij}\right)$$

Department Proportionality

The next constraint that should be addressed is the proportionality of each department. There are often minimum values, if the department is composed of discrete subunits. In manufacturing environment, these may correspond to CNC machines, while in an office environment they may correspond to cubicles. In the case where the departments are not square there is the possibility that a simple 90^{o} rotation might result in a lower facility cost. Each department may also have a maximum length beyond which inefficiencies in intra-departmental travel may result, or beyond which the layouts are just not feasible.

For example, consider a three department problem where all departments are a 4x1 rectangle and department 1 and 3 are oriented with their long axis parallel to the y-axis while department 2 is parallel to the x-axis. If they have an equal closeness rating, then depending upon the initialization, the optimal solution would either be a H shaped layout or a thick T shaped layout. The simplest approach is to fix the distances with parameters L and W, however, this extremely limits the flexibility of the optimization program and will be discussed later. The maximum and minimum values for length and width are properties unique to each department and require careful judgment to determine, however it may be cost prohibitive to determine the exact parameters and instead an approximate estimate maybe used.

Proportionality Ratio

For cases where it may be too data intensive to calculate the optimal proportionality ratio, a proportionality ratio may be used, k. The ratio k is set equal to the maximum distance of either length or width, divided by the minimum distance of the other parameter as shown below. There are a number of ways to solve for the maximum and minimum values for length and width. All distances parameters in this thesis were calculated using a simple linear search algorithm available in Microsoft Excel 2007, Goal Seek.

$$k_i = \frac{Wmax_i}{Lmin\_i} = \frac{Lmax_i}{Wmin_i} \ \forall i$$

$$Pmax_i = 2 * (Lmin_i + \ Wmin_i) = \ 2 * (Lmax_i + \ Wmin_i)\forall i$$

$$Pmin_i = 4 * Ls_i = 4 * Ws_i \forall i$$

$$Ls_i = WsI = \sqrt{(A_i)} \ \forall i$$

In order to constrain the sides, each department has parameters on the maximum length and width. $Lmin_i$ and $Lmax_i$ correspond to the lengths, while $Wmin_i$ and $Wmax_i$ are the widths. If only length and width are constrained, then for positive distance costs, the program forces both to the minimum values. For the special case of square departments, this is acceptable. However, for departments where the minimum distance is less than the square root of the area, this poses a problem. By constraining the perimeter it is possible to prevent the departments from being forced into a layout which is smaller than the required area. $Pmax_i$ is calculated as twice the sum of $Lmin_i$ and $Wmax_i$ which is equal to twice the sum of $Lmax_i$ and $Wmin_i$. $Pmin_i$ is calculated as four times the square root of the area of the department, since for a rectangle, the minimum perimeter is found in the form of a square.

$$Xe_i - \ Xw_i \geq Lmin_i \forall i$$

$$Xe_i - \ Xw_i < +Lmax_i \forall i$$

$$Yn_i - Ys_i \geq Wmin_i \forall i$$

$$Yn_i - Ys_i \leq Wmax_i \ \forall i$$

$$2 * (Yn_i - Ys_i + Xe_i - Xw_i) \geq Pmin_i \ \forall i$$

$$2 * (Yn_i - Ys_i + Xe_i - Xw_i) \leq Pmax_i \ \forall i$$

Simplified Fixed Department Distances

In the special case of departments which are fixed in length, then the above solution can be simplified. The minimum and maximum equations can be simplified into a single equality, and the perimeter constraints can be removed in their entirety.

$$Xe_i - Xw_i = L_i \ \forall i$$

$$Yn_i - Ys_i = W_i \ \forall i$$

Facility Dimensioning

Now that the individual departments have been bounded, it is time to bound the facility itself. While there may be practical constraints such as the dimensions of the parcel of land, there may also be architectural constraints. The architect may desire a specific shape in order to fit in with the existing plant, or it may be purely for aesthetic reasons. This problem only deals with situations where the building is a rectangle, to solve for L and other building shapes, a ‘dummy department’ can be used. A dummy department is an additional department over the actual department count whose position is fixed. The dummy department is created by specifying the x,y coordinates of the corner points and ensuring the dimensions of the department are valid with the length, width and perimeter constraints. In order to bound the department layout on the north and east sides, the building length and width are specified by *Bx* and *By* respectively. The building does not have to be bound on the south and west sides because that was previously accomplished by constraining the problem to the right upper quadrant. The length constraints, by the order of the equations, has already defined $Yn_i > Ys_i$ and $Xe_i > Xw_i$ so there is no need to put a redundant equation forcing that relationship. This allows only the east and north coordinates to be constrained within the building dimensions.

$$Xe_i \leq Bx \; \forall i$$

$$Yn_i \leq By \; \forall i$$

Centroid Definition

In order to determine the distance between the departments which is required for the optimization function, the centroid of each department must be defined. Since the corner points have already been defined, it is a simple matter to define them. Once again the x and y components of the position have been separated out. The x-coordinate of the centroid of department *i* is Xc_i which is simply the averages of the two x-coordinates of the department (Xw_i and Xe_i). The y-coordinate is likewise Yc_i which is also the average of the respective components (Ys_i and Yn_i).

$$Xc_i = \; 0.5 * (Xw_i + Xe_i) \forall i$$

$$Yc_i = 0.5 * (Yn_i + \; Ys_i) \forall i$$

Centroid to Centroid Distance Calculation

Montreuil's Method

Calculating the distance between the centroids of departments while preserving the linearity of the problem is not a straightforward issue. Montreuil's method is as follows. In order to avoid having absolute values in the optimization function (which creates non-linearities), we decompose numbers in their positive and negative components. Setting the difference between the centroids equal to these two variables makes it possible to keep all variables positive. Then the absolute value of the difference between the centroids is equal to the sum of the positive and negative components.

$$Xc_i - Xc_j = X_{ij}^{+} - X_{ij}^{-} \; \forall i, j \; i \neq j$$

$$|Xc_i - Xc_i| = X_{ij}^{+} - X_{ij}^{-} \; \forall i, j$$

Likewise for the y coordinate components:

$$Yc_i - Yc_j = Y_{ij}^{+} - Y_{ij}^{-} \; \forall i, j \; i \neq j$$

$$|Yc_i - Yc_i| = Y_{ij}^{+} - Y_{ij}^{-} \; \forall i, j$$

The combination of the above formulas creates the total distance between the centroids of the respective departments, which can then be substituted into the optimization function to complete the development of the basic problem.

$$D_{ij} = X_{ij}^{+} + X_{ij}^{-} + Y_{ij}^{+} + Y_{ij}^{-} \; \forall i, j$$

$$Minimize\ Z = \sum_{i=1}^{n} \sum_{j=1}^{n} (X_{ij}^{+} + X_{ij}^{-} + Y_{ij}^{+} + Y_{ij}^{-}) * \mathrm{v}_{\mathrm{ij}}$$

Alternative Distance Calculation

The rectilinear distance calculation method used in this paper is derived from Sherali (2003). Instead of subtracting the negative component, it linearizes the convex piecewise linear terms through inequalities: it calculates the x and y distance from both department *i* to department *j* and from department *j* to department *i*; by setting the distance greater than or equal to both of them, it forces the variable to the positive value.

Blanks (1985) has shown as the number of departments increases, rectilinear and Euclidian distances converge.

$$dx_{ij} \geq Xc_i - Xc_j \forall i, j$$

$$dx_{ij} \geq Xc_j - Xc_i \ \forall i, j$$

$$dy_{ij} \geq Yc_i - Yc_j \forall i, j$$

$$dy_{ij} \geq Yc_j - Yc_i \ \forall i, j$$

$$dx_{ij} <= \left(Xc_i - Xc_j\right) + \ Mx * Tx_{ij} \ \forall i, j$$

$$dx_{ij} <= \left(Xc_j - Xc_i\right) + \ Mx * (1 - Tx_{ij}) \ \forall i, j$$

$$dy_{ij} <= \left(Yc_i - Yc_j\right) + \ My * Ty_{ij} \ \forall i, j$$

$$dy_{ij} <= \left(Yc_j - Yc_i\right) + \ My * (1 - Ty_{ij}) \ \forall i, j$$

CHAPTER 3: Case Study 1

PdM RUS Office Layout

Introduction

This case study deals with an office (white collar) environment. In 2005, the Department of Defense (DoD) Base Realignment and Closure (BRAC) commission recommended that Fort Monmouth, NJ be closed by 15 September 2011 and the vast majority of responsibility transferred 150 miles to Aberdeen Proving Grounds (APG), MD. Currently APG does not have the infrastructure to absorb the thousands of employees who will be relocating. This has created an opportunity for a green field design for the offices.

DoD Acquisition Command Structure

This case study deals with Product Manager Robotic and Unmanned Sensors (PdM RUS), composed of a Product Manager (PdM) which is an Lieutenant Colonel (O-5) level slot and his deputy and 4 Assistant Product Managers (APM). PdM RUS reports to Program Manager Night Vision/Reconnaissance, Surveillance, and Target Acquisition (PM NV/RSTA) which is a Colonel (O-6) level slot. PM NV/RSTA reports directly to Program Executive Office, Intelligence, Electronic Warfare and Sensors (PEO IEW&S).

The Program Executive Officers report directly to the Army Acquisition Executive (AAE), the AAE reports directly to the DAE, or Defense Acquisition Executive. The AAE and DAE are on the staff of the appropriate secretary, with the AAE being the Assistant Secretary of the Army for Acquisition, Logistics and Technology (ASA(ALT)), and the DAE is the Under Secretary of Defense for

Acquisition and Technology and Logistics (USD(ATL)). (Department of Defense Instruction, 2007).

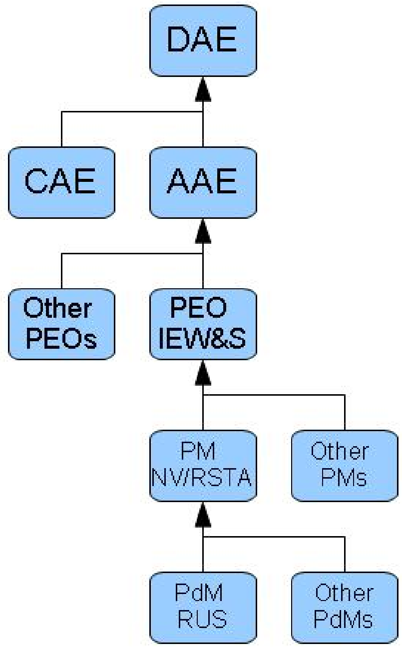

Figure 3 Diagram of Department of Defense Acquisition Chain of Command

The DoD uses a tiered hierarchy to manage their programs (Department of Defense Instruction, 2008). The Army divides their formal acquisition programs into 3 separate acquisition categories (ACAT) based on dollar value shown in Table 1 below. Automated Information Systems (AIS) fall under a different ACAT system which is beyond the scope of this thesis. The important distinction between the ACAT levels is the milestone decision authority (MDA). The MDA is ultimately responsible for the success or failure, along with all strategic decisions. ACAT I may either be ACAT ID which the MDA is the DAE, or ACAT IC which the MDA is the Component Acquisition Executive (CAE) such as the AAE. ACAT II's MDA is the CAE while ACAT III MDA's are at the PEO level. The PEO is Major General (0-8) command slot, which may occupied by either a 2 star general or a Senior Executive Service (SES) employee which is the civilian equivalent of a general officer. (Civil Reform Act, 1978)

	RDT&E	Procurement
ACAT I	> $355	> $2,135
ACAT II	> $140	> $645
ACAT III	< $140	< $645

Table 1 ACAT Threshold Requirements

(all dollars are in FY 1996 million dollars)

Joint Capabilities Integration Development System

There are two types of acquisition programs in the DoD, Programs of Record (POR) which are divided up into the different ACAT levels, and QRCs.

