

Fall 2016

Development of a DSM-Based Model for Managing the Design of Complex Systems Considering the Impact of Technological Obsolescence

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**DEVELOPMENT OF A DSM-BASED MODEL FOR MANAGING THE
DESIGN OF COMPLEX SYSTEMS CONSIDERING THE IMPACT OF
TECHNOLOGICAL OBSOLESCENCE**

by

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B.S. May 2011, Old Dominion University
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A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

MECHANICAL ENGINEERING

OLD DOMINION UNIVERSITY
December 2016

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ABSTRACT

DEVELOPMENT OF A DSM-BASED MODEL FOR MANAGING THE DESIGN OF COMPLEX SYSTEMS CONSIDERING THE IMPACT OF TECHNOLOGICAL OBSOLESCENCE

Gershom Kwaku Obeng
Old Dominion University, 2016
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Obsolescence has been a constant issue for process planners and designers and if not properly accounted for, obsolescence can become an expensive issue. As systems become more complex, interconnected, and nonhomogeneous, separate studies of single groups of equipment are no longer sufficient in modeling the obsolescence of the systems that they make up. The purpose of this dissertation is to model the likelihood of a process's design becoming obsolescent given the obsolescent behavior of the equipment used to complete the process. The methodology discussed in this work is based on a combination of using a systems engineering tool called the DSM (Design Structure Matrix) and a technological forecasting tool known as the growth curve to simulate the duration and cost of completing a process, and to determine if the process's design will keep its utility as it ages.

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This thesis is dedicated to my father Ebenezer, my mother Ama and the rest of my family
and friends.

ACKNOWLEDGMENTS

I would like to thank my adviser, Dr. Han Bao for allowing me to work with him on his research and for the useful advise on being successful academically and professionally. I would also like to thank Dr. Tony Dean, Dr. Jennifer Micheali and the rest of ASNE (American Society Of Naval Engineers) for the invites to conferences, facility tours and helping me expand my network. Many thanks to Old Dominion University and its NSBE (National Society Of Black Engineers) chapter for the professional development and providing many good friends.

NOTATIONS

i	a row number in a DSM or table unless otherwise specified
j	a column number in a DSM or table unless otherwise specified
n	number of tasks needed to complete a process
$v(i,j)$	the value of element (i, j) of a DSM
$mutmaster$	mute (mutation) master
PBM	Percent of Backtracking Move
LM	Loop Master
m	number of rows in the final loop master
DSM_{TS}	Design Structure Matrix for Task Sorting
a^p	adjacency matrix raised to power p
RC	Rework Coefficient of task(s)
$DSMR_{Start}$	Design Structure Matrix for Rework Starts
$DSMR_{Rate}$	Design Structure Matrix for Rates
$DSMMAT$	Design Structure Matrix for MATurities
$DSMR(t)$	Design Structure Matrix for Rework at year t
T	Duration of Tasks Vector
C	Cost of Tasks Vector
$Redo$	Redo Matrix
T_{total}	total duration of a process
T_0	duration of zero order rework
T_1	duration of first order rework
T_2	duration of second order rework
C_{total}	total cost of a process
C_0	cost of zero order rework
C_1	cost of first order rework
C_2	cost of second order rework

FOV	First Order Vector
$T_{embedded}$	duration of second order rework of an embedded loop
$C_{embedded}$	cost of second order rework of an embedded loop

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CHAPTER 1

INTRODUCTION

1.1 Importance of Technological Forecasting in Process Planning

1.1.1 Background of Study

Systems Engineering has been used many times to ensure that projects have been completed within duration and cost constraints. Locatelli et al. [1]¹ suggested that project managers using Systems Engineering should not only look inward at themselves, but also outward to ensure that projects are delivered and perform successfully. Because of changing standards of customers and/or failing equipment, the ability of a manager to meet goals on time and budget becomes increasingly difficult because of equipment or process obsolescence. During the design phase of a process, attempts are made so that the process in question can continuously meet given targets during its useful life and keep its utility. The design phase of a process is the best time to make changes because the process has not been implemented yet, and all changes are on paper and/or digital in nature when it is cheapest.

1.1.2 Purpose of Study

The purpose of this study is to develop a method of modeling obsolescence effects on process duration and cost due to the changes in properties of the interactions between tasks in a process. These interactions are typically represented in a Design Structure Matrix (DSM) in its design phase.

1.1.3 Statement of the Problem

Obsolescence impacts a process's task interfaces through deterioration of performance and quality necessitating rework. Few technological forecasting methods exists that aid in address-

¹The documentation style in this dissertation is written in format of the American Society of Mechanical Engineers (ASME).

ing obsolescence effects on interface interactions during the design phase of a process. Common methods of forecasting include analogies and extrapolations of curves such as Neilson's law of bandwidth. Analogies and extrapolations are commonly used for examining obsolescence in equipment but not the effects of obsolescence on the behavior of non-homogeneous equipment-equipment and equipment-method task interfaces. The DSM is used to study and model equipment interfaces by studying the tasks to which they are applied, but current DSM based literature does not consider rework whose probability of rework is not constant due to obsolescence. Process design, however, must consider also the requirement that a process's duration and cost will stay below acceptable thresholds as the probability of rework changes due to obsolescence.

1.1.4 Research Hypotheses

As time passes, the quality of interactions between tasks degrades because the equipment used to complete them becomes obsolescent. This will make the probability of rework increase. As the probability of rework increases, the distribution of time and cost will change.

1.2 Dissertation Overview

1.2.1 Preview of Chapters

Chapter 2 contains a literature review. This chapter will present some popular tools in examining obsolescence. Then, an explanation of how to use DSMs will be given along with some applications. At the end of this chapter, a literature review of papers that represent the intersection of obsolescence and DSMs research will be given along with an extended description of the gaps in the literature that this dissertation will attempt to address.

Chapter 3 explains the methodology of modeling obsolescence effects on process duration and cost due to the failing interactions between tasks in a process by using Monte Carlo simulations. Software was written in MatLab (Matrix Laboratory Version R2013b) for automation purposes, and the software's architecture will be explained in this chapter. This chapter will refer to

Appendix A which contains the software's codes.

Chapter 4 will demonstrate the use of the software in a case study. This chapter will show the manual calculation of one data point with the methodology explained in Chapter 3. Discussion of results will be given in this chapter.

Chapter 5 has the conclusion and suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

A literature review will be given in this chapter. The first section will explain the definition of obsolescence and review the use of curve fitting and extrapolation for measuring obsolescence. The second section will explain what a DSM is, how to read one, and some recent applications of the DSM. The third section will discuss the intersections of obsolescence and DSM research. The final section of this chapter will point out the gaps in research that this dissertation will attempt to address in greater detail.

2.1 Review of Obsolescence

2.1.1 Definition of Obsolescence

The definition of obsolescence in this dissertation is the inability of a piece of equipment or a process to perform at a certain standard. For example, a company has a standard of fuel consumption that is 25 miles/gallon buys a truck that meets that standard now; later, the truck ages, and it operates at 20 miles/gallon. In the company's eyes, the truck is now obsolete because it cannot meet the company's standard. Obsolescence can also come from a change in the standard. An example of such a situation is if the truck manages to continually operate at 25 miles/gallon and the company's operations now require a truck that operates at 30 miles/gallon the truck is obsolete in the company's eyes. In both cases, the occurrence of obsolescence is involuntary because all equipment will eventually age when used and, organizations must continuously make improvements to be competitive.

2.1.2 How Obsolescence is Measured

The issue with the use of analogies is that an existing process is needed for comparison. A notable example of a failed application in forecasting using analogies was explained by Martino in [2]. The French engineer deLesseps tried to construct the Panama Canal based on his

experience of the Suez Canal 40 years earlier. The Suez Canal was made on flat, desert terrain by moving sand and mud. The Panama Canal needed to be built in a swampy jungle with many mountains. The types of soil that had to be moved for the Panama Canal were rock and clay. The first attempt to construct the Panama Canal failed because the issues of designing the locks needed to over the mountains and the epidemics of malaria and yellow fever could not be solved.

It is common to use the extrapolation of curves to measure obsolescence. An example of a basic extrapolation is for studying a phenomenon called Nielson's Law of internet bandwidth shown in Fig. 2.1. The data points Nielson [3] collected were obtained by measuring the bandwidth given from high end internet providers, and it was determined that the internet providers' connectivity grows by 50% per year. This has become an expectation of customers of internet service.

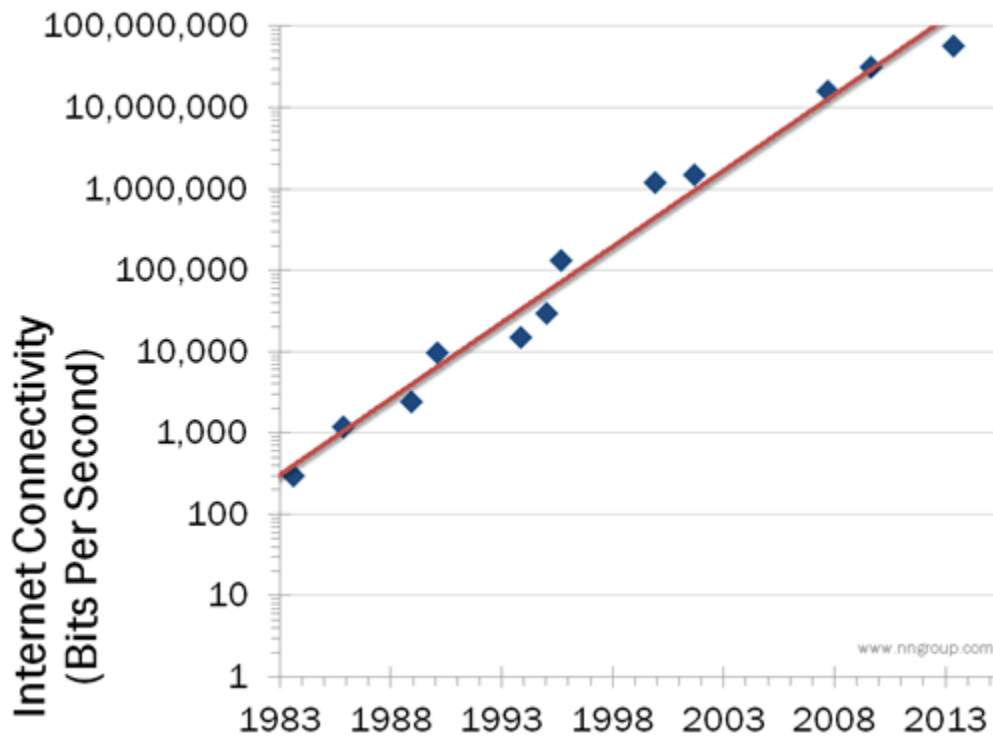


Figure 2.1: Plot Showing Nielson's Law. (Made by Nielson [3])

Biological systems provide a good paradigm for the life cycle of products and man-made systems. The s-shaped growth curve has been used to model market share and failure rates of different products. An example of a growth curve and its derivative is shown in Fig. 2.2 made by Kucharavy and DeGuio [4]. The life cycle of a product is in four stages. The first stage is when the product is first introduced to the market and growth rate of market share and/or failure is increasing slowly. The second stage occurs when growth is increasing at an exponential rate. The third stage starts when the growth rate begins to slow down. The fourth and final stage occurs when the growth rate is level. In economic terms, the product has reached saturation and no more can be sold. In failure terms, all devices in a given batch are “broken.”

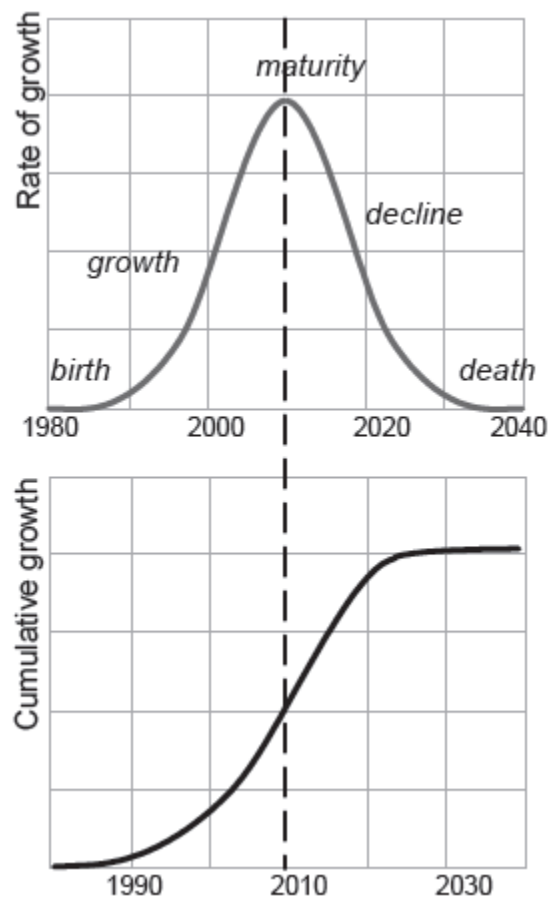


Figure 2.2: An Cumulative S-Curve And Bell Shaped Curve Showing Change In Rate. (Made by Kucharavy and DeGuio [4])

Figure 2.3 shows an example of an application of using a growth curve for technological forecasting by Intepe and Koc [5]. They predicted that the number of patents for 3D televisions will stop at around 500 in the year 2050. Growth curves are good for forecasting because no previous item is needed for comparisons and most of the subjectivity is removed because data is collected by simple counting.

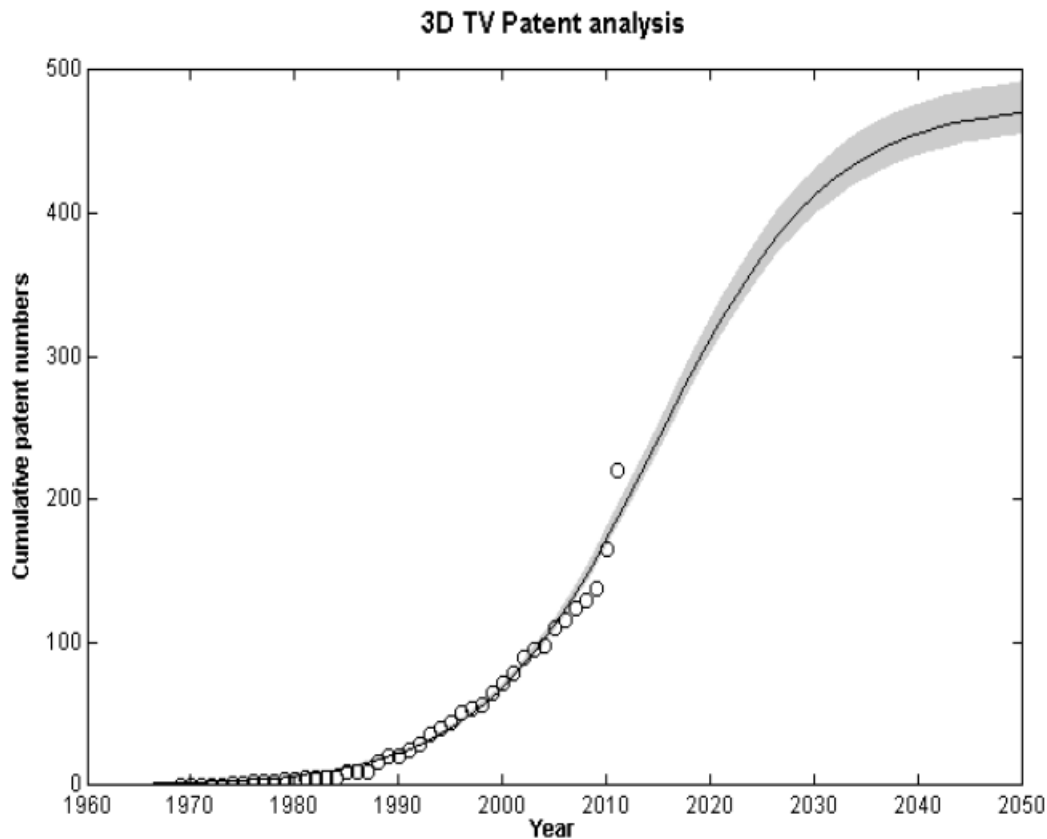


Figure 2.3: Growth Curve Of 3D Television Patents. (Made by Intepe and Koc [5])

Not all growth curve literature measures cumulative growth in terms of market patents. Many authors such as Lam, et al. [6] and Ryu and Byeon [7] used growth curves to track market saturation of devices. Miranda and Lima [8] conducted a study on the market saturation of digital cameras in the United States. The use of growth curves for examining market saturation

is as common as counting unit sales of devices. Figure 2.4 made by Miranda and Lima [8] contains a growth curve based on counting sales of digital cameras.

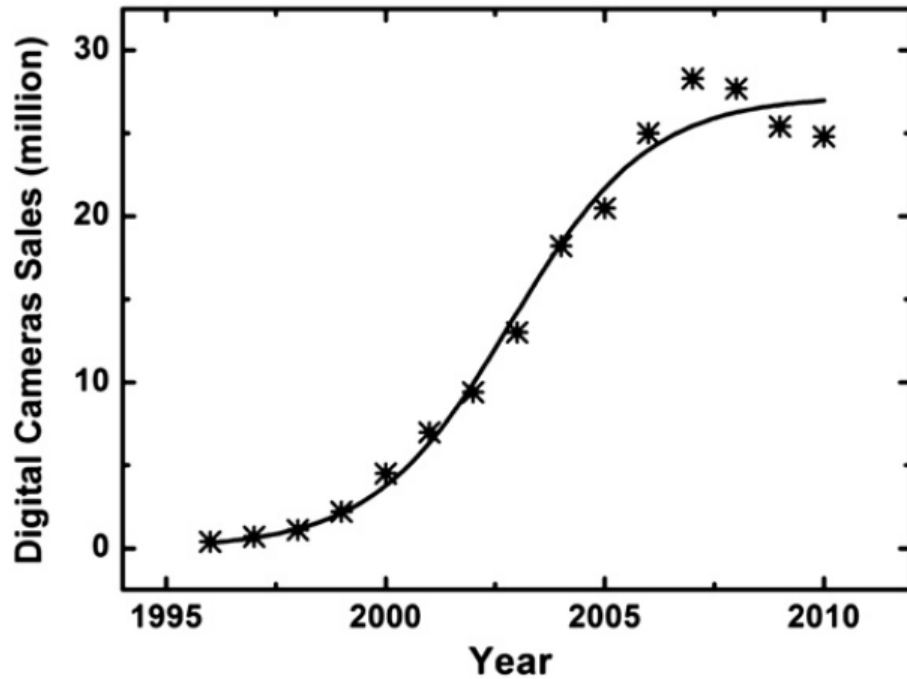


Figure 2.4: Growth Curve Of Digital Camera Sales. (Made by Miranda and Lima [8])

The literature also contains various attempts that use the derivative of the growth curve in Fig. 2.2 to measure the obsolescence of devices. The derivative of the growth curve is shaped as a Gaussian curve and is treated as such. An example of how a Gaussian curve is used to fit units shipped per unit time was made by Solomon, et al. [9] and is shown in Figure 2.5. Such authors use the time when the most units are shipped and/or sold to mark the time of device maturity, μ (mean), and σ (standard deviation) is used to frame the phases of the device's life cycle. Figure 2.6 contains a life cycle curve that was fitted by Karls et al. [10] for a type of device known as a DRAM (Dynamic Random Access Memory). What Karls et al. [10] predicted was that the sale of DRAMs would peak in the first quarter of 1998 with 2500 million units being shipped at

that time. The standard deviation is 1.6 years. The DRAMs were expected to become obsolete in early 2002. Bartels et al. [11] used life cycle curves to measure the obsolescence of various devices such as SRAMs (Static Random Access Memory), microprocessors, microcontrollers, logic parts, analog parts, and different types of integrated circuits.