PORs have gone through the formal Joint Capabilities Integration Development System (JCIDS) process and have a Joint Requirements Oversight Council (JROC) approved Initial Capability Document (ICD), Capability Development Document (CDD) or Capability Production Document (CPD). Each document corresponds to a phase in the JCIDS process, the ICD is used during the Material Solution Analysis Phase which feeds in to Technology Development, which uses the CDD, and the CPD a product of the Engineering and Manufacturing Development Phase. More in depth information on the JCIDS process can be found on Intelink. (Department of Defense Joint Integration Manual).

The PORs have guaranteed funding for out years and are permanent programs while QRCs are temporary programs which are fielded until the POR has time to come along and fulfill the need. QRCs are fielded in response to three different documents, a JUONS, ONS and a directed requirement.

A JUONS is a Joint Urgent Operation Needs Statement (Chairman of the Joint Chiefs of Staff Instruction, 2007), which means more than one service (Army, Navy, etc) has an urgent need for the capability, the recent Mine Resistant Ambush Protected All Terrain Vehicle (M-ATV) is a good example of a system which was developed and procured rapidly in response to a JUONS.

An ONS is an Operational Needs Statement (Department of the Army, 1997) which is service specific, the ADS and the C2 systems are examples of systems that were developed and fielded in response to an ONS. With both JUONS and ONS, a unit in theater will determine they have a capability shortfall and write up either a JUONS or ONS which describes what they need. The document then goes into a very complicated staffing process with the end result in either J-8, for JUONS, or G-3 for ONS, validating the need and assigning the MDA to the appropriate authority. J-8 is the department responsible for the Rapid Acquisition Cell at the Office of the Secretary of Defense (OSD) level while G-3 is the validation authority at the Office of the Secretary of the Army (OSA) level.

Directed Requirements are slightly different than JUONS or ONS, where as JUONS or ONS specify a required *capability*, a directed requirement specifies a *material solution.* In other words, while a JUONS or ONS may require a vehicle to drive 350 miles without refueling and carry at least 4 people, a directed requirement will require a 2007 Chevrolet Suburban.

ARP Development

The focus of the PdM is to develop, procure, field and sustain a capability which is required by the US Army in accordance with the aforementioned acquisition framework. The office will contract with a prime contractor for the development and production of a system. The main focus of the contract development is the Acquisition Requirements Package (ARP). (Department of the Army, Program Executive Office, 2007) An ARP is composed of over two dozen interdisciplinary documents; however, the majority of the effort is spent on three documents, the main requirement document, the technical requirements document and the Source Selection Evaluation Plan (SSEP). Each of these documents requires input from all the stakeholders. IPT's will be formed which incorporate experts from all essential acquisition domains (Department of Defense Handbook, 1998), who will provide input and develop these documents. The main requirement document can take three forms, a Statement of Work (SOW), which is the standard contractual document used in the commercial world; a Statement of Objectives, which layouts what the Army expects the contractor to perform, the contractor then developments a SOW in response; and a Performance Work Statement (PWS), which lays out performance requirements and is used only for service contracts. The technical requirements document can take several forms also, which are Performance Specifications (PS), which details exactly how the system will perform; Performance Based Specification (PBS), which the contractor turns into a PS similarly to how a SOO becomes a SOW; and drawings which specify every parameter of the product.

Office Description

PdM RUS personnel are located at two geographically different locations, with two APdM's at each location; this case study will only deal with one location. At the current location there are two APM's and their support personnel. The two APM's have a total of 29 personnel and 2,820 ft and are organized as follows:

Table 2 Case Study 1 Department Summary

	APdM 1	#	Sq Ft[1]	Total	APdM 2	#	Sq Ft	Total	Shared Assets	#	Sq Ft	Total
	APdM	1	196	196	APdM	1	196	196	1 Cost Analyst	1	64	64
	2 Project Leads	2	64	128	3 Project Leads	3	64	192	1 IMS Manager	1	64	64
	4 Logisticians	4	64	256	3 Logisticians	3	64	192	2 Admin's	2	64	128
	1 Systems Engineer	1	64	64	2 System Engineers	2	64	128				
	1 Test Engineer	1	64	64	1 Test Engineer	1	64	64				
	1 Production Engineer	1	64	64	1 Radar Engineer	1	64	64				
	1 Program Analyst	1	64	64	2 Program Analysts	2	64	128				
					1 Configuration Manager	1	64	64				
Subtotals		11		836		14		1028		4		256

[1]Note: Square Footage includes the necessary walkways and aisles.

APM 1 has 2 Quick Reaction Capability (QRC) programs (the ADS and C2 systems mentioned in Case Study 3) while APM 2 has 2 ACAT III programs and a single QRC. In addition to the personnel, the office has various support rooms necessary for the functioning of business; these are listed in Table 3.

Table 3 Case Study 1 Facility Summary

Room	Size (ft^2)
Conference Room	216
Bathroom	288
Secure Storage	36
Kitchen	24
A/C & Heat	144
Total	708

Assumptions

The following assumptions were made to determine the various importance ratings.

Inter APdM

Each APdM is composed of an IPT, Integrated Product Team (Department of Defense, Defense Acquisition Guidebook). An IPT is composed of subject matter experts (SME) from various functional areas to achieve an objective. An IPT format will ensure all relevant stakeholders are involved in the process from the beginning. These IPT's are divided into 3 functional areas, engineering, logistics and program support. Due to the interdependence of the IPT format, each functional area has a location importance rating to each other of 0.33.

Within these functional areas, the personnel are very interdependent, the test engineer would consult both the system engineers and production engineer while working on the PS/PBS. A good example of the interface between logistics and engineering is the packaging and handling requirements in the PBS. An airdrop from a C-17 Globemaster III to warfighters on the ground has a much different physical environment than ordering a textbook off of Amazon and having UPS drop it off on your doorstep.

All three main components of the ARP require input from all three functional areas, depending on the location in the JCIDS lifecycle, engineering and logistics will vary in importance. In the beginning Material Solution Analysis Phase, engineering, specifically system engineering is most important, while in the second to final phase Production & Deployment, logistics is just as important as engineering, and in Operations and Support Phase, logistics is more important than engineering. Program support will always be required. Due to variability in the JCIDS lifecycle, it cannot be determined which is more important to the APdM so the location importance rating to the APdM is equal for engineering, logistics and program support.

Due to the high interdependence in the functional areas, it is essential that they are located together; therefore each member of a function area will have the highest rating to others of their same area.

Project Leads are assigned to individual products, for APdM 1, a Project Lead is assigned to the ADS and C2 products. The functional areas however are assigned to all products within a APdM so their location importance rating is equal for each PL. Due to the need for management, the PL will have a closeness important rating of 0.5 to their respective APdM while standard personnel will have one of 0.33

There is little contact between PL's, aside from schedule conflicts with the functional support. Therefore there is a very low location importance rating between PL's.

Program Analysts functions as a second in command to the Project Lead so both are included in the Program Support functional area.

Shared Assets

The APdM staff works a nominal 08:00-16:30 schedule with a half hour for lunch. However, this is variable due to the unpredictable workload. It is assumed that the workload variations will average out so that neither APdM has a greater need for the kitchen nor restroom facilities, therefore the location importance rating will be equal for all staff, since these facilities will only be used sparingly during the day compared to interactions amongst team members, a location importance rating of 0.15 was assigned.

Both cost estimates (Independent Government Cost Estimates (IGCE) and Program Office Estimates (POE)) and an Integrated Master Schedule (IMS) are required by the PEO for all programs. Both ACAT III and QRCs documentation requirements are tailorable by the MDA, so it is assumed that they have equal requirements. Therefore the APdM's and program support have a location importance rating to the Cost Analyst and IMS Manager which is proportional to the number of programs, 2/(2+3)=0.4 for APdM 1, and 0.6 for APdM 2.

Similar to the cost analyst and IMS manager, the conference room is assumed to be used in proportion to the number of program, APdM 1=0.4 and APdM=0.6.

Administrative support involves travel orders, office supplies and other services which are approximately equal per person. Therefore the location importance rating is equal for all personnel of APdM's, but is proportional between the APdM and the number of personnel they supervise. Therefore APdM 1 has 11 personnel while APdM has 14, so APdM location importance rating is 11/(11+14)=0.44 while APdM 2 is 0.56.

The secure storage will be used to store various classified documents. JUONS and ONS are normally classified SECRET since they state a shortfall in operational capability[i]. Also, before a system can fielded, a Capability and Limitations (C&L) report must be prepared by the Army Test and Evaluation Command (ATEC)[ii]. These are also classified at a minimum of SECRET. Various other documents including intelligence reports maybe used to prepare the ARP. The logistics area is fundamentally interested in the locations to be fielded to in the JUONS/ONS, while engineering and program support are interested in all reports. Therefore logistics is given a location importance rating of 1/3=0.33 while engineering and program support are given a rating of 0.67.

The air conditioning and heating system is not expected to be maintain by office personnel, a contractor is responsible for maintenance. However, all environmentally conditioning systems make noise which is a negative. This is most important for meetings, large meetings will be held in the conference room while smaller meetings are routinely held in the APdM's office. Therefore the conference room has a location importance rating of -1.0 with the A/C and heating system, while the APdM's have a -0.66 and the rest of the personnel have -0.33. The bathroom, kitchen and secure storage have a rating of 0.0.

Location Importance Rating Development

Closeness Relationships

The closeness relationships are summarized below, a complete chart is available for reference in appendix. Identical values have been color coded to ease of reference.

Table 4 Case Study 1 Relationship Diagram

	APdM 1	APdM 1 PL 1	APdM 1 PL 2	APdM 1 Log Team	APdM 1 Eng Team	APdM 1 Prog Supp	APdM 2	APdM 2 PL 1	APdM 2 PL 2	APdM 2 PL 3	APdM 2 Log Team	APdM 2 Eng Team	APdM 2 Prog Supp	Cost Analyst	IMS Man	Admin 1	Admin 2	Con Rm	B Rm	Sec Stor	Kitchen	A/C & Heat
APdM 1		0.50	0.50	0.33	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.44	0.44	0.40	0.15	0.67	0.15	-0.67
APdM 1 PL 1			0.00	0.33	0.33	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.44	0.44	0.40	0.15	0.67	0.15	-0.33
APdM 1 PL 2				0.33	0.33	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.44	0.44	0.40	0.15	0.67	0.15	-0.33
APdM 1 Log Team					0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.44	0.44	0.40	0.15	0.33	0.15	-0.33
APdM 1 Eng Team						0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.44	0.44	0.40	0.15	0.67	0.15	-0.33
APdM 1 Prog Supp							0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.44	0.44	0.40	0.15	0.67	0.15	-0.33
APdM 2								0.50	0.50	0.50	0.33	0.33	0.33	0.60	0.60	0.56	0.56	0.60	0.15	0.67	0.15	-0.67
APdM 2 PL 1									0.00	0.00	0.33	0.33	1.00	0.60	0.60	0.56	0.56	0.60	0.15	0.67	0.15	-0.33
APdM 2 PL 2										0.00	0.33	0.33	1.00	0.60	0.60	0.56	0.56	0.60	0.15	0.67	0.15	-0.33
APdM 2 PL 3											0.33	0.33	1.00	0.60	0.60	0.56	0.56	0.60	0.15	0.67	0.15	-0.33
APdM 2 Log Team												0.33	0.33	0.33	0.33	0.56	0.56	0.60	0.15	0.33	0.15	-0.33
APdM 2 Eng Team													0.33	0.33	0.33	0.56	0.56	0.60	0.15	0.67	0.15	-0.33
APdM 2 Prog Supp														0.60	0.60	0.56	0.56	0.60	0.15	0.67	0.15	-0.33
Cost Analyst															1.00	0.56	0.56	0.60	0.15	0.00	0.15	-0.33
IMS Man																0.56	0.56	0.60	0.15	0.00	0.15	-0.33
Admin 1																	1.00	0.60	0.15	0.00	0.15	-0.33
Admin 2																		0.60	0.15	0.00	0.15	-0.33
Con Rm																			0.15	0.00	0.15	-1.00
B Rm																				0.00	0.15	0.00
Sec Stor																					0.15	0.00
Kitchen																						0.00
A/C & Heat																						

CHAPTER 4: Case Study 2

Company A Layout Problem

Introduction

This case study deals with a medium sized electronics manufacturing house, whose product line was previously composed of three different products, one of which has potential for a very large amount of growth. The company has decided to reorganize their manufacturing facility to optimize production of their main product.