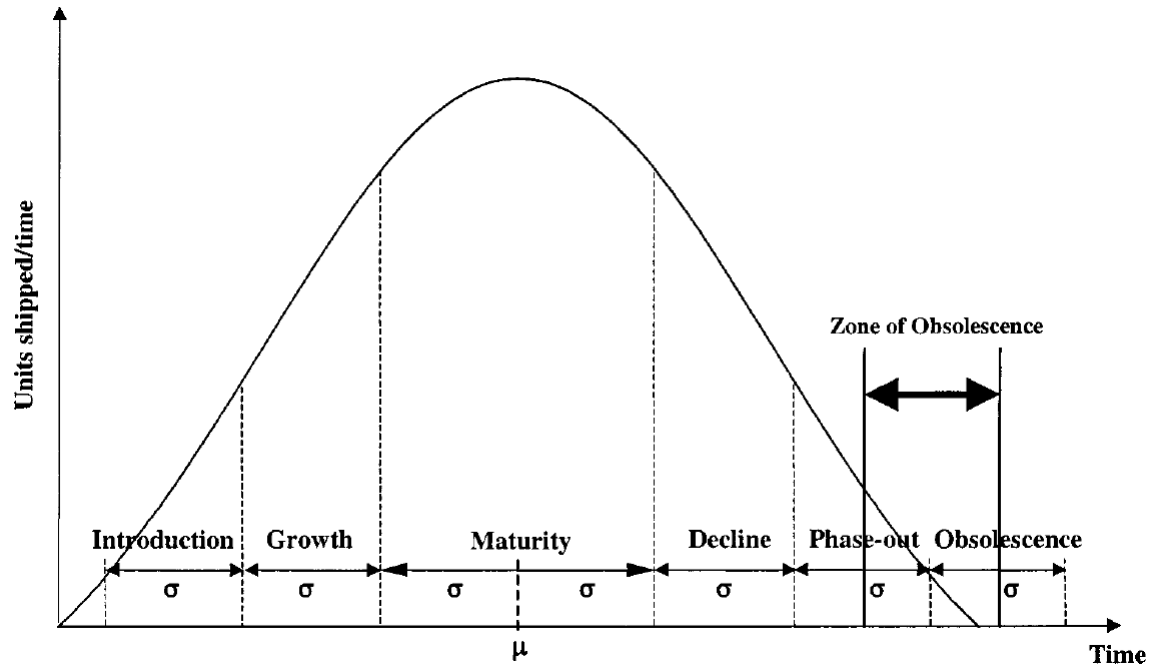


Figure 2.5: Derivative Of A Growth Curve With Life Cycle Phases. (Made by Solomon, et al. [9])

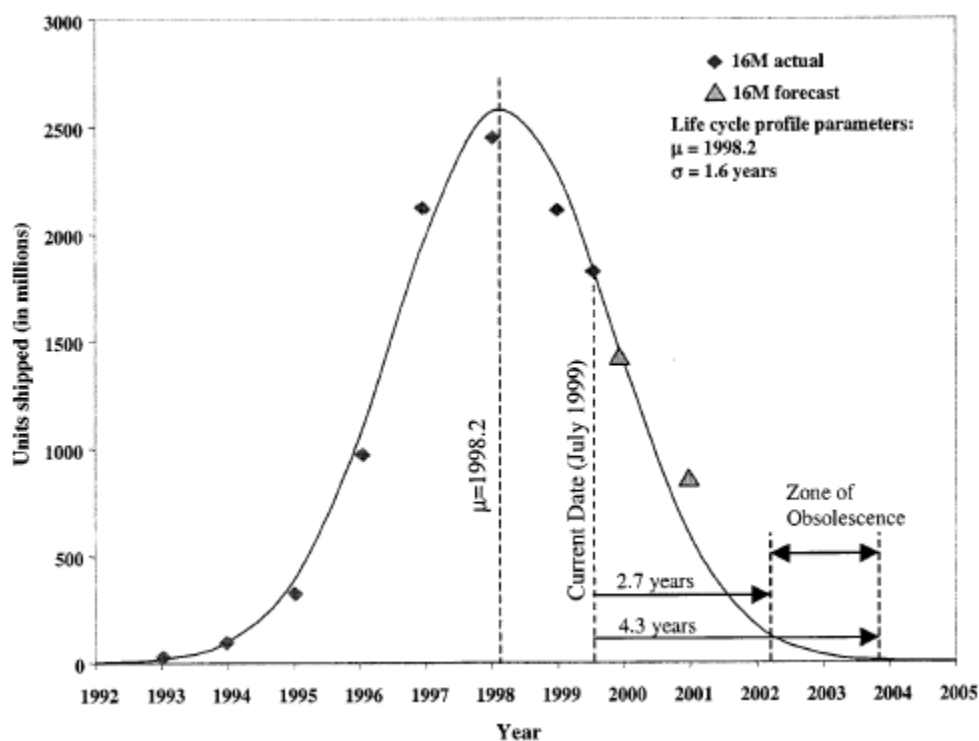


Figure 2.6: Life Cycle Curve For DRAMS. (Made by Karls et al. [10])

Barreca [12] has shown a methodology that involves treating obsolescence as a mode of failure for devices from market share and device sales. Barreca has expressed concern about not including the effects of the obsolescence of equipment while creating maintenance plans. Barreca maintained that if equipment obsolescence is considered while making a maintenance plan then the probability of failure for this equipment would be higher than the probability of failure due to the physical deterioration alone. Barreca explained that it is important to combine failure by obsolescence with failure by physical means to make the failure analyses of devices more accurate. Figure 2.7 made by Barreca [12] shows an illustration of such a situation. When the total probability of failure is lower at a given time than expected, the cost associated with these failures can catch equipment operators off guard, and budget overruns can occur. Obeng [13] has written software to implement Barreca's methodology of combining the failure curves and used it to estimate the total probability of failure of computer hard drives with Bao [24] and Obeng [25] for various types of cars.

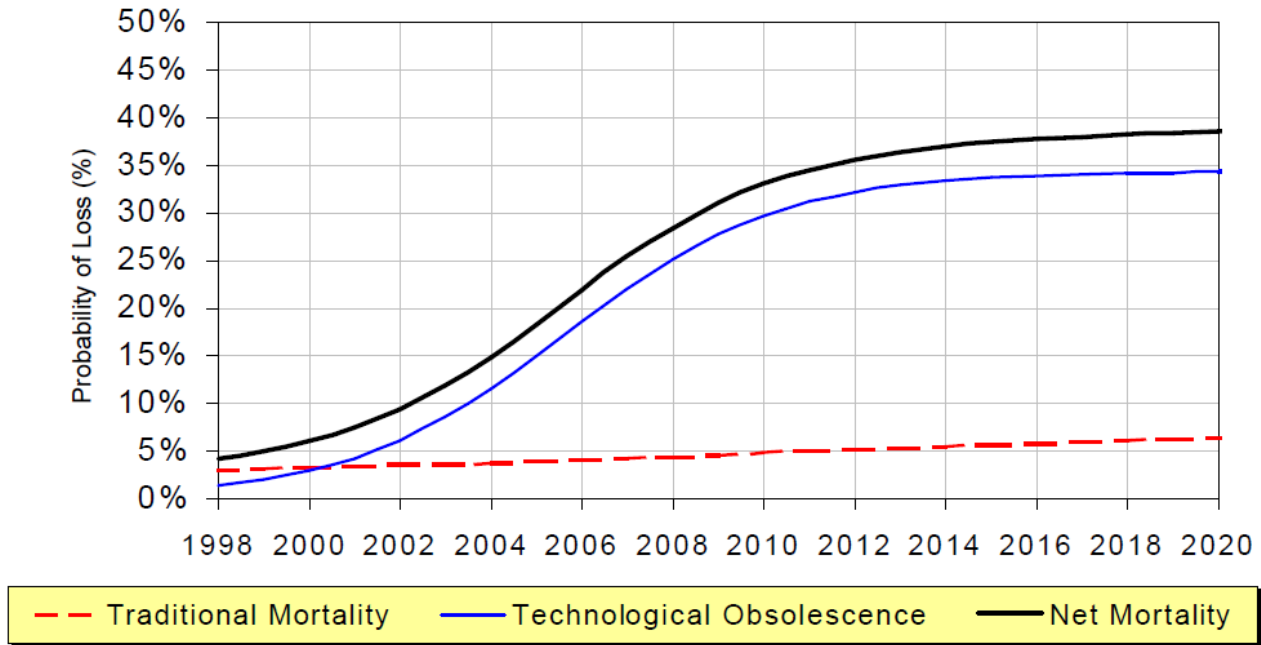


Figure 2.7: Failure Curves Representing Modes Of Failure. (Made by Barreca [12])

2.2 Review of the Design Structure Matrix (DSM)

2.2.1 What is a DSM and How to Read One

The purpose of the DSM is to model a system by showing how components interact with each other. There are four types of DSMs respectively for product architecture, organization architecture, process architecture and multidomain that is a combination of the previous three. The type of DSM that will be used for this research is the process based DSM. The process based DSM is used to show how tasks interact. The DSM is an $n \times n$ matrix where n is the number of tasks needed to complete a process. Interactions that exist between tasks are usually shown with a “one” or “X.” Non-binary DSMs use numbers to show the weight of interactions.

Figure 2.8 shows an example of a simple, binary DSM. To determine the order of completing the tasks in the process, read the headings on the rows or columns. The notation used in this research is called IR/FAD (Input shown in Rows/ Feedback is Above Diagonal). Interactions below the diagonal are feedforward moves, and interactions above the diagonal are feedback

moves. Reading the rows shows which tasks need input from which others and reading the columns shows which tasks give output to which others. Reading across the first row in Figure 2.8 shows that Task A needs inputs from Task B and Task E. Reading down the first column in Figure 2.8 shows that Task A gives output to Task C. Figure 2.9 shows the DSM in Figure 2.8 after being optimized. Figure 2.10 shows the resulting digraph (directed graph). The digraph is a chart that graphically shows how tasks in a project interact. The digraph in Figure 2.10 is read from left to right. The optimal order of doing the tasks are B, D, E, A, C, and F is completed last. Note that some tasks can be performed concurrently. For example, Tasks B and E can be performed at the same time. The process in this case has one incident of feedback (rework) if completed in the optimal order. Tasks E, A, and C form a loop (or circuit). A loop is a group of tasks that repeat because of the existence of feedback moves.

		From					
		A	B	C	D	E	F
To	A		X			X	
	B						
	C	X			X		
	D		X				
	E			X			
	F			X			

Figure 2.8: DSM Example.

		From					
		B	D	E	A	C	F
To	B						
	D	X					
	E					X	
	A	X		X			
	C		X		X		
	F					X	

Figure 2.9: DSM From Figure 2.8 After Optimization.

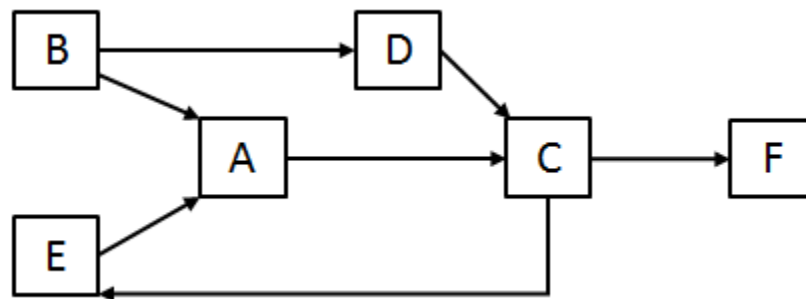


Figure 2.10: Digraph Of DSM From Figure 2.8.

Figure 2.11 was made by Browning [14] and shows the types of interactions that exist between the tasks in a project and how they are represented in a DSM. The DSM is better at modeling interactions than methods such as the critical path method (CPM) and Gantt charts because the latter two cannot properly represent feedback.

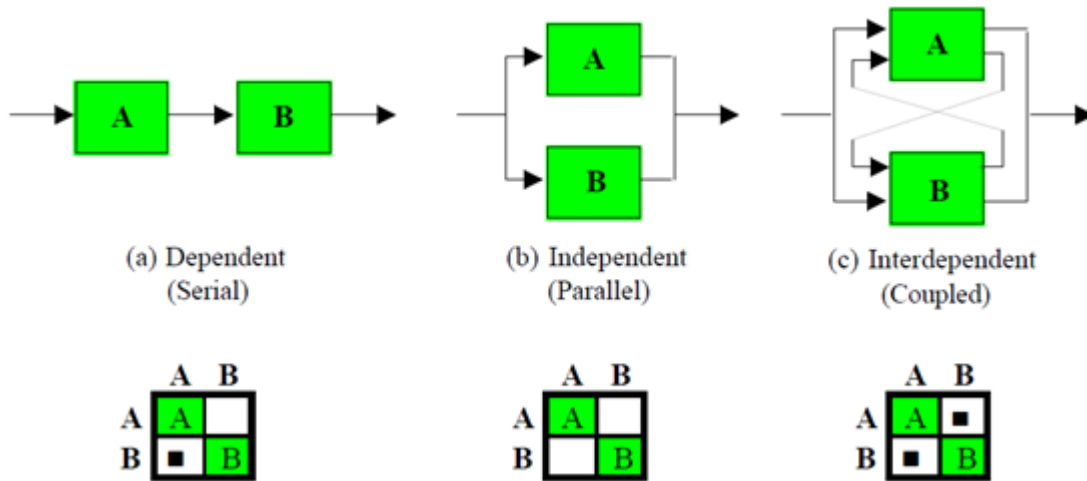


Figure 2.11: Types Of Tasks Interactions. (Made by Browning [14])

2.2.2 Examples of DSM Applications

Figures 2.12 and 2.13 contain an application of binary DSMs by Gunawan [15] for the development of an oil field. Figure 2.12 shows the unsolved DSM, and Fig. 2.13 shows the solved DSM. The highlighted blocks in Fig. 2.13 show which tasks form loops. In this case, Tasks 1.1, 1.3, 3.3, and 3.6 are part of a loop, and Tasks 2.5, 4.1, 4.2, and 4.3 are part of another loop. The first five tasks can be completed in parallel.

	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	3.5	3.6	4.1	4.2	4.3	4.4	5.1	5.2	5.3	5.4	5.5	
1.1	5														X										
1.2		15																							
1.3	X	X	5																						
1.4			X	10																					
2.1				X	5										X										
2.2					X	5																			
2.3				X		X	5																		
2.4							X	2																	
2.5								X	10									X							
3.1										15															
3.2											5														
3.3			X								X	10													
3.4											X		10												
3.5											X			10											
3.6									X		X	X	X	X	10										
4.1								X							X	5								X	
4.2																X	3								
4.3																	X	5							
4.4																		X	15						
5.1																				10					
5.2																					5				
5.3																					X	15			
5.4																					X		30		
5.5																				X		X	X	10	

Note: The numbers on the diagonals indicate days needed to complete its corresponding task.

Figure 2.12: Staring DSM For Oil Field Development Project. (Made by Gunawan [15])

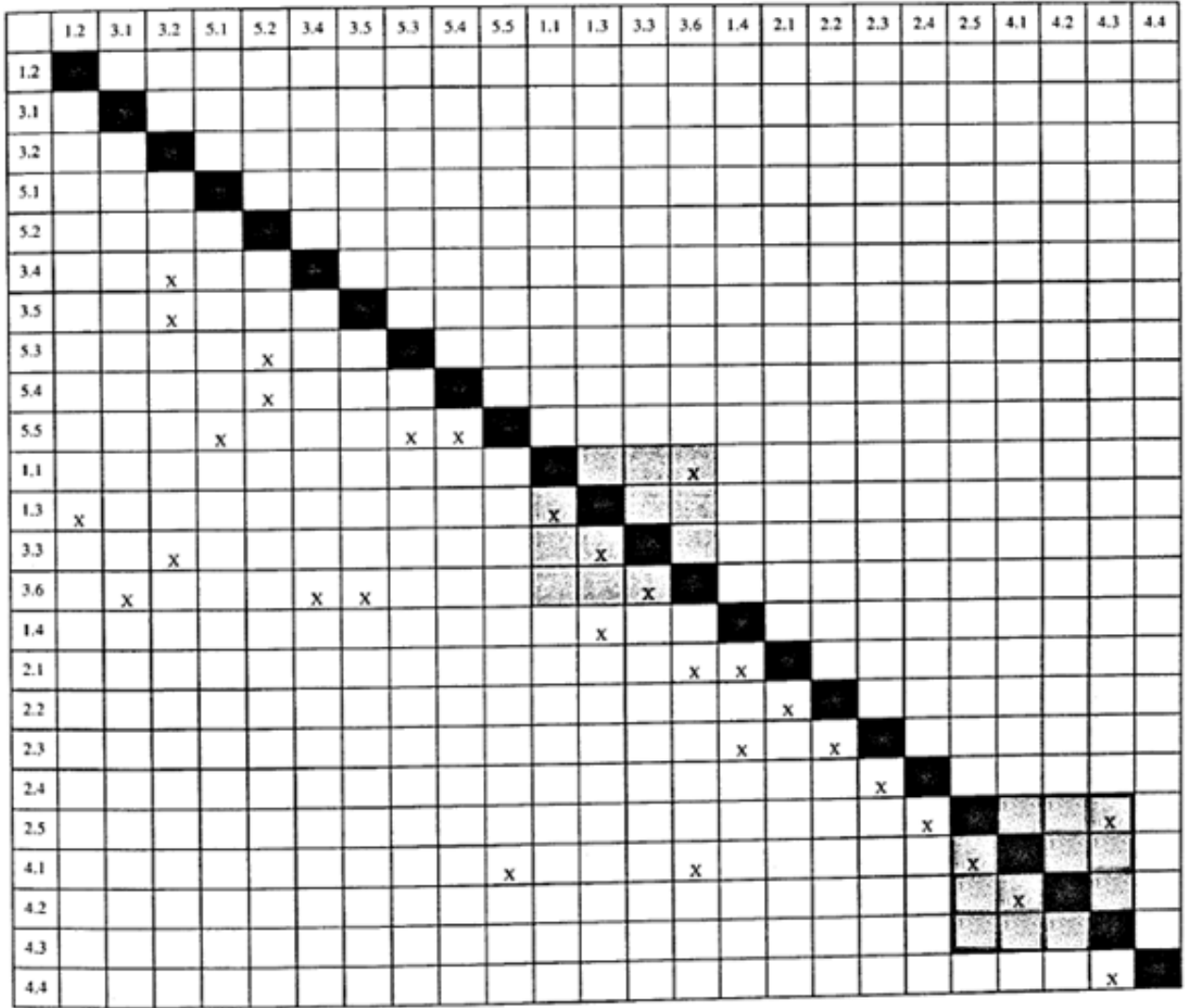


Figure 2.13: Solved DSM For Oil Field Development Project With Highlighted Blocks. (Made by Gunawan [15])

Tripathy and Eppinger [16] used a binary DSM, shown in Fig. 2.14, to help Dover Motion develop a process for creating air bearing technology. A “toll gate” was placed at the end of each block. The quality control of the tasks occurs at those points and not after the completion of each individual task.