Background

The three main products manufactured by Company A are a helicopter radio, a commercial telephone family of systems, and an Acoustic Detection System (ADS). The helicopter radio is nearing the end of its lifecycle and will soon be phased out. The commercial telephone system has never been a large money maker, it was intended only to keep the production line open. The ADS was previously produced in small quantities, (~250 systems), in the past year the company has received orders for over 5,000 systems with at least that many expected in the future. Accordingly they have decided to reorganize the plant around this system which will be their bread and butter for the next few years.

System Description

The ADS is composed of two major subsystems, an acoustic array which is mounted on the exterior of the vehicle, and a processing/display unit (PDU) which is installed on the interior of the vehicle. Due to the differences on vehicles, there are 3 different sets of lengths of cables. Company A has done some careful engineering and created a one size fits all for the mounting plates for the system.

The acoustic array is composed of four different components, the mounting bracket, the mast, the mast hub and 8 microphones. The mast hub is composed of a plastic housing and an PWB with a Analog to Digital (A/D) Converter inside. Each microphone is composed of a plastic spine, a microphone and wiring, and a foam cover.

The display unit is composed of a metal exterior shell, an LCD display, two PWB's one of which included a computer on a chip (CoC), power supply, interior speaker, 3 external connectors. The following Table 5 summarizes the component breakdown. The yellow coded components are manufactured in house while the blue components are outsourced to various vendors. The complete system is composed of 1 each P/N 1.0, 2.0 and 3.0, its P/N is 4.0.

Table 5 Case Study 2 Component Breakdown

Q	Top Level Component	P/N		P/N		P/N		P/N
1	Acoustic Array	1.0						
1			Mounting Bracket	1.1				
1			Mast	1.2				
1			Mast Hub	1.3				
1					Hub Cover	1.3.1		
1					Assembled PWB	1.3.2		
1							A/D Converter	1.3.2.1
N/A							Assorted Components	1.3.2.2
1							PWB	1.3.2.3
8			Microphones	1.4				
8					Spine	1.4.1		
8					Microphone & Wiring	1.4.2		
8					Foam Cover	1.4.3		
1	PDU	2.0						
1			Metal Shell	2.1				
1			LCD Display	2.2				
2			Assembled PWB	2.3				
1					CoC	2.3.1		
N/A					Assorted Components	2.3.2		
2					PWB	2.3.3		
3			Mil-Spec Connector	2.4				
1			Speaker	2.5				
1			Power Supply	2.6				
1			Mounting Bracket	2.7				
1	Vehicle Cables	3.0						
1			Power Cable	3.1				
1			Mast Cable	3.2				

Manufacturing

Company A outsources the hardware manufacturing and concentrates on the assembly of PWB's with their components which they reflow in-house along with final assembly of the systems. The following table has a list of the components which are outsourced and manufactured in-house. The company currently uses Pb-Sn solder for all military applications due to the risk of tin whiskers. Tin whiskers are a direct product of the European Union's RoHS (Reduction of Hazardous Substances) regulations (European Parliament, 2003). Company A also maintains a RoHS compliant wave solder tank, but it is only rarely used for high priority short production runs.

Table 6 Case Study 2 Vendor Outsourcing Table

Sub-Vendor 1		Sub-Vendor 2		Sub-Vendor 3		Sub-Vendor 4		Sub-Vendor 5	
Mounting Bracket	1.1	Mast	1.2	A/D Converter	1.3.2.1	Mil-Spec Connector	2.4	PWB	1.3.2.3
Metal Shell	2.1	Hub Cover	1.3.1	Assorted Components	1.3.2.2	Power Cable	3.1	PWB	2.3.3
Mounting Bracket	2.7	Spine	1.4.1	Microphone & Wiring	1.4.2	Mast Cable	3.2		
		Foam Cover	1.4.3	LCD Display	2.2				
				CoC	2.3.1				
				Assorted Components	2.3.2				
				Speaker	2.5				
				Power Supply	2.6				

Company A’s Facilities consist of the following departments:

1.Shipping and Receiving
2.Acoustic Array Assembly and Test
3.Mast Hub Assembly
4.Microphone Assembly and Test
5.PWB Print and Pick & Place
6.PWB Reflow
7.PWB Rework
8.PDU Assembly and Test
9.System Test and Packaging
10. Storage
11. Cable Kitting
12. Management/Facilities

Assumptions

The importance of a single product is the largest underlying assumption. It is relatively safe to assume that the ADS will be in high demand in the next few years due to the large current order and the future expect orders.

The material handling is very simple, all parts are received on standard pallets (40”x48”) at shipping and receiving. They are then moved into the storage area where they are kept until the components are required by the various departments. Each department uses a 4 wheeled chart to transport material from the storage area to the department and between departments. While there is potential improvement by reducing the storage area and keeping a pallet of components at each desired department, Company A has chosen to not pursue this route due to concerns about worker safety and the danger of Electro-Static Discharge (ESD) from the forklift.

The PWB Reflow Department (Department 6) produces off odors during reflow and pre-baking of the CoC ball grid array (BGA).

Location Importance Rating Development

Introduction

This paper examines two possible methods to derive a location importance rating from material routing data, other possible methods are discussed in Article 12 Areas of Future Study. The two possible methods are the material trip based approach and the part number ID based approach.

Material Trip Approach

The Material Handling Trip approach uses the total number of trips from department to department to decide the closeness rating. This is useful when the material doesn't change mass or size an appreciable amount during the course of manufacturing. This would be ideal for manufacturing a PWB where it is double sided and used both RoHS and Pb-Sn solder.

Part Number Trip Approach

The Part Number Trip approach uses the total number of part numbers, even if the part numbers have been subsumed into another part number. This is useful when it is important to account for the change in mass which accompanies an assembly operation. This would account for differences so that a 8oz gear shift knob traveling 50 feet is not counted the same as a 800lb engine traveling the same distance. While calculating mass distance would be a more accurate way to account for disparity between different component travel distances, this approach at least partially accounts for the difference when mass data is not available.

Discussion of the Approaches

While both approaches have value in different situations, it is hypothesized that the material trip approach would be better for this case study due to the small mass of the ADS and the relatively small number of trips required. The table below shows the routing for both methods, the Material Trip approach is in black while the additional states from the Part Number Trip approach are in green. It is important to note that Part Number Trip approach has the same basic routing as the Material Trip, only with additional trips for components since the Material Trip approach stops tracking a component once it has been assembled into a larger component.

Table 7 P/N and Manufacturing Steps for Component Routing

Q	P/N	1	2	3	4	5	6	7	8	9	10
1	1.0							2	9	10	1
1	1.1					1	10	2	9	10	1
1	1.2					1	10	2	9	10	1
1	1.3						3	2	9	10	1
1	1.3.1				1	10	3	2	9	10	1
1	1.3.2			5	6	7	3	2	9	10	1
1	1.3.2.1	1	10	5	6	7	3	2	9	10	1
1	1.3.2.2	1	10	5	6	7	3	2	9	10	1
1	1.3.2.3	1	10	5	6	7	3	2	9	10	1
8	1.4						4	2	9	10	1
8	1.4.1				1	10	4	2	9	10	1
8	1.4.2				1	10	4	2	9	10	1
8	1.4.3				1	10	4	2	9	10	1
1	2.0							8	9	10	1
1	2.1					1	10	8	9	10	1
1	2.2					1	10	8	9	10	1
2	2.3				5	6	7	8	9	10	1
1	2.3.1		1	10	5	6	7	8	9	10	1
1	2.3.2		1	10	5	6	7	8	9	10	1
2	2.3.3		1	10	5	6	7	8	9	10	1
3	2.4					1	10	8	9	10	1
1	2.5					1	10	8	9	10	1
1	2.6					1	10	8	9	10	1
1	2.7					1	10	8	9	10	1
1	3.0							11	9	10	1
1	3.1					1	10	11	9	10	1
1	3.2					1	10	11	9	10	1
1	4.0								9	10	1

As shown in the above chart the later steps are accounted for much more substantially in the Part Number Trip approach than in the Material Trip. The following From/To charts can be used to create the location importance ratings for the departments.

Table 8 From/To Charts

Material Trip Based From/To

	1	2	3	4	5	6	7	8	9	10	11	12
1										44		
2									1			
3		1										
4		1										
5						3						
6							3					
7			1					2				
8									1			
9										1		
10	1	2	1	24	7			10			2	
11									1			
12												

Part Number Based From/To

	1	2	3	4	5	6	7	8	9	10	11	12
1										44		
2									40			
3		6										
4		32										
5						10						
6							10					
7			4					6				
8									15			
9										60		
10	60	2	1	24	7			8			2	
11									3			
12												

There are several methods for assigning location importance ratings to the different department relationships. We provide relevant statistics below.

Table 9 Location Importance Ratings

ID		Trip	
N	Q	N	Q
60	60	44	44
60	60	24	24
44	44	10	10
40	40	7	7
32	32	3	3
24	24	3	3
15	15	2	2
10	10	2	2
10	10	2	2
8	8	1	1
7	7	1	1
6	6	1	1
6	6	1	1
4	4	1	1
3	3	1	1
2	2	1	1
2	2	1	1
1	1	1	1

Key	Normal	Quartile
	0.90-1.00	0.75-1.00
	0.75-0.90	0.50-0.75
	0.50-0.75	0.25-0.50
	0.25-0.50	0.00-0.25
	0.00-0.25	

Quartile Values

P/N	Material
60	44
45	33
30	22
15	11
0	0

CHAPTER 5: Case Study 3

Company C

Introduction

This case study deals with a small research and development (R&D) company which was recently awarded a large production scale contract. Prior contracts were a small fraction of this contract so a total redesign of the manufacturing plant was called for.

SBIR

As part of the Small Business Administration, the US Government encourages small business to develop innovative technology in support of the Department of Defense and the rest of the government. The Small Business Innovative Research (SBIR) program is overseen by the Small Business Administration (SBA). The SBIR program is divided up into three phases. Phase I is a feasibility study, with an award amount up to $100,000. Phase I contracts can last up to six months. The follow on to the initial SBIR award is a Phase II award which can last up to two years and be up to $750,000. The goal of the Phase II contract is prototype development and initial test results. The overall goal of all SBIR programs is Phase III which is the commercialization of the technology. Phase III has several unique attributes, especially regarding the funding. Phase I and II are funded through a "SBIR Tax" of approximately 2.5% of the Research Development, Test and Evaluation (RDT&E) budget of all Federal Agencies with a RDT&E Budget greater than $100 million.

Background

Company C was founded in 2003 to focus on several unique innovations of interest to the Department of Defense and other governmental agencies. Under a number of SBIR Phase I and II contracts through a variety of agencies the company developed a command and control (C2) system. These initial systems were fielded in support of the Global War on Terror (GWOT) starting in 2005. GWOT includes Operation Enduring Freedom (OEF), Afghanistan, Operation Iraqi Freedom (OIF), Iraq, and Operation Nobel Eagle (ONF), the United States of America. After feedback and several advances in the state of the art, a second version was designed.

The US Army indentified this version as an urgent requirement to support GWOT. A sole source request for proposal (RFP) under a SBIR Phase III was released in February 2009 and the vendor responded in March 2009. The Government accepted the proposal and a contract was signed in March 2009 for a 5 year Indefinite Date Indefinite Quantity (IDIQ) with an initial task order for 800 systems. IDIQ contracts allow the Government to have a contractual instrument in place when the future demand is known to exist but specific quantities and delivery dates are unknown.