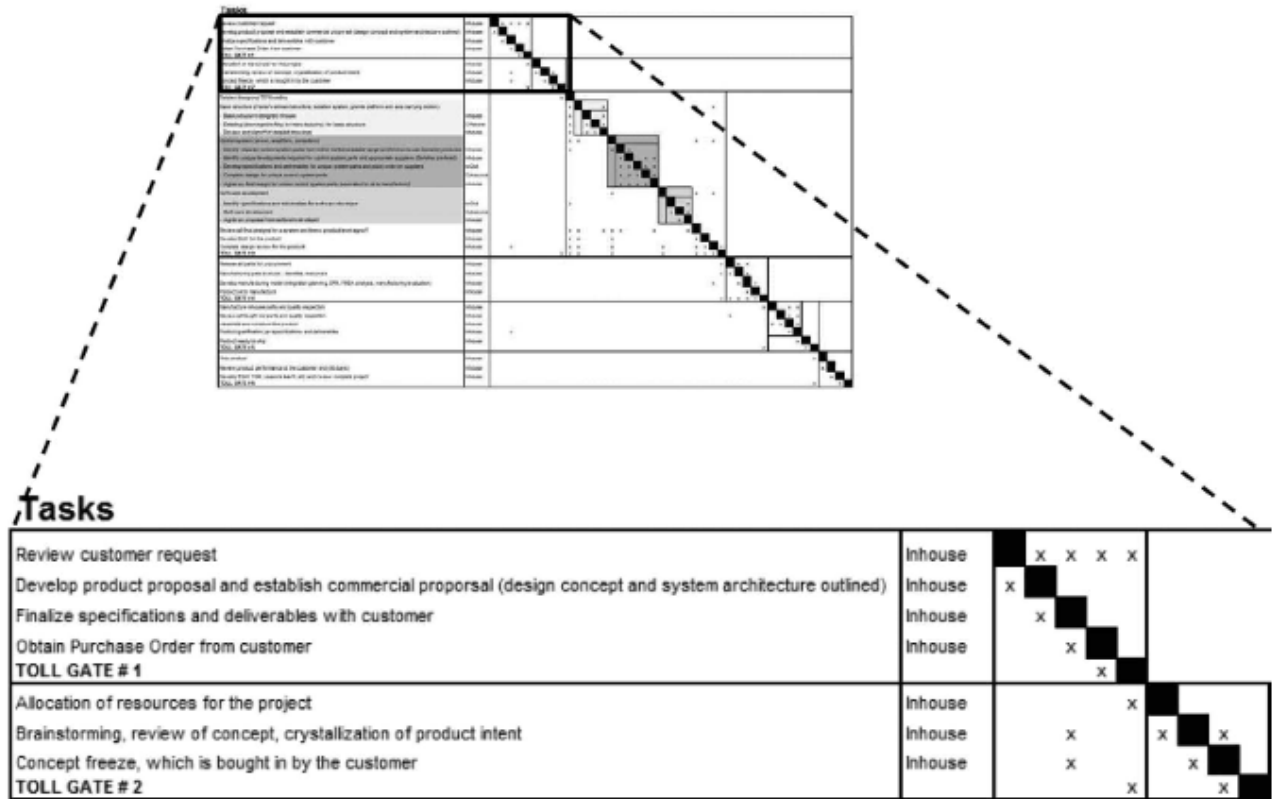


Figure 2.14: Solved DSM From Dover Motion. (Made by Tripathy and Eppinger [16])

Non-binary DSMs use numbers to show the weight of interactions. Abdelsalam and Bao [17] used DSM weights that indicate the strength of the task interaction with one being extremely weak to nine being extremely strong. Browning and Eppinger [18] used non-binary DSMs that included the probability and impact of rework to make estimates of duration, cost, and risk of projects. An example is shown in Fig. 2.15 for the development of UCAVs (Unmanned Combat

Aerial Vehicles). If i is a DSM row and j is a DSM column, then element (i,j) is read as “the probability that task i has to be repeated because of an error in task j .” An example from Fig. 2.15 is element (2,1) shows that Task 2 (Creating UCAV Preliminary Design Architecture) has a 40% chance of being reworked because of an error in Task 1(Preparing UCAV Preliminary DR&O). With this DSM, Browning and Eppinger made a joint PDF (Probability Density Function) of process duration and cost.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Prepare UCAV Preliminary DR&O	1													
Create UCAV Preliminary Design Architecture	2	.4							.2					
Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings	3		.5											
Perform Aerodynamics Analyses & Evaluation	4			.4										
Create Initial Structural Geometry	5	.3		.5										
Prepare Structural Geometry & Notes for FEM	6	.4		.5								.3	.1	
Develop Structural Design Conditions	7	.1			.4									
Perform Weights & Inertias Analyses	8	.4				.4								
Perform S&C Analyses & Evaluation	9					.5						.5		
Develop Balanced Freebody Diagrams & Ext. Applied Loads	10				.5	.2	.1					.4		
Establish Internal Load Distributions	11				.1	.5	.2	.1				.4		
Evaluate Structural Strength, Stiffness, & Life	12					.5	.5	.5				.5	.4	
Preliminary Manufacturing Planning & Analyses	13	.4				.4	.5					.5	.4	
Prepare UCAV Proposal	14	.5			.5							.4		
	14	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4

Figure 2.15: Browning And Eppinger’s DSM Of Rework Probabilities. (Made by Browning and Eppinger [18])

2.3 Intersections of Obsolescence and DSM Research

2.3.1 The Need To Consider System Interfaces

Khadke and Gershenson [19] discussed the importance of considering the role of technology evolution in the design of products and platforms that they make up to avoid frequent redesigns and premature obsolescence. Devereaux [20] worried about complex defense systems whose

components have useful lives that are extremely short compared to the design life of the system that they are used for. Both Khadke and Gershenson [19] and Devereaux [20] have suggested using the DSM for system mapping.

2.3.2 Metrics For Describing Interfaces

Khadke and Gershenson [19] decided to use three metrics to measure technology change. The first metric is called performance level, and it describes how well a given technology can perform based on its function. The second metric is called principle of operation and describes how the function is fulfilled. The third metric is technology architecture which is a basic description. Technology architecture is described in terms of its spatial, material, energy, and information needs. Next, two DSMs (one for internal dependency and another for external dependency) are filled out based on how likely of the technologies' metrics are to change based on numbers such as 5 (strong), 3 (medium), and 1 (weak) for weight, used to identify technologies in a platform that will cause problems later.

Devereaux [20] suggested using numbers and colors to fill DSMs. An example is shown in Figure 2.16 and the legend is shown in Fig. 2.17. Figure 2.18 shows the legend for the diagonal elements. The higher the element number, the more complex the interactions between subsystems are, and the more likely these elements become obsolete.

Command & Control Level 2	0	4	7	7	0	0	5	0	0	0
0	Power 1	0	0	0	0	0	4	4	0	0
4	0	Power 2	0	0	4	4	0	0	0	0
7	0	0	Antenna Transmit	3	7	0	7	0	0	0
7	0	0	3	Antenna Receive	3	7	7	0	0	0
0	0	4	7	3	Relay Transmit	3	0	0	3_5	0
0	0	4	0	7	3	Relay Receive	0	0	3_5	0
5	4	0	7	7	0	0	Command & Control Level 1	5	3_5	0
0	4	0	0	0	0	0	5	Sensor	0	3
0	0	0	0	0	3_5	3_5	3_5	0	Weapon Platform	7
0	0	0	0	0	0	0	0	3	7	Weapon 1

Figure 2.16: A DSM Considering Subsystem Strength. (Made by Devereaux [20])

Legend	
0	No Connection
1	Physical Connection Only
2	Power Connection Only
3	Information Connection Only
4	Physical and Power Connection
5	Physical and Information Connection
6	Power and Information Connection
7	Physical, Power and Information Connection

Figure 2.17: Legend For The DSM In Fig. 2.16. (Made by Devereaux [20])

Diagonal Legend	
	Obsolescence Evaluation Not Performed
	Obsolescence Evaluation Underway
	Obsolescence Identified
	No Obsolescence Impact

Figure 2.18: Diagonal Legend For The DSM In Fig. 2.16. (Made by Devereaux [20])

2.4 Research Gaps This Dissertation Will Address

2.4.1 Static Time Domain of Interface Study

There are many papers that assume that the nature of system interfaces stays the same as time passes. Browning and Eppinger [18] assumed that their DSM for probability of rework will stay constant as time passes. Khadke and Gershenson [19] and Devereaux [20] assumed that the obsolescence between system components is also constant. Nomaguchi et al. [21] used the growth curve and fuzzy numbers for making DSMs that are a function of time, but the growth curves were used to measure technical performance and task integrity. Also, the methodology of Nomaguchi et al. [21] only tracks process performance and not how a future process may appear to replace the current and obsolescent one.

2.4.2 Subjectivity of Interface Study

An issue with the papers in the previous section is that they both use DSMs that were assembled with expert opinion, but not all experts are the same. The second paper does not consider how the connection is made. An example of what the second paper misses is that

there is more than one type of power connections and not all have equal influences or impacts.

The goal of this dissertation is to use the DSM for to keep track of interactions. The interactions will be made more objective by using growth curves whose parameters were obtained by examining the markets from which the equipment came that was used for completing the process and failure studies. The use of growth curves will make the DSMs not static in nature. The next chapter will explain the methodology used in this dissertation to create a non-static DSMs that will be used in modeling how obsolescence affects the design of a process's design as it ages.

CHAPTER 3

METHODOLOGY AND PROGRAM ARCHITECTURE

This chapter will discuss the methodology of using DSMs to determine how obsolescence affects the design of a process as time passes. A flowchart of the methodology is shown in Figure 3.1. Software was written for automation and is shown in Appendix A which will be referenced multiple times. The chapter is divided into four sections. The first section will discuss how the optimizer (computer codes shown in Appendices A.3 and A.4) works. Because the focus of this dissertation is on simulating the effects of obsolescence and not DSM optimization, the first section will be extremely brief. The second section will discuss what a loop master is, how to read one, and how to make one (codes shown in Appendix A.6). This input for the simulations is so important that it was given its own section. The next section will discuss the rest of the inputs needed and how to conduct the simulations themselves (using code shown in Appendix A.7). The last section will discuss how to determine if a process will become obsolescent during its life.