An elementary example would be whiteboard markers. Demand for the markers is dependent upon the amount of use by professor and students. The demand cannot be forecast with any degree of certainty due to the rotation of professors and classes. Due to the low cost of the product and the lack of bureaucracy (relative to the federal government) in an academic setting, an IDIQ contract would not make sense. In the real world, a professor would simply ask an administrative assistant to provide another marker when it runs dry. When the inventory reaches the reorder point, the administrative assistant simple orders from Staples or an equivalent office supply store. However if the lead time to buy markers was 9 months and the cost of each marker was $250,000 then a different model would be employed.

System Description

The system serves as a C2 system for an integrated weapon system (IWS) currently being fielded in support of GWOT. The C2 system interfaces with an acoustic sensor system (ADS) and a weapons system (WS) to allow engagement of targets with lethal force. The C2 consists of two primary subsystems, the Display Unit and the Input/Output (I/O) Box, and the Vehicle Integration Kit (VIK) which is Vehicle Unique (VU). The full system list is located in the table below:

Table 10 Case Study 3 Component Breakdown

Primary Items	**VIK Items**
Display Unit	Power Cable (VU)
I/O Box	ADS Cable (VU)
	WS Cable (VU)
	Installation Kit

The IWS will be fielded onto 7 different vehicles with different mounting locations depending upon the vehicle. This has resulted in 7 different Vehicle Integration Kits (VIK) listed as contract line items on the contract. The VIK's different on the mounting bracket necessary to integrate onto the vehicle and the length of the cables. Each VIK has a different quantity as listed in Table 11:

Table 11 Case Study 3 VIK Breakdown

VIK	Quantity	Proportion
VIK A	300	0.38
VIK B	100	0.13
VIK C	50	0.06
VIK D	75	0.09
VIK E	75	0.09
VIK F	125	0.16
VIK G	75	0.09

Manufacturing

Previous contracts had a production delivery rate of between 5 and 20 systems a month. The production contract has a firm delivery rate of 100 systems per month for 8 months. The systems will be delivered in a monthly rate relative to the overall percentage of the order, for example, 38 Systems with VIK A will be delivered per month. Due to the low volume and numerous configuration changes, all previous systems were manufactured in house with only the printed wire board (PWB) outsourced. With the much higher demand the company has chosen to outsource production of all hardware items. The manufacturing activities which will be conducted in-house are limited to loading software onto the Display Unit and the I/O Box, kitting of the components to form a complete system, and testing. The system manufacturing is outsourced as listed in the table below:

Table 12 Case Study 3 Sub-vendor List

Sub-Vendor A	Sub-Vendor B	Sub-Vendor C
Display Unit	I/O Box	Power Cable
	Mounting Bracket	ADS Cable
	Installation Kit	WS Cable

As each sub-component is received at the Company C Facility from the sub-vendor, it is inspected with the shipping manifest to confirm the order before payment is made to the sub-vendor. It is then put into storage until it is required for assembly. Display Units and I/O Boxes are delivered from the sub-vendors every 2 months while Mounting Brackets, Installation Kits and Cables are delivered every 4 months. Company C's Facility consists of the following departments:

1. Software Load
2. Functional Test
3. Cable Storage
4. Mounting/Install Kit Storage
5. Display Unit/I/O Box Storage
6. Assembly Area
7. Shipping and Receiving
8. Management/Facilities

The material flow of the system is listed in the table below:

Table 13 Case Study 3 Component Routing

Component/Routing	1	2	3	4	5	6
Display Unit	7	5	1	6	2	7
I/O Box	7	5	1	6	2	7
Power Cable (VU)	7	3	6	2	7	
ADS Cable (VU)	7	3	6	2	7	
WS Cable (VU)	7	3	6	2	7	
Installation Kit	7	4	6	2	7	

Assumptions

As this is a small research and development house which is transitioning into a manufacturing house, the most important factor to consider is the increased scale of work. Hand built prototypes can accommodate a very inefficient manufacturing process, but production requires far greater efficiencies to be profitable. The manufacturing processes also increase the rate of all activities. Shipping and receiving is a key example, for small prototypes, the shipment of the prototype to the customer or testing facility can be a cause of celebration, in production, it's just another event. Through using a negative relationship rating of -0.1, the shipping and receiving department can be located as far as possible from the management area.

Location Importance Rating Development

We developed the relationship matrix using the same approach as earlier. It can be found in appendix.

CHAPTER 6: Discussion of the Case Studies

Execution of the Models

Every case study was formulated as an AMPL data file. For the variants where the proportionality ratio, *k*, was equal to 1, which corresponds to fixed department dimensions, a simplified model was used. When attempting to start AMPL CPLEX, it would occasionally declare the model infeasible when setting $Lmin_i$ equal to $Lmax_i$, and $Wmin_i$ equal to $Wmax_i$, and $Pmin_i$ equal to $Pmax_i$ are not required since the perimeter constraint exists to account for non-square departments. Lehigh University's Industrial and Systems Engineering Department's COR@L (Computational Operations Research Laboratory) was used for all problems. Due to the size and complexity of the problems, the Polyps processors were used. AMPL CPLEX was set to write the nodefile uncompressed to disk. Attempts to set the temporary directory to /scratch were unsuccessful, and in order to run the problems, the model, data, and run files were copied to the respective Polyp and run from there. Experimentation soon revealed that some problems were beyond the scope of this research project because COR@L, Polyps and AMPL licenses are a shared resource, which constrained the scope of this project. In order to limit the utilization of computer resources to an appropriate level, several methods were employed. The first was the most elementary: only a portion of the total AMPL licenses were used. The second was a test/fix/test approach using a subset of the total problems. The final approach limited the required optimality, based on the previous testing. Without this technique, only three of the eighteen problems would have been solved, instead of the six that were successfully solved. We provide a representative AMPL CPLEX run file below.

```
reset;
model mod6.mod;
data g14.dat;
option cplex_options 'mipdisplay=2 mipinterval=1000000 timing=1
nodefile=2 mipgap=0.30';
solve;
display Xe, Xw, Yn, Ys, Xc, Yc > g14-30.txt;
quit;
```

The options mipdisplay and mipinterval provide additional information about the progress of CPLEX, while timing provides a summary of the processing times. Nodefile directs CPLEX to write the nodefile to disk uncompressed, while mipgap sets a parameter for CPLEX to return the current solution as optimal when the relative difference between the current solution and the optimal solution is less than or equal to the value. Each problem was assigned an alphanumeric identifier, listed below.

Table 14 Alphanumeric Identifiers for the Problems

g1	Problem 1 k=1	g10	Problem 2 Normal Trip K=1
g2	Problem 1 k=2	g11	Problem 2 Normal Trip K=2
g3	Problem 1 k=3	g12	Problem 2 Normal Trip K=3
g4	Problem 2 Quartile Trip K=1	g13	Problem 2 Normal ID K=1
g5	Problem 2 Quartile Trip K=2	g14	Problem 2 Normal ID K=2
g6	Problem 2 Quartile Trip K=3	g15	Problem 2 Normal ID K=3
g7	Problem 2 Quartile ID K=1	g16	Problem 3 K=1
g8	Problem 2 Quartile ID K=2	g17	Problem 3 K=2
g9	Problem 2 Quartile ID K=3	g18	Problem 3 K=3

An unexpected large amount of time was spent on the actual run of the problems. Unfamiliarity with Linux and the various CPLEX directives delayed the running of problems by at least 6 weeks. Run, data, and model files are included in appendix and hopefully will prevent others from falling into this pitfall.

Case Study 1

Case Study 1 presents the largest problems, with 35 departments. Despite the use of Polyps, these problems proved far too large to run in an appropriate timeframe. In the fixed department distance problem, there were 2975 binary variables alone. After over a week (~288 hours), the best solution was still 117.92% of the optimal solution.

Case Study 2

Case Study 2 was intended to provide a very thorough analysis of differences between using normal and quartile distributions for assignment of location importance ratings, Trip Number and Part Number approaches, in addition to the proportionality constraint which was the primary focus and the only difference examined in all three case studies. However, it quickly became clear than attempting to find the optimal solution was also beyond the scope of the project. Instead, the optimality goal was set to 70% of the optimal solution, which corresponds to a mipgap equal to 0.30. Even with this relaxation, only four of the twelve problems were run to completion and an error resulted in rejection of one of the four results. The percentage left until the optimal solution is found is plotted versus the number of nodes, in millions, in the following chart.

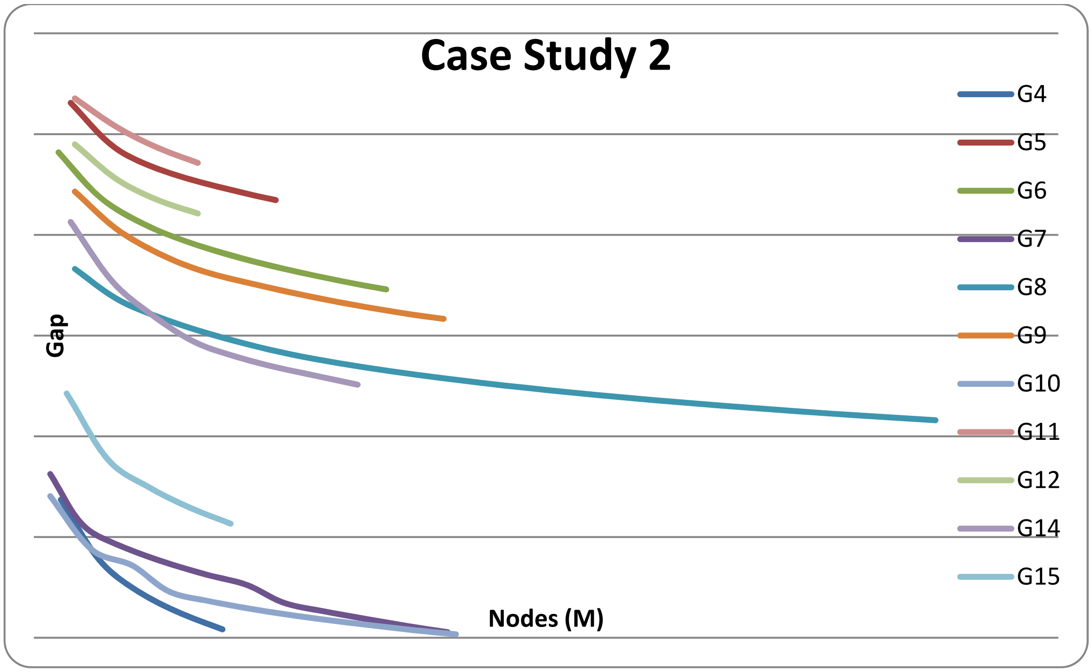

Figure 4 Case Study 2 Summary Chart

There is a definite difference among the problems: the only three problems which ran to solution were the three with the proportionality ratio *k* set equal to 1. In fact, the fourth problem which was rejected also had k equal to one. All the Case Study Graphs are provided in appendix.