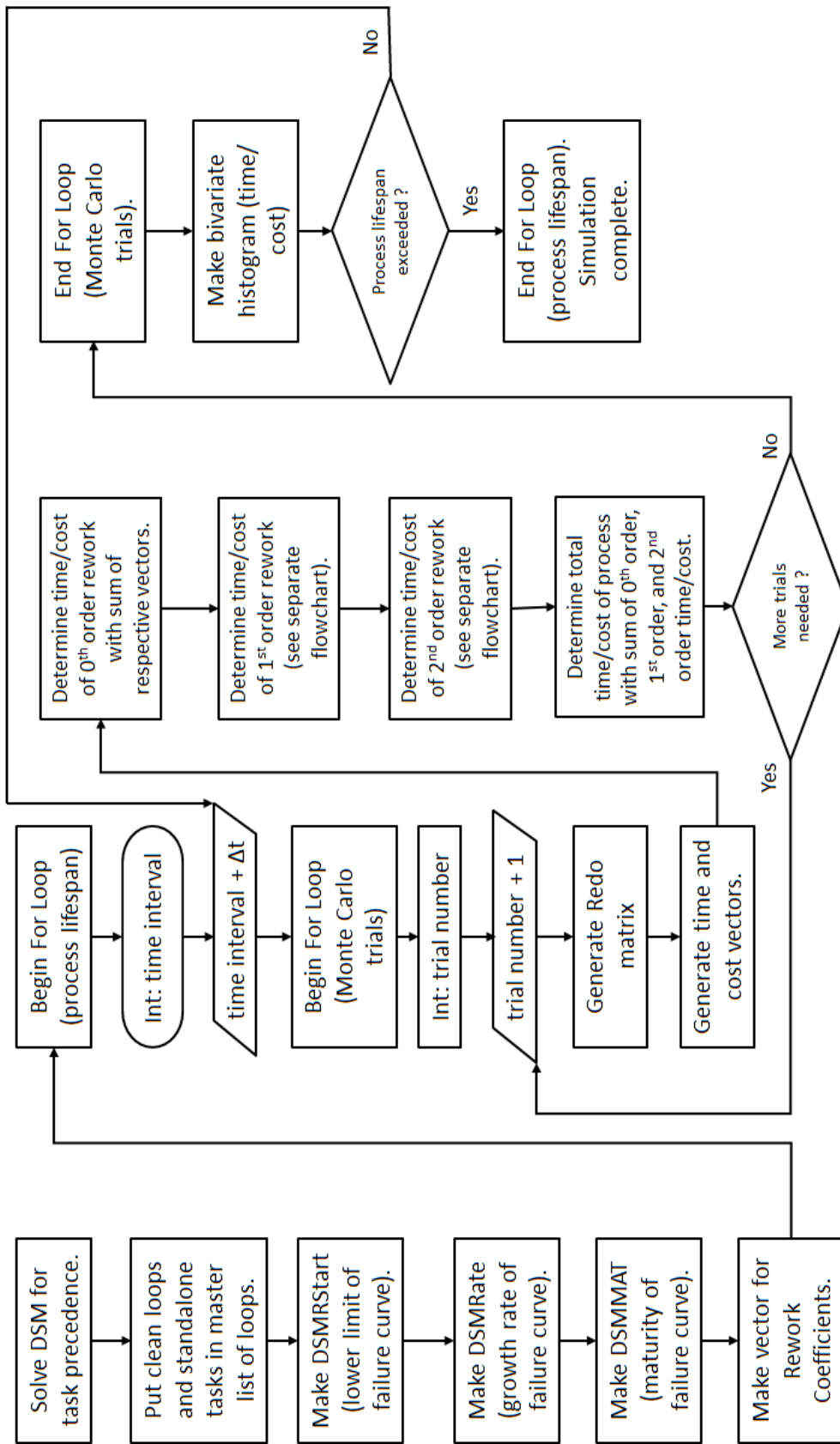


Figure 3.1: Overall Flowchart Of Methodology.

3.1 DSM Optimization

3.1.1 Method of Optimization

The optimizer given in this dissertation uses a search method called differential evaluation. This method was preferred because it is simple to implement and does not need to use any differential calculus involved in methods such as the steepest decent method, linear programming, etc. Differential evaluation is a direct search method that uses multiple iterations for optimization. The purpose of the optimizer is to find an order of tasks that allows the process to be completed as smoothly as possible. To do this, the optimizer puts the interactions as close to the underside of the diagonal as possible. This will result in interactions being placed into sequential blocks of iteration like the solved binary DSM in Fig.3.2 by Gebala and Eppinger [22]. The first block is made of Tasks I, A, and J. The second block is made of Tasks F, K, and C. The third block is made of Tasks H, E, and D. The fourth block is made of Tasks L, G, and B. To complete the process, the tasks in the first block are repeated until their outputs are satisfactory. The tasks in the second block are worked on, then the third block, and then the final fourth block.

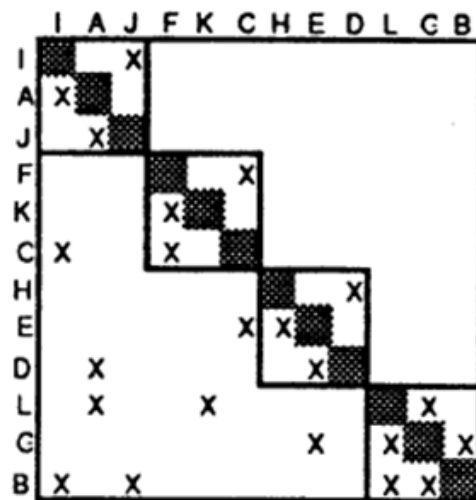


Figure 3.2: Example Of A Solved DSM With Blocks Of Iteration. (Made by Gebala and Eppinger [22])

An iteration of differential evaluation usually comes in four steps: 1) population initialization, 2) mutation, 3) crossover, 4) fitness evaluation. More details of how the optimizer will do these steps will be shown later in this section.

3.1.2 Extraction of Data From Excel

The data is processed in MatLab, but the program inputs are placed in Microsoft Excel. The file names for the inputs and outputs of the optimizer are located as specified in lines 22 and 23. The optimizer extracts the given Design Structure Matrix for Task Sorting (DSMTS) here.

3.1.3 Population Initialization

Equation (3.1) contains the objective function that the optimizer uses (see Appendix A.3) to reduce feedback. Each element in DSM is given a score, and the scores are added to determine the total score of the DSMTS.

$$Score_{total} = \left| \sum_{i=1}^n \sum_{j=1}^n (j - i) * v_{(i,j)} \right| \quad (3.1)$$

where

i is the row,

j is the column,

n in the number of tasks in the process,

$v(i, j)$ is the value of element (i, j) .

The first step that the optimizer does is to generate a set of candidate solutions (individuals) called a population. In differential evaluation, a chromosome is an arrangement of variables (alleles) that describes each individual. The optimizer in this dissertation creates individuals whose number of alleles is equal to twice the square of the number of tasks that make up the process. An example is that, if four tasks are needed to be completed, then the optimizer will make individuals with chromosomes that contain 32 alleles. 16 alleles control the i 's of the element's values and 16 alleles control the j 's of the element's values. Because the DSM heading for the rows must match the columns, the alleles are made such that no element

locations are repeated. Table 3.1 shows how the chromosomes for the unsolved DSM in Fig. 3.3 are represented. Table 3.2 shows how the chromosomes for the solved DSM in Fig. 3.4 are represented.

Table 3.1: Table Explaining The Allele Values For The DSM In Fig. 3.3.

To Task	From Task	i	j	Value	Score
1	1	1	1	0	0
1	2	1	2	0	0
1	3	1	3	1	2
1	4	1	4	1	3
2	1	2	1	0	0
2	2	2	2	0	0
2	3	2	3	0	0
2	4	2	4	0	0
3	1	3	1	0	0
3	2	3	2	1	-1
3	3	3	3	0	0
3	4	3	4	1	1
4	1	4	1	0	0
4	2	4	2	1	-2
4	3	4	3	0	0
4	4	4	4	0	0
Total Score					3

Note: The lower the score, the better.

		From			
		1	2	3	4
To	1	1		1	1
	2		1		
	3		1	1	1
	4		1		1

Figure 3.3: Resulting DSM From Allele Values In Table 3.1.

		From			
		2	4	3	1
To	2	1			
	4	1	1		
	3	1	1	1	
	1		1	1	1

Figure 3.4: Resulting DSM From Allele Values In Table 3.2.

Table 3.2: Table Explaining The Allele Values For The DSM In Fig. 3.4.

To Task	From Task	i	j	Value	Score
1	1	4	4	0	0
1	2	4	1	0	0
1	3	4	3	1	-1
1	4	4	2	1	-2
2	1	1	4	0	0
2	2	1	1	0	0
2	3	1	3	0	0
2	4	1	2	0	0
3	1	3	4	0	0
3	2	3	1	1	-2
3	3	3	3	0	0
3	4	3	2	1	-1
4	1	2	4	0	0
4	2	2	1	1	-1
4	3	2	3	0	0
4	4	2	2	0	0
Total Score					-7

3.1.4 Mutation and Crossover

Mutation and crossover are steps that differential evolution takes to make populations more diverse. Diverse populations are more likely to contain better solutions than those which are not diverse. Mutation is randomly rearranging the alleles in a single individual's chromosome. The optimizer in this dissertation (see lines 95 - 102 in Appendix A.4) does mutation by first generating a permutation of numbers. The vector (called "mutmaster") represents the order that in which the tasks are completed. Every n alleles in an individual's chromosome that controls DSM rows is made equal to the mutmaster component i . Every n alleles in an individual's chromosome that controls DSM columns are made equal to the mutmaster. The mutmaster from Table 3.1 is [1 2 3 4]. The mutmaster from Table 3.2 is [4 1 3 2].

Crossover is switching alleles from one individual to another. The optimizer in the dissertation does not do crossover because it will result in chromosomes becoming jumbled and after sorting them out, the new chromosomes will resemble another chromosome.

3.1.5 Fitness Evaluation

The next step in an iteration of differential evaluation is called fitness evaluation. In this step, the objective function of each individual is evaluated (determining score) and compared to the others. The more desirable and individual's trait is, the more "fit" it is. An example is that in an minimization problem, individuals with lower scores have higher fitness than individuals with higher scores.

Figure 3.5 shows how the optimizer given in this dissertation works in finding the individual(s) with the most fitness (see lines 109 to 176 in Appendix A.4). Equation (3.1) is used for looking for individuals whose interactions are as close to the diagonal as possible. A problem with using Eq. (3.1) alone is that it allows for the opportunity for interactions placed above the diagonal to be stuck there. To prevent this, another metric called the PBM (Percent of Backtracking Moves) is used. The PBM of a DSM can be determined by dividing the number of interactions above the diagonal by the total number of interactions. The optimizer will first separate the individuals from the population with the lowest scores called the elite (the second and third individuals). Then the members of the elite with the lowest PBMs are determined to have the most fitness (third individual).

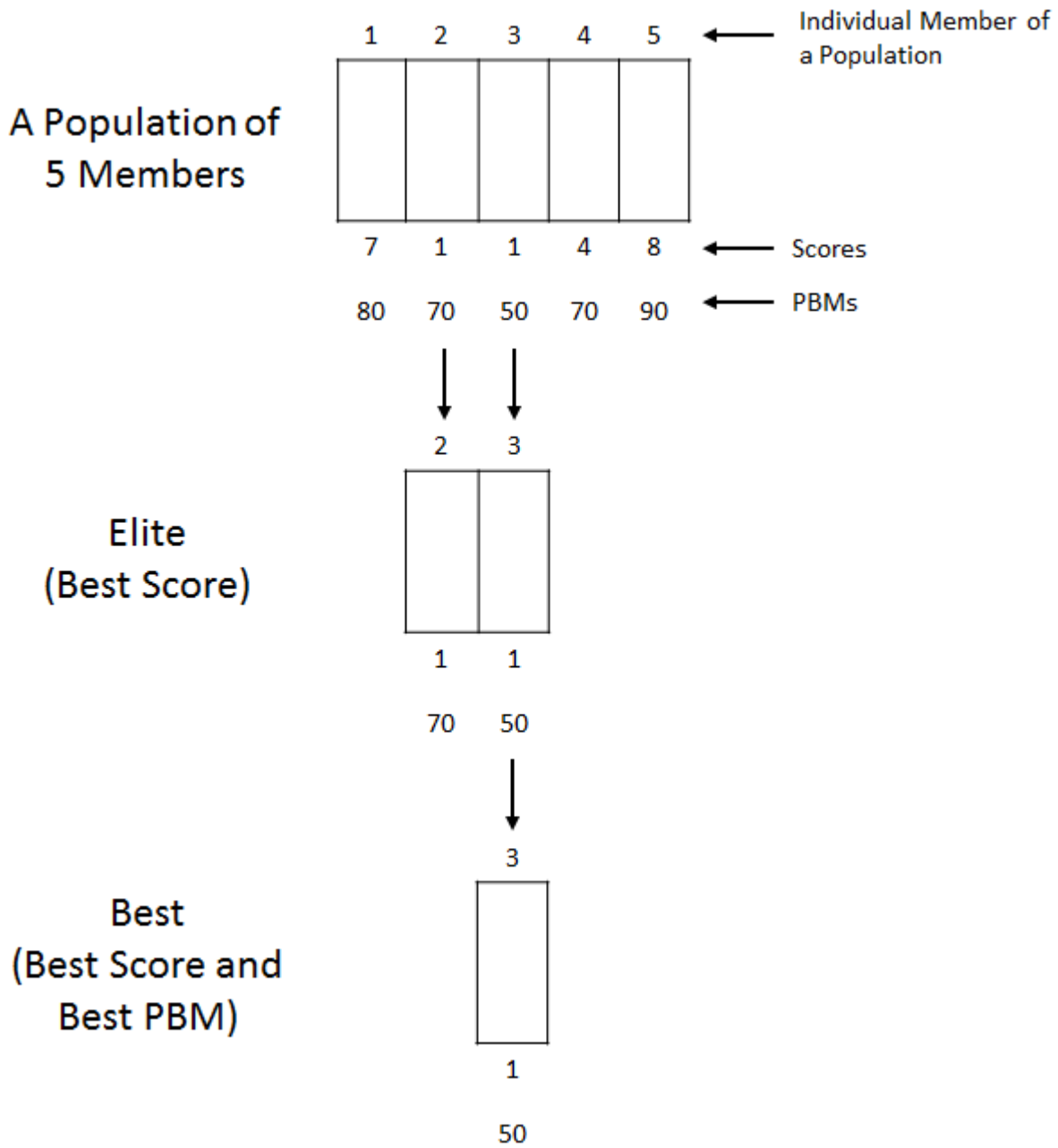


Figure 3.5: Example Of Optimizer's Determination Of Best Individuals.

The best of the population in the current iteration (generation) of the optimizer is compared to the best of the last generation. If the best of the current generation is more fit (having lower score and PBM) than the last generation, then the current generation is kept and is compared to the next generation. If the best of the last generation is more fit than the best in the current

generation, then the last generation is kept and is compared to the next generation.

3.1.6 Special Case for Presolved DSMs

If one wishes to use the software to implement the methodology, but already has an optimized DSMTS, the code in Appendix A.5 can be used instead of using the optimizer. This code will take that DSM and determine the mutmaster which will be used by software. The DSMTS will be used to assemble the loop master.

3.2 Loop Master Characterization

3.2.1 Loop Master Notation

The loop master (LM) is a table that contains a list of loops and shows which tasks make them up. The purpose of the loop master is to help process designers determine which loops will become problems. The final loop master is $m \times n$ where m is the number of rows and n is the number of tasks in the process. The number of rows in the final loop master is one plus the number of “clean” loops. A clean loop is a loop that is not nested in another loop. If a loop is nested in another loop, it is called an “embedded” loop. There are three classes of loops in the loop master. The first class is for clean loops that contain three or more tasks. The second class is for clean loops that contain only two tasks (often called “coupled pairs”). The third class is for “standalone” tasks. Standalone tasks are tasks that not part of any loop.

Table 3.3 contains an example of a loop master that was made from the digraph in Fig.3.6. The loop (made up of Tasks 1, 2, and 3) in the first row is assigned a Class 1 loop because there are three more tasks and it is not embedded. Tasks 1 and 2 form a coupled pair, but they are not given a row in the loop master in Table 3.3. If the coupled pair was not nested in the loop made of Tasks 1, 2 and 3, then it would have been given its own row and called a Class 2 loop. Task 4 is not part of any loop and therefore is a standalone task. It is placed in the row of the loop master for standalone tasks. The loop master is binary in nature. If an element (i,j) in the master list of loops row has a one, it means that loop i has task j .

Table 3.3: Loop Master For Digraph In Fig. 3.6.

Task ID	1	2	3	4
Class	1	1	1	0
	3	0	0	1

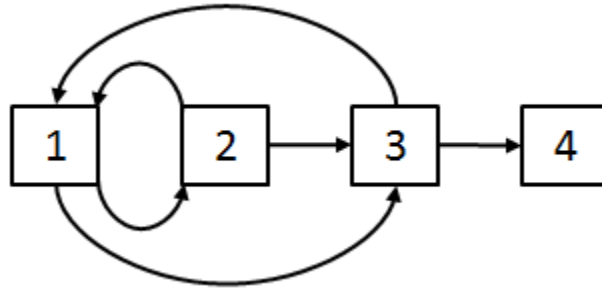


Figure 3.6: Digraph For Loop Master In Table 3.3.

Because the methodology presented in this dissertation assumes that the loops are completed sequentially, there is no need for the rows in the loop master to be in any order. The duration and cost of process as a whole will be the same regardless of the order of rework calculation of the loops. The software shown in Appendix A.6 places the row for standalone tasks at the bottom row of the loop master so that it can be easily found.

3.2.2 Finding Coupled Pairs

To ensure that all the loops in a process are found, the software in Appendix A.6 will use multiple methods to find loops. One method the software (see lines 20 to 57) uses to look for loops is to examine the DSMTS for pairs of coupled tasks. Tasks i and j make a coupled pair if and only if $DSMTS_{(i,j)}$ and $DSMTS_{(j,i)}$ are both not equal to zero.

3.2.3 Powers of Adjacency Matrix

Another method the software uses to look for loops is the powers of adjacency matrix method (see lines 58 through 96 in Appendix A.6). An adjacency matrix is made from the binary form of the DSMTS. Raising the adjacency matrix to the p^{th} power will show which tasks are p steps from each other. At first, the loop master's number of rows will be the same as the number of tasks. Each row of the loop master is coincident with the power of the adjacency matrix. For the software to know which tasks are in a loop, the software looks at each power of the adjacency matrix. If any diagonal elements in the adjacency matrix have any ones, then it is possible that those tasks representing those diagonals are in a loop. The matching row in the loop master is filled out accordingly. To keep each power of the adjacency matrix binary, the software follows the method by Gunawan [15]. What the software does is that after calculating each power, all non-zero elements are given a value of one. The software in this dissertation will calculate adjacency matrices to the n^{th} power because any higher powers are redundant. An example of this redundancy is that tasks in a five task loop are not just five steps apart, but 10, 15, 20, etc.

An example of using a power of an adjacency matrix is shown in Fig. 3.7. The adjacency matrix shown is of a second power. Ones in the diagonals show that Tasks 1 and 2 are in a loop. In the second row of the loop master, ones are placed in elements $LM_{(1,2)}$ and $LM_{(2,2)}$ to show that Tasks 1 and 2 are two steps apart.