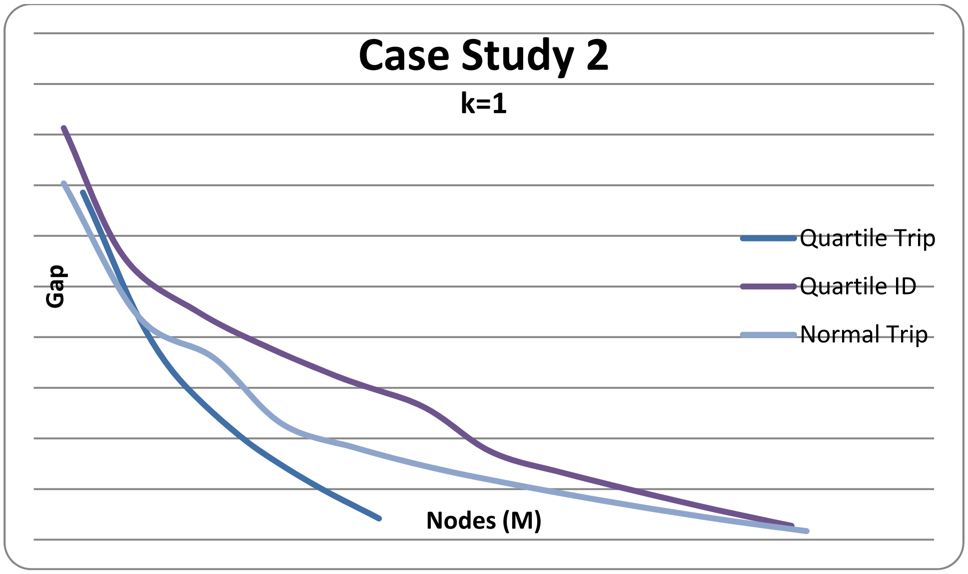

Figure 5 Case Study 2 Graph, k=1

Case Study 2, *k=1*, Quartile, Trip Problem was solved for both 70% of the optimal solution and 80% of the optimal solution. A plot of the results and the facility layout costs are provided below in the G4 70% and 80% Diagrams. The remaining Case Study 2 layouts are provided in appendix.

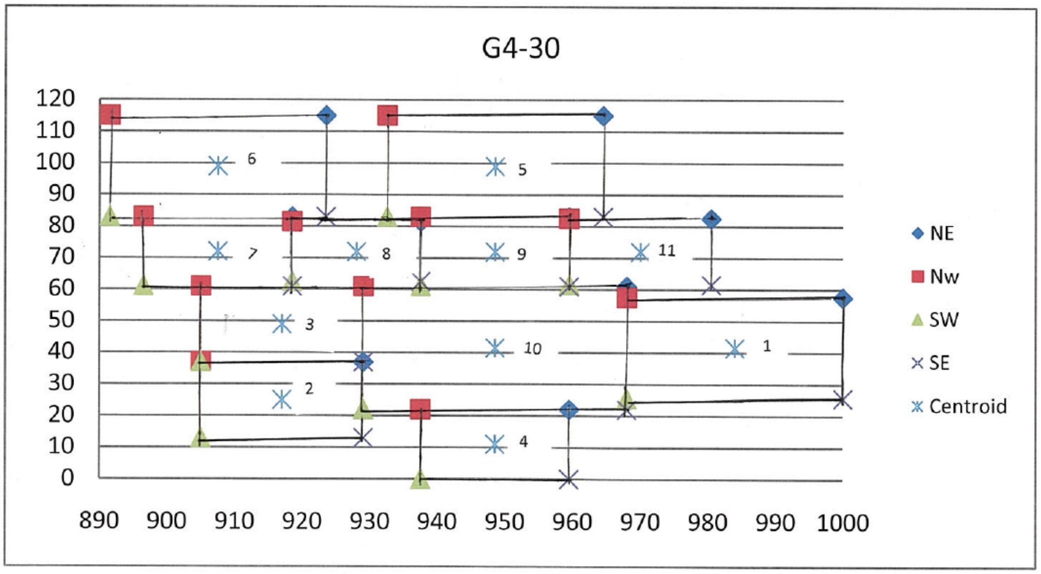

Figure 6 G4 70% Diagram Layout Cost=206.5419

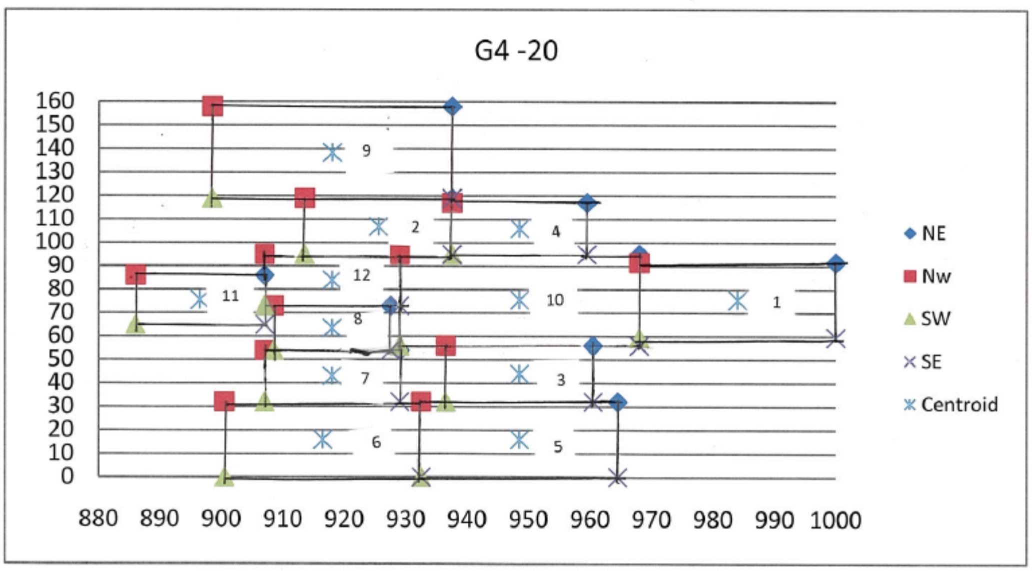

Figure 7 G4 80% Diagram Objective=234.2823

Case Study 3

Case Study 3 was the only case study to actually reach the optimal solution. However, the small number of departments and the relatively simple material flow presents limited opportunities for detailed analysis. The results from the problems are listed below.

Table 15 Case Study 3 Results

Problem	Objective Solution	Time to Solution (seconds)	Total Nodes
G16, k=1	119.86	45673.37	153,055,335
G17, k=2	99.895	1563.59	125,798,970
G18, k=3	88.17	82919.63	273,258,119

The G17 Problem, with the proportional ratio, k, equal to two, is unexpectedly the quickest to reach the optimal solution. As stated before, COR@L is a shared resource, and the first explanation was that other users used the same machine as G16 and G18. However, when the number of total branch and bound nodes is examined, G17 again is the lowest. Further research is needed in order to explain this result, since as the k value increases, the total layout cost will decrease, but the complexity of the problem will increase, as well as the time and resources required to solve. The la

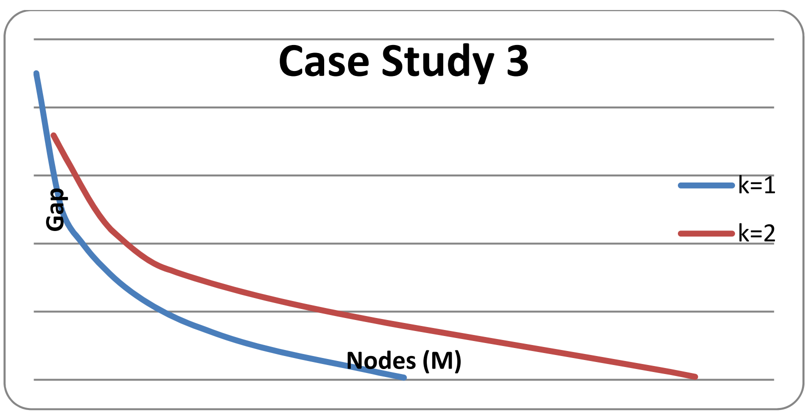

Figure 8 Case Study 3 Gap/Node Chart

CHAPTER 7: Areas of Future Study

Data Analysis

Agard (2006) presents a proposed methodology for data mining in order to improve the layout of a manufacturer specializing in mass customization. Likewise, Case Study 1 dealt with a DoD Product Manager office which deals with many complex and rapidly changing situations that are unknown in advance, not unlike a mass customization manufacturer. There are a number of possible techniques, but a very simple, but potentially controversial technique is email analysis. A very large portion of communications is now conducted by email. Link analysis and email traffic density between co-workers could serve as a potential basis for a location importance rating.

Iterative Approach

There are several possible iterative approaches that could be used to reduce Case Study 1 to a manageable level. A key factor is the lack of interaction between APdMs in PdM RUS. The location importance rating is zero between members of the APdMs. If each APdM was formulated as a standalone problem, then analysis conducted to calculated the minimum and maximum department parameters, then only the shared assets and facilities would remain to be assigned. Xu (2007) also proposed an approach targeted toward process plants, which may be of use in this example.

Non-Centroid Based Distance Calculation

For a manufacturing environment on an open factory layout, the rectilinear centroid to centroid distance measurement is a good representation. However, office layout, the “cubicle farm” has many barriers and rectilinear distance calculation maybe very misleading. Instead, Norman’s (1998) perimeter distance measure with input locations, such as office doors or cubicle openings, may be of use.

Increased Granularity of Proportionality Ratio

In this thesis, only three values for the proportionality ratio, *k*, were analyzed. Case Study 3 presented an interesting and non-intuitive result with $k=2$. Case Study 3 is currently solvable with present resources. By performing increased analysis on the proportionality ratio, greater insights would be gained into the tradeoffs between optimality, reality and resources.

CHAPTER 8: Conclusion

A MIP was formulated and solved with industry representative data for a subset of the problems, based on facility layout issues currently faced by the Department of Defense. There were significant shortfalls due to the complexity of the problems. Both Castillo (2005) and Meller (2010) imposed a time limit of 24 hours, while this project ran problems for over 288 hours. Even by extending the time period by over an order of magnitude compared to previous research, only a subset of the problems were able to be solved, with a further subset solved to optimality. Overall, the project met the goal of successfully demonstrating a MIP solution to the facility layout problem. Future research directions include refining the impact of the proportionality factor on problem instances and their solutions. It is hoped that further advances in high-performance computing capabilities will allow real-life facility layout problems as those described in this thesis to be solved to optimality. In the meantime, this thesis provides the theoretical framework, the software files and the preliminary analysis for mixed integer programming approaches to facility layout.

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APPENDIX A: Acronym List

A/D	Analog to Digital
AAE	Army Acquisition Executive
ACAT	Acquisition Category
AIS	Automated Information System
APG	Aberdeen Proving Grounds
APM	Assistant Product Manager
ARP	Acquisition Requirements Package
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics and Technology
ADS	Acoustic Sensor System
ATEC	Army Test and Evaluation Command
BGA	Ball Grid Array
BRAC	Base Realignment and Closure
C&L	Capability and Limitations
C2	Command and Control
CAE	Component Acquisition Executive
CDD	Capability Development Document
CNC	Computer Numerical Control
CoC	Computer on a Chip
CPD	Capability Production Document
CRAFT	Computerized Relative Allocation of Facilities Technique

DoD	Department of Defense
ESD	Electro-Static Discharge
FLP	Facility Layout Problem
GWOT	Global War On Terror
I/O	Input and Output
ICD	Initial Capability Document
IGCE	Independent Government Cost Estimate
IMS	Integrated Master Schedule
IPT	Integrated Product/Process Team
IWS	Integrated Weapon System
JCIDS	Joint Capabilities Integration Development System
JUONS	Joint Urgent Operation Needs Statement
M-ATV	MRAP All Terrain Vehicle
MIP	Mixed Integer Problem
MRAP	Mine Resistant Ambush Protected
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
ONF	Operation Nobel Eagle
OSA	Office of the Secretary of the Army
OSD	Office of the Secretary of Defense
P/N	Part Number
PBS	Performance Based Specifications

PDU	Processing/Display Unit
PEO IEW&S	Program Executive Office, Intelligence, Electronic Warfare and Sensors
PM NV/RSTA	Program Manager Night Vision/Reconnaissance Surveillance and Target Acquisition
PM RUS	Product Manager Robotic and Unmanned Sensors
POE	Program Office Estimate
POR	Program of Record
PS	Performance Specification
PWB	Printed Wire Board
PWS	Performance Work Statement
QRC	Quick Reaction Capability
R&D	Research and Development
RDT&E	Research, Development, Test and Evaluation
RoHS	Reduction of Hazardous Substances
SBA	Small Business Administration
SBIR	Small Business Innovative Research
SES	Senior Executive Service
SME	Subject Matter Expert
SOO	Statement of Objectives
SOW	Statement of Work
SSEP	Source Selection Evaluation Plan
USD(ATL)	Under Secretary of Defense for Acquisition and Technology and Logistics

VIK Vehicle Integration Kit

VU Vehicle Unique

WS Weapon System

APPENDIX B: Data Files

Case Study 1 Data File Example

```
param n := 35;

param v:
   1    2    3    4    5    6    7    8    9    10    11    12    13    14
15   16   17   18   19   20   21   22   23   24   25   26
27   28   29   30   31   32   33   34   35:=
1   0   0.50   0.50   0.33   0.33   0.33   0.33   0.33   0.33   0.33   0.33   0.33   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.40   0.40   0.44   0.44   0.40   0.15   0.67   0.15   -0.67
2   0   0   0   0.33   0.33   0.33   0.33   0.33   0.33   0.33   0.33   1.00   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.40   0.40   0.44   0.44   0.40   0.15   0.67   0.15   -0.33
3   0   0   0   0.33   0.33   0.33   0.33   0.33   0.33   0.33   0.33   1.00   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.40   0.40   0.44   0.44   0.40   0.15   0.67   0.15   -0.33
4   0   0   0   0   1.00   1.00   1.00   0.33   0.33   0.33   0.33   0.33   0.00   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.67   0.15   -0.33
5   0   0   0   0   0   1.00   1.00   0.33   0.33   0.33   0.33   0.33   0.00   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.33   0.15   -0.33
6   0   0   0   0   0   0   1.00   0.33   0.33   0.33   0.33   0.33   0.00
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.33   0.15   -0.33
7   0   0   0   0   0   0   0   0.33   0.33   0.33   0.33
    0.33   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.33
    0.15   -0.33
8   0   0   0   0   0   0   0   0   1.00   1.00   1.00
    0.33   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.33
    0.15   -0.33
9   0   0   0   0   0   0   0   0   0   1.00   1.00
    0.33   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.67
    0.15   -0.33
10   0   0   0   0   0   0   0   0   0   0   1.00
    0.33   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.67
    0.15   -0.33
11   0   0   0   0   0   0   0   0   0   0   0
    0.33   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.00   0.33   0.33   0.44   0.44   0.40   0.15   0.67
    0.15   -0.33
12   0   0   0   0   0   0   0   0   0   0   0
0   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
    0.00   0.00   0.00   0.40   0.40   0.44   0.44   0.40   0.15   0.67   0.15
    -0.33
```

13 0 0 0 0 0 0 0 0 0 0 0
0 0 0.50 0.50 0.50 0.33 0.33 0.33 0.33 0.33 0.33 0.33 0.33
0.33 0.33 0.60 0.60 0.56 0.56 0.60 0.15 0.67 0.15 -0.67
14 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0.00 0.00 0.33 0.33 0.33 0.33 0.33 0.33 0.33 1.00
1.00 1.00 0.60 0.60 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
15 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0.00 0.33 0.33 0.33 0.33 0.33 0.33 0.33 1.00
1.00 1.00 0.60 0.60 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
16 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0.33 0.33 0.33 0.33 0.33 0.33 0.33 1.00
1.00 1.00 0.60 0.60 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
17 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 1.00 1.00 0.33 0.33 0.33 0.33 0.33
0.33 0.33 0.33 0.33 0.56 0.56 0.60 0.15 0.33 0.15 -0.33
18 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1.00 0.33 0.33 0.33 0.33 0.33
0.33 0.33 0.33 0.33 0.56 0.56 0.60 0.15 0.33 0.15 -0.33
19 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0.33 0.33 0.33 0.33 0.33 0.33 0.33
0.33 0.33 0.56 0.56 0.60 0.15 0.33 0.15 -0.33
20 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 1.00 1.00 1.00 0.33 0.33 0.33
0.33 0.33 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
21 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 1.00 1.00 0.33 0.33 0.33
0.33 0.33 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
22 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1.00 0.33 0.33 0.33
0.33 0.33 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
23 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0.33 0.33 0.33 0.33
0.33 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
24 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 1.00 1.00 0.60
0.60 0.56 0.56 0.60 0.15 0.67 0.15 -0.33
25 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1.00 0.60 0.60
0.56 0.56 0.60 0.15 0.67 0.15 -0.33
26 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0.60 0.60
0.56 0.56 0.60 0.15 0.67 0.15 -0.33
27 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1.00
0.56 0.56 0.60 0.15 0.00 0.15 -0.33
28 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0.56 0.56 0.60 0.15 0.00 0.15 -0.33
29 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 1.00 0.60 0.15 0.00 0.15 -0.33
30 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0.60 0.15 0.00 0.15 -0.33
31 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0.15 0.00 0.15 -1.00
32 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0.00 0.15 0.00
33 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0.15 0.00
34 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0.00

```
35	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0
;

param L:=
1	14
2	8
3	8
4	8
5	8
6	8
7	8
8	8
9	8
10	8
11	8
12	8
13	14
14	8
15	8
16	8
17	8
18	8
19	8
20	8
21	8
22	8
23	8
24	8
25	8
26	8
27	8
28	8
29	8
30	8
31	14.7
32	17
33	6
34	4.9
35	12;

param W:=
1	14
2	8
3	8
4	8
5	8
6	8
7	8
8	8
9	8
10	8
11	8
12	8
13	14
14	8
15	8
16	8
17	8
18	8
19	8
20	8
21	8
22	8
23	8
24	8
```

```
25	8
26	8
27	8
28	8
29	8
30	8
31	14.7
32	17
33	6
34	4.9
35	12;


param Bx := 2000;
param By := 2000;
param Mx := 1000;
param My := 1000;
```

Case Study 2 Data File Example

```
param n := 12;

param v:
   1   2   3   4   5   6   7   8   9   10   11   12:=
1   0   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   1.00   0.00   0.00
2   0   0   0.40   0.40   0.00   0.00   0.00   0.00   0.40   0.40   0.00   0.00
3   0   0   0   0.00   0.00   0.00   0.40   0.00   0.00   0.40   0.00   0.00
4   0   0   0   0   0.00   0.00   0.00   0.00   0.00   0.80   0.00   0.00
5   0   0   0   0   0   0.40   0.00   0.00   0.00   0.40   0.00   0.00
6   0   0   0   0   0   0   0.40   0.00   0.00   0.00   0.00   0.00
7   0   0   0   0   0   0   0   0.40   0.00   0.00   0.00   0.00
8   0   0   0   0   0   0   0   0   0.40   0.40   0.00   0.00
9   0   0   0   0   0   0   0   0   0   0.40   0.40
    0.00
10   0   0   0   0   0   0   0   0   0   0   0.40
    0.00
11   0   0   0   0   0   0   0   0   0   0   0
    0.00
12   0   0   0   0   0   0   0   0   0   0   0
0
;

param Lmin:=
1	32
2	24
3	24
4	22
5	32
6	32
7	22
8	19
9	22
10	39
11	21
12	39
;

param Lmax:=
1	32
2	24
3	24
4	22
5	32
6	32
7	22
8	19
```

```
9		22
10		39
11		21
12		39
;

param Wmin:=
1		32
2		24
3		24
4		22
5		32
6		32
7		22
8		19
9		22
10		39
11		21
12		39
;

param Wmax:=
1		32
2		24
3		24
4		22
5		32
6		32
7		22
8		19
9		22
10		39
11		21
12		39
;

param Pmin:=
1		128
2		96
3		96
4		88
5		128
6		128
7		88
8		76
9		88
10		156
11		84
12		156
;

param Pmax:=
1		128
2		96
3		96
4		88
5		128
6		128
7		88
8		76
9		88
10		156
11		84
12		156
;

param Bx := 1000;
```

```
param By := 1000;
param Mx := 1000;
param My := 1000;
```

Case Study 3 Data File Example

```
param n := 8;

param v:
    1    2    3    4    5    6         7        8:=
1   0   0.00   0.00  0.00  0.50      0.50  0.00       0.25
2   0    0    0.00  0.00  0.00       1.00  1.00       0.25
3   0    0     0   0.00  0.00        0.75  0.75       0.00
4   0    0     0    0   0.00  0.25  0.25       0.00
5   0    0     0    0    0   0.00  0.50       0.00
6   0    0          0         0        0        0        0.00  0.25
7        0          0         0        0        0        0        0        -0.1
8        0          0         0        0        0        0        0         0
;


param L:=
1        14.1
2        7.1
3        12.2
4        15.8
5        10
6        15.5
7        20
8        38.7
;


param W:=
1        14.1
2        7.1
3        12.2
4        15.8
5        10
6        15.5
7        20
8        38.7
;

param Bx := 1000;
param By := 1000;
param Mx := 1000;
param My := 1000;
```

Case Study 1 Run File Example

```
 reset;
model mod7.mod;
data g1.dat;
option cplex_options 'mipdisplay=2 mipinterval=1000000 timing=1 nodefile=2 mipgap=0.20';
option TMPDIR '/scratch';
solve;
display Xe, Xw, Yn, Ys, Xc, Yc > g1-20.txt;
quit;
```

Case Study 2 Run File Example

```
reset;
model mod6.mod;
data g4.dat;
option cplex_options 'mipdisplay=2 mipinterval=1000000 timing=1 nodefile=2 mipgap=0.30';
option TMPDIR '/scratch';
solve;
display Xe, Xw, Yn, Ys, Xc, Yc > g4-30.txt;
quit;
```

Case Study 3 Run File Example

```
reset;
model mod7.mod;
data g16.dat;
option cplex_options 'mipdisplay=2 mipinterval=1000000 timing=1 nodefile=2';
option TMPDIR '/scratch';
solve;
display Xe, Xw, Yn, Ys, Xc, Yc > g16.txt;
quit;
```

Model Files

Model 7

```
param n;
param v{1..n,1..n};
param Lmin{1..n};
param Lmax{1..n};
param Wmin{1..n};
param Wmax{1..n};
param Pmin{1..n};
param Pmax{1..n};

param Bx;
param By;
param Mx;
param My;

var Xe{1..n}>=0;
var Xw{1..n}>=0;
var Yn{1..n}>=0;
var Ys{1..n}>=0;
var Xc{1..n}>=0;
var Yc{1..n}>=0;

var d{i in 1..n, j in 1..n} >=0;
var dx{i in 1..n, j in 1..n} >=0;
var dy{i in 1..n, j in 1..n} >=0;

var Tx{i in 1..n, j in 1..n} binary;
var Ty{i in 1..n, j in 1..n} binary;
var S{i in 1..n, j in 1..n} binary;

minimize Obj: sum{i in 1..n, j in 1..n} v[i,j]*(dx[i,j] + dy[i,j]);

subject to Zcontrol{i in 1..n, j in (i+1)..n}: Xc[j] - Xc[i] >= 0.5*(Xe[i]-Xw[i]+Xe[j]-Xw[j])-Mx*(S[i,j]) -Mx*(1-Tx[i,j]);
subject to Zcontrola{i in 1..n, j in (i+1)..n}: Xc[i] - Xc[j] >= 0.5*(Xe[i]-Xw[i]+Xe[j]-Xw[j])-Mx*(S[i,j]) -Mx*(Tx[i,j]);

subject to Zcontrol2{i in 1..n, j in (i+1)..n}: Yc[j] - Yc[i] >= 0.5*(Yn[i]-Ys[i]+Yn[j]-Ys[j])-My*(1-S[i,j])-My*(1-Ty[i,j]);
subject to Zcontrol2a{i in 1..n, j in (i+1)..n}: Yc[i] - Yc[j] >= 0.5*(Yn[i]-Ys[i]+Yn[j]-Ys[j])-My*(1-S[i,j])-My*(Ty[i,j]);
```

```
subject to Lcontrol{i in 1..n}: Xe[i]-Xw[i] >= Lmin[i];
subject to Lcontrol2{i in 1..n}: Xe[i]-Xw[i] <= Lmax[i];

subject to Wcontrol{i in 1..n}: Wmin[i] <= (Yn[i] - Ys[i]);
subject to Wcontrol2{i in 1..n}: (Yn[i] - Ys[i]) <= Wmax[i];

subject to Pcontrol{i in 1..n}: Pmin[i] <= 2*(Yn[i] - Ys[i] + Xe[i]-Xw[i]);
subject to Pcontrol2{i in 1..n}: 2*(Yn[i] - Ys[i] + Xe[i]-Xw[i]) <= Pmax[i];

subject to Blength3{i in 1..n}: Xe[i] <= Bx;
subject to Bwidth3{i in 1..n}: Yn[i] <= By;

subject to Xcent{i in 1..n}: Xc[i] = 0.5 * (Xw[i] + Xe[i]);
subject to Ycent{i in 1..n}: Yc[i] = 0.5 * (Yn[i] + Ys[i]);

subject to Discalcx1{i in 1..n, j in 1..n}:  dx[i,j] >= Xc[i] - Xc[j];
subject to Discalcx2{i in 1..n, j in 1..n}:  dx[i,j] >= Xc[j] - Xc[i];

subject to Discalcx1b{i in 1..n, j in 1..n}:  dx[i,j] - (Xc[i] - Xc[j]) <= Mx* Tx[i,j];
subject to Discalcx2b{i in 1..n, j in 1..n}:  dx[i,j] - (Xc[j] - Xc[i]) <= Mx*(1-Tx[i,j]);

subject to Discalcy1{i in 1..n, j in 1..n}:  dy[i,j] >= Yc[i] - Yc[j];
subject to Discalcy2{i in 1..n, j in 1..n}:  dy[i,j] >= Yc[j] - Yc[i];

subject to Discalcy1b{i in 1..n, j in 1..n}:  dy[i,j] - (Yc[i] - Yc[j]) <= My* Ty[i,j];
subject to Discalcy2b{i in 1..n, j in 1..n}:  dy[i,j] - (Yc[j] - Yc[i]) <= My*(1-Ty[i,j]);
```

Model 7

```
param n;
param v{1..n,1..n};
param L{1..n};
param W{1..n};


param Bx;
param By;
param Mx;
param My;

var Xe{1..n}>=0;
var Xw{1..n}>=0;
var Yn{1..n}>=0;
var Ys{1..n}>=0;
var Xc{1..n}>=0;
var Yc{1..n}>=0;

var d{i in 1..n, j in 1..n} >=0;
var dx{i in 1..n, j in 1..n} >=0;
var dy{i in 1..n, j in 1..n} >=0;

var new{i in 1..n, j in 1..n} binary;
var newy{i in 1..n, j in 1..n} binary;
var u{i in 1..n, j in 1..n} binary;

minimize Obj: sum{i in 1..n, j in 1..n} v[i,j]*(dx[i,j] + dy[i,j]);

subject to Zcontrol{i in 1..n, j in (i+1)..n}: Xc[j] - Xc[i] >= 0.5*(Xe[i]-Xw[i]+Xe[j]-Xw[j])-Mx*(u[i,j]) -Mx*(1-new[i,j]);
subject to Zcontrola{i in 1..n, j in (i+1)..n}: Xc[i] - Xc[j] >= 0.5*(Xe[i]-Xw[i]+Xe[j]-Xw[j])-Mx*(u[i,j]) -Mx*(new[i,j]);

subject to Zcontrol2{i in 1..n, j in (i+1)..n}: Yc[j] - Yc[i] >= 0.5*(Yn[i]-Ys[i]+Yn[j]-Ys[j])-My*(1-u[i,j])-My*(1-newy[i,j]);
subject to Zcontrol2a{i in 1..n, j in (i+1)..n}: Yc[i] - Yc[j] >= 0.5*(Yn[i]-Ys[i]+Yn[j]-Ys[j])-My*(1-u[i,j])-My*(newy[i,j]);

subject to Lcontrol{i in 1..n}: Xe[i]-Xw[i] = L[i];

subject to Wcontrol{i in 1..n}: W[i] = (Yn[i] - Ys[i]);
```

```
subject to Blength3{i in 1..n}: Xe[i] <= Bx;
subject to Bwidth3{i in 1..n}: Yn[i] <= By;

subject to Xcent{i in 1..n}: Xc[i] = 0.5 * (Xw[i] + Xe[i]);
subject to Ycent{i in 1..n}: Yc[i] = 0.5 * (Yn[i] + Ys[i]);

subject to Discalcx1{i in 1..n, j in 1..n}:  dx[i,j] >= Xc[i] - Xc[j];
subject to Discalcx2{i in 1..n, j in 1..n}:  dx[i,j] >= Xc[j] - Xc[i];

subject to Discalcx1b{i in 1..n, j in 1..n}:  dx[i,j] - (Xc[i] - Xc[j]) <= Mx* new[i,j];
subject to Discalcx2b{i in 1..n, j in 1..n}:  dx[i,j] - (Xc[j] - Xc[i]) <= Mx*(1-new[i,j]);

subject to Discalcy1{i in 1..n, j in 1..n}:  dy[i,j] >= Yc[i] - Yc[j];
subject to Discalcy2{i in 1..n, j in 1..n}:  dy[i,j] >= Yc[j] - Yc[i];

subject to Discalcy1b{i in 1..n, j in 1..n}:  dy[i,j] - (Yc[i] - Yc[j]) <= My* newy[i,j];
subject to Discalcy2b{i in 1..n, j in 1..n}:  dy[i,j] - (Yc[j] - Yc[i]) <= My*(1-newy[i,j]);
```

Appendix C: Material Trip Approach Component Routing

The table below shows only the routing when the Material Trip approach is used.

Table 16 Material Trip Approach Component Routing

Q		1	2	3	4	5	6	7	8	9	10
1	1.0							2	9		
1	1.1					1	10	2			
1	1.2					1	10	2			
1	1.3						3	2			
1	1.3.1				1	10	3				
1	1.3.2			5	6	7	3				
1	1.3.2.1	1	10	5							
1	1.3.2.2	1	10	5							
1	1.3.2.3	1	10	5							
8	1.4						4	2			
8	1.4.1				1	10	4				
8	1.4.2				1	10	4				
8	1.4.3				1	10	4				
1	2.0							8	9		
1	2.1					1	10	8			
1	2.2					1	10	8			
2	2.3				5	6	7	8			
1	2.3.1		1	10	5						
1	2.3.2		1	10	5						
2	2.3.3		1	10	5						
3	2.4					1	10	8			
1	2.5					1	10	8			
1	2.6					1	10	8			
1	2.7					1	10	8			
1	3.0							11	9		
1	3.1					1	10	11			
1	3.2					1	10	11			
1	4.0								9	10	1

Appendix D: Case Study 2 Gap/Node Charts

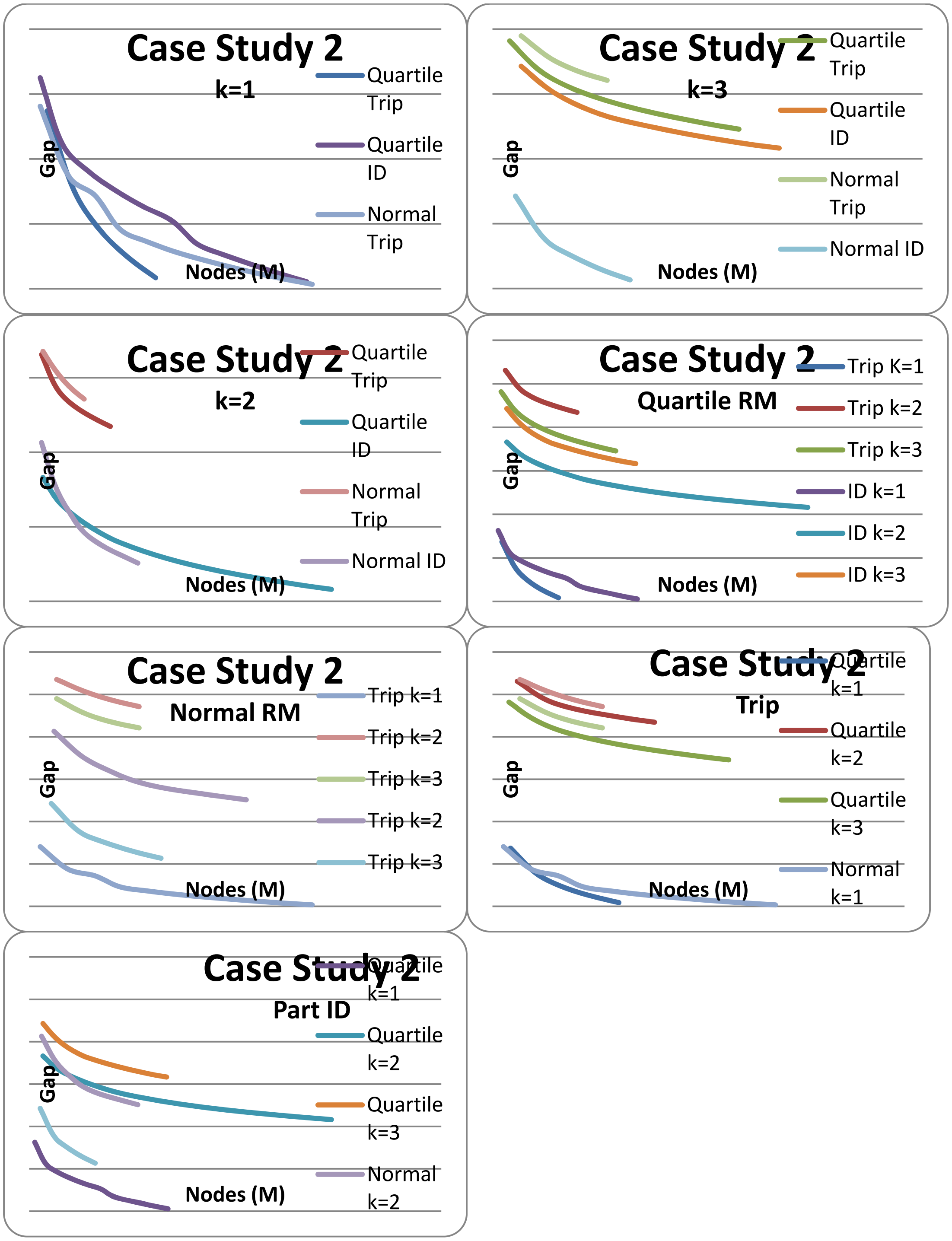
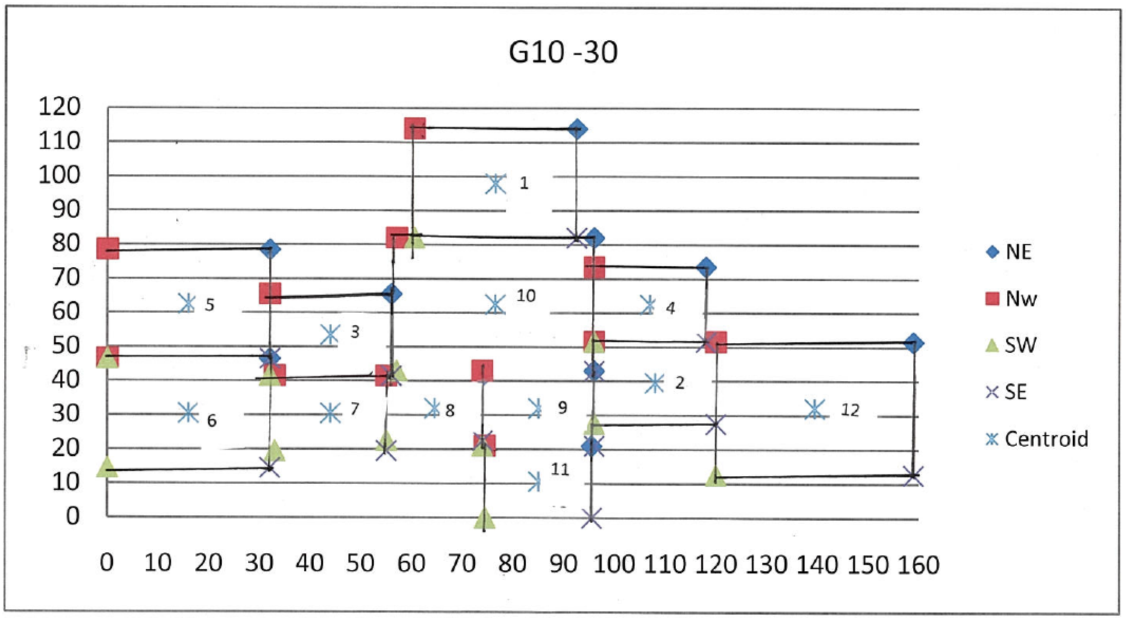


Figure 9 Case Study 2 Gap/Node Charts

Appendix E: Case Studies 2 and 3 Layout Diagrams



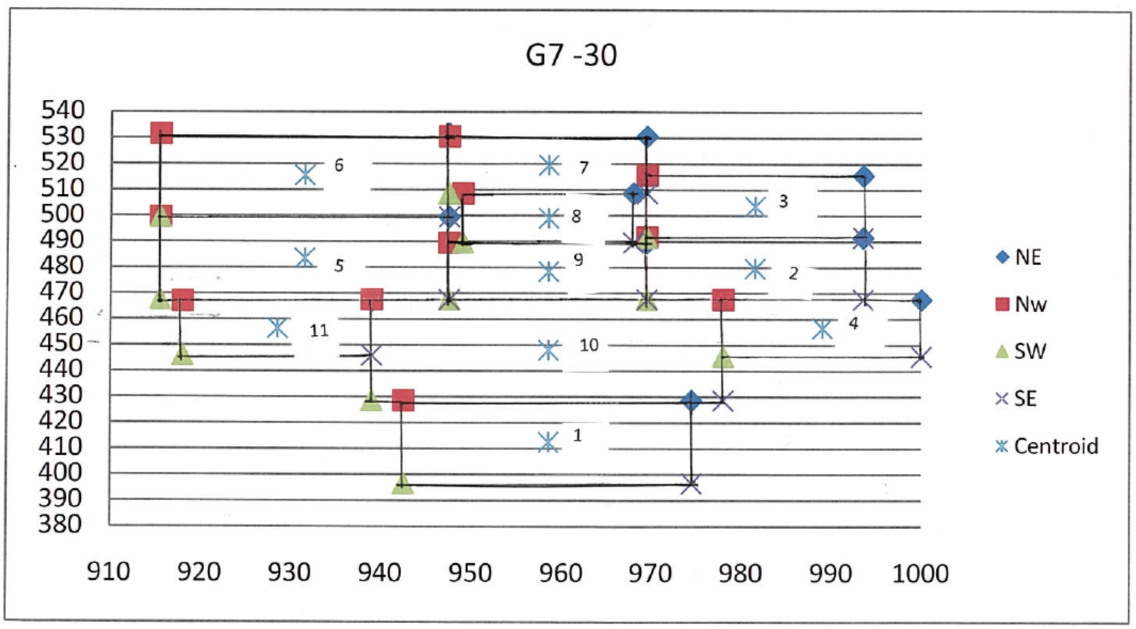
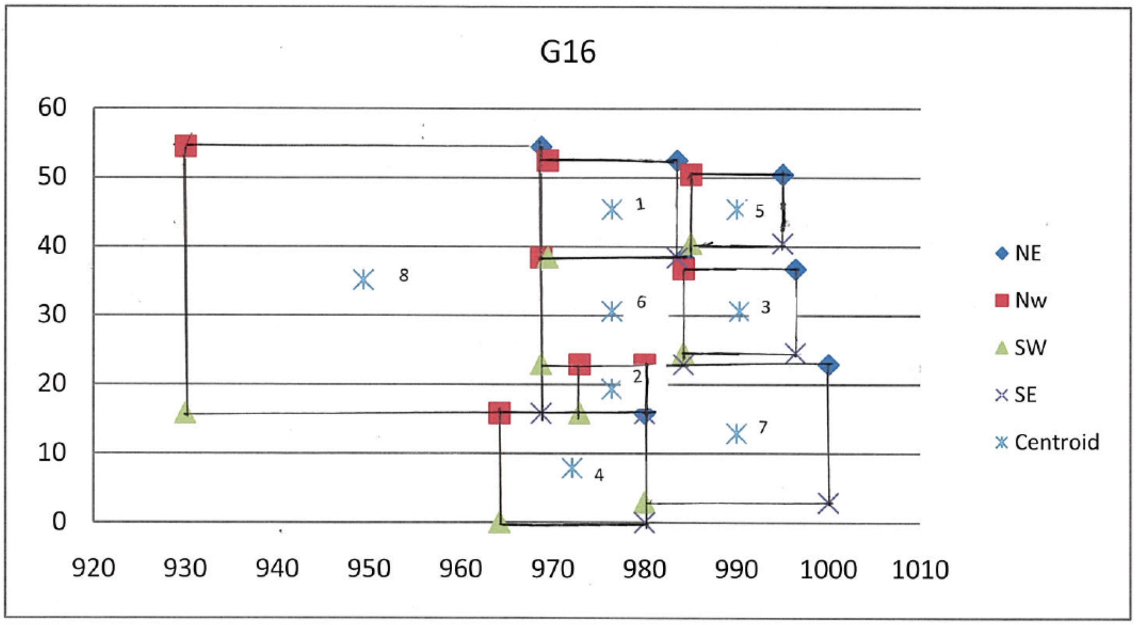
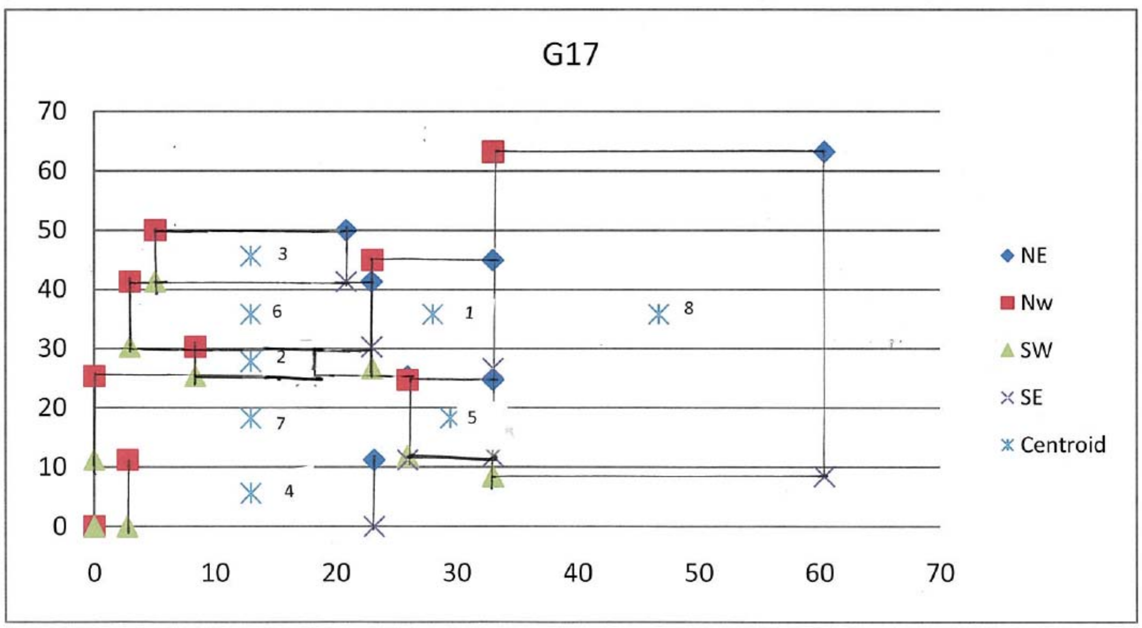


Figure 10 Case Study 2 Layout Diagrams


G16
60
50
40
30
20
10
0
920
930
940
950
960
970
980
990
1000
1010
1
2
3
4
5
6
7
8
NE
Nw
SW
SE
Centroid


G17
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
1
2
3
4
5
6
7
8
NE
Nw
SW
SE
Centroid

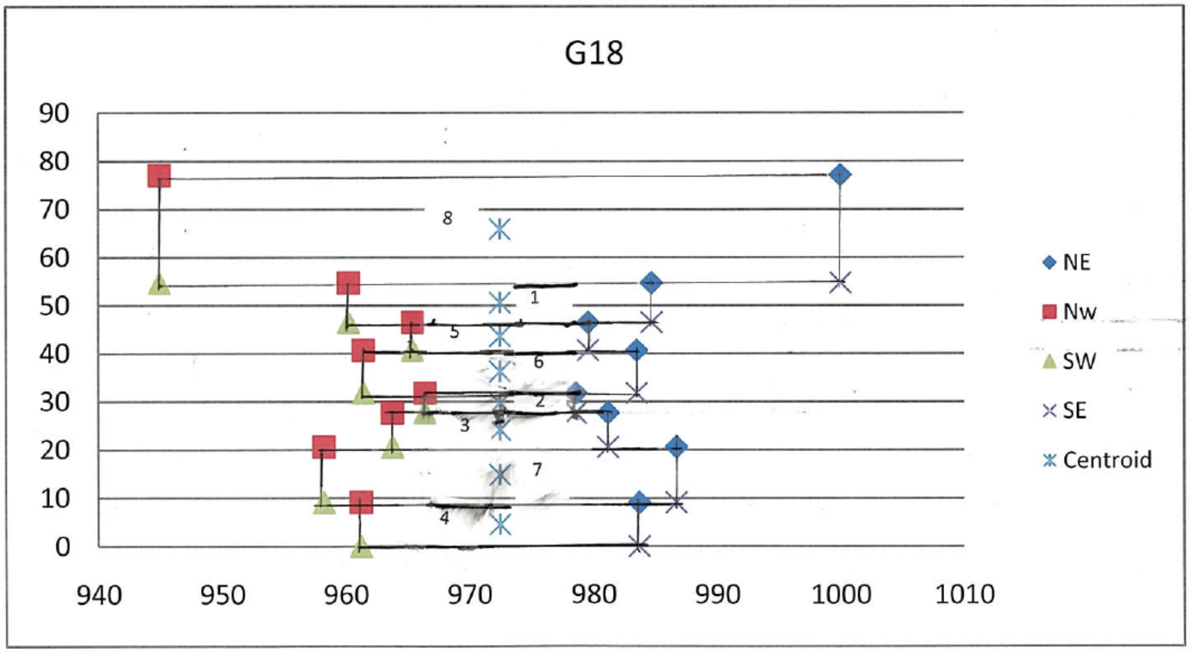


Figure 111 Case Study 3 Layout Diagrams

VITA

Todd Simkins was born in Coudersport, Pennsylvania in 1985 and graduated from Lehigh University with a Bachelor of Science in Industrial Engineering in 2007. After graduation he started work with the US Army's Communication-Electronics Research, Development and Engineering Center, Product Realization Directorate. He initially supported the sustainment of night vision and thermal imagers before supporting the procurement of various Counter Sniper systems. He now supports Program Executive Officer, Intelligence, Electronic Warfare and Sensors as a staff systems engineer. In addition to interests in facility layout and linear programming, he also has interests in exotic metal machining and game theory. For copies of models, data file format, or other questions, email tos5 |at| lehigh.edu.