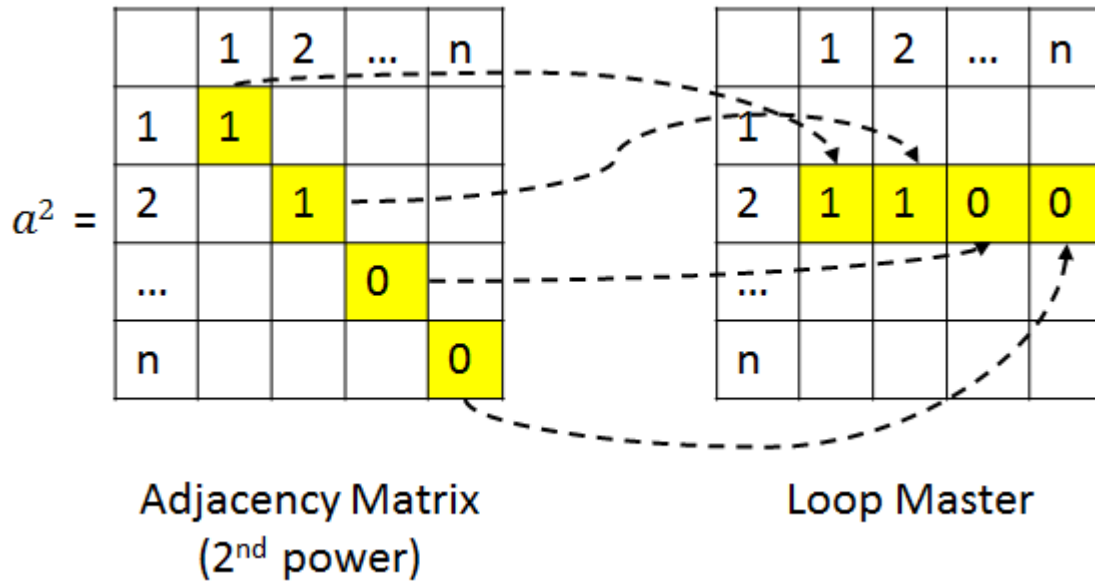


Figure 3.7: An Example Of Using An Adjacency Matrix To Fill A Loop Master.

3.2.4 Finding Standalone Tasks and Removing Connected Loops From Loop Master

At this point, standalone tasks can be found in the columns in the loop master that have a sum of zero (see lines 98 through 106 in Appendix A.6).

The powers of adjacency matrix method is not a perfect method of finding loops. Gunawan [15] and Maurer [23] noticed that if multiple loops exist, they can be entangled with each other. The extra steps in the software were written to remove the connected loops (see lines 108 through 159 of Appendix A.6). If a row in the loop master and the sum of its row are equal, then software will examine above the diagonal in the DSMTS. If element locations made by filled in columns of the loop master show no interaction in the DSMTS, loops of the same length exist and the row in question in the loop master is made all zeros. An example of this type of situation will be shown in the case study in the next chapter.

Another method the software uses for finding connected loops (see lines 98 through 106 of Appendix A.6) is looking for rows in the loop master whose sum is greater than its row number. These rows in the loop master will be made into all zeros. After this step in making the loop master, the coupled pairs are re-added to the loop master and duplicate rows are removed. Rows that have all zeros are also removed. Here, row number no longer matters.

3.2.5 Removing Embedded Loops From Loop Master

The software (see lines 190 through 220 in Appendix A.6) determines if a loop is embedded in another loop by adding their two loop master rows. If any components of the resulting vector is two or more, then the loop whose row sum is smaller loop is the embedded loop and the loop whose row sum is larger is the clean loop. All embedded loops are removed from the loop master.

3.2.6 Final Assembly and Exportation of Loop Master

Now the loop master row for standalone tasks is added to the loop master and the classes are assigned. The final loop master is exported to Excel for the software user to examine (see lines 222 through 278 in Appendix A.6).

3.3 Generation of Process Joint Duration/Cost Distribution Plots

3.3.1 Other Required Inputs and Preparation

There are more required inputs than the DSMTS and the loop master to make the distribution plots. Other inputs for the simulations are the duration and cost of each task in the form of a distribution. The software in this dissertation assumes that duration and cost of each task follow a triangular distribution. An example of a triangular distribution is shown in Fig. 3.8.

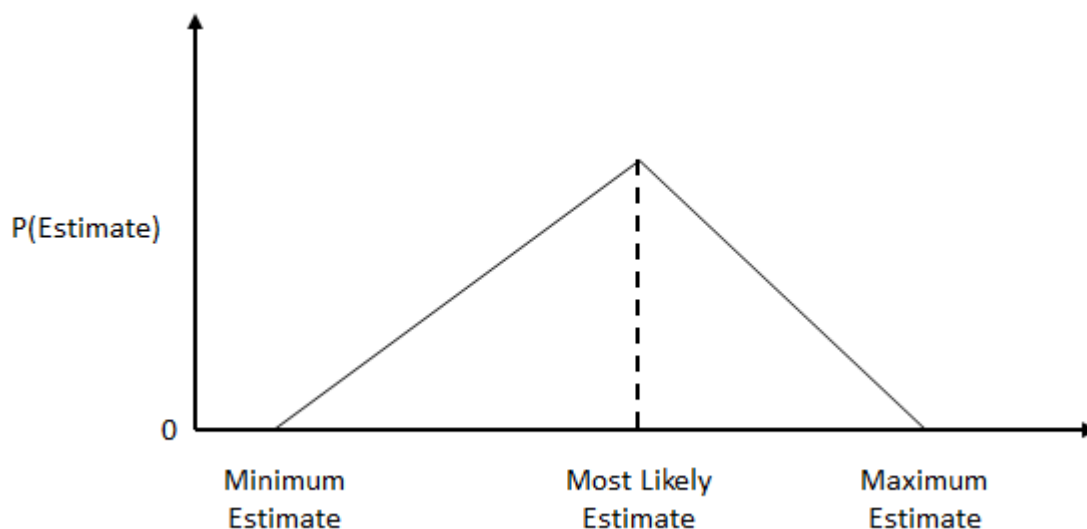


Figure 3.8: Triangular Distribution Example.

The next needed input is the Rework Coefficient (RC) of each task. An assumption of this methodology is that if a task has to be reworked then only parts of the task have to be redone. The RCs of the tasks are in terms of percentages. An example is, if a task needed an hour and 1000 USD (United States Dollars) to complete and the RC is 50, then half an hour (30 minutes) and 500 USD is spent each time the task has to be repeated. The RCs must be arranged into a vector (called RC) in which each component represents the rework to complete each task.

The growth curves that represent the probability of failure of the dominant devices used to complete each task are the next needed inputs. Figure 3.9 contains two examples of such failure curves. The failure curves are assumed to have the combined probability of failure from device mortality and device obsolescence and are also s-shaped. The parameters of the curves that are needed are the starting probabilities of the failure curves, the growth rate (controls slope of curve's center) and time of maturity (β). The maturity times are in reference to when the process is first used. The blue curve in Fig. 3.9 represents a technology that matured before the start of the process's life; therefore, β_1 would be a negative number. The red curve in Fig. 3.9 represents a technology that matured after the start of the process's life; therefore, β_2 would

be a positive number.

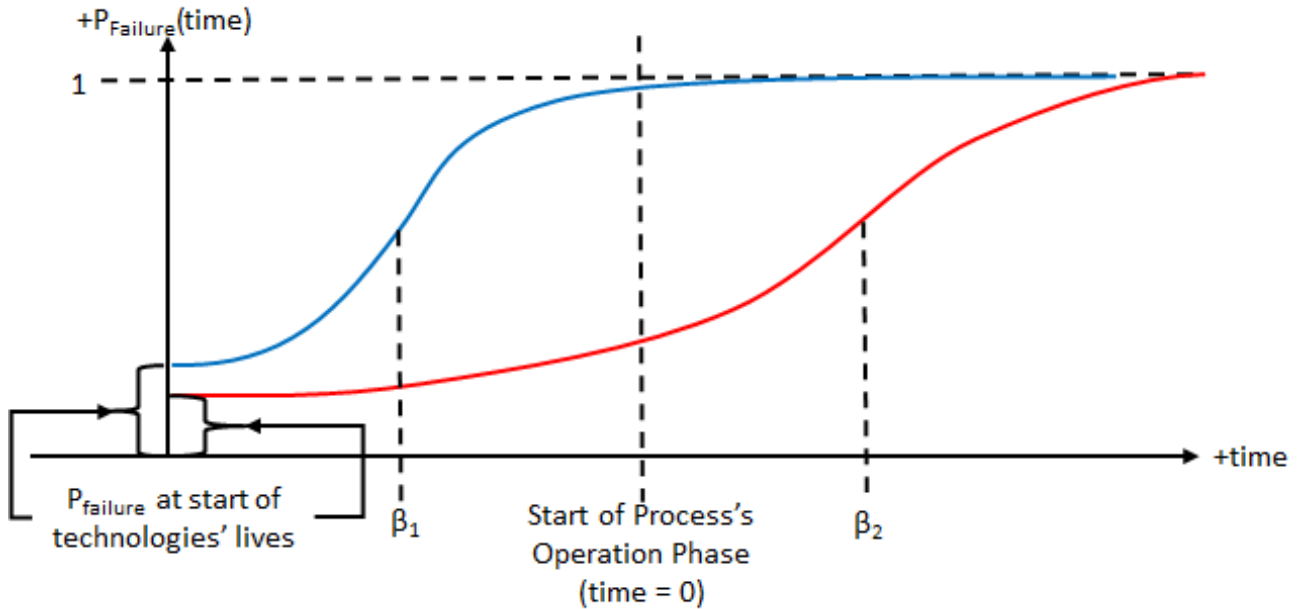


Figure 3.9: Examples Of Failure Curves.

The curve parameters are arranged into three DSMs. The first DSM is called the DSMRStart (Design Structure Matrix for Rework Starts). This DSM contains the starting probabilities of failure. An element in the DSMRStart, is read as “Task i depends on Task j and the connection’s starting probability of failure is $DSMRStart_{(i,j)}$.” The elements in the DSMRStart should be adjusted because the technology needed to complete a task might not interface the same with all its successors. The second DSM is called the DSMRate (Design Structure Matrix for Rates) and it is made of the growth rates. Reading across a task’s row shows the rate of failure of technologies used to complete its predecessors. An element in the DSMRate is read as “Task i depends on Task j whose rate of failure is $DSMRate_{(i,j)}$.” The third DSM is called the DSMMAT (Design Structure Matrix for MATurities) and it is made of the maturities. Reading across a task’s row shows when the failure curves of the technologies used to complete

its predecessors mature relative to the start of the use of the process. An element in the DSMMAT, is read as “Task i depends on Task j whose technology matures $DSMMAT_{(i,j)}$ before the start of the process.”

Figure 3.10 shows how the software make the PDFs. The process resembles three nested loops. The process’s lifespan is divided into intervals and each interval’s PDF is made with a number of Monte Carlo trials. The software user needs to define the number of time intervals of interest and the number of Monte Carlo trials (see lines 3 through 11 in Appendix A.7).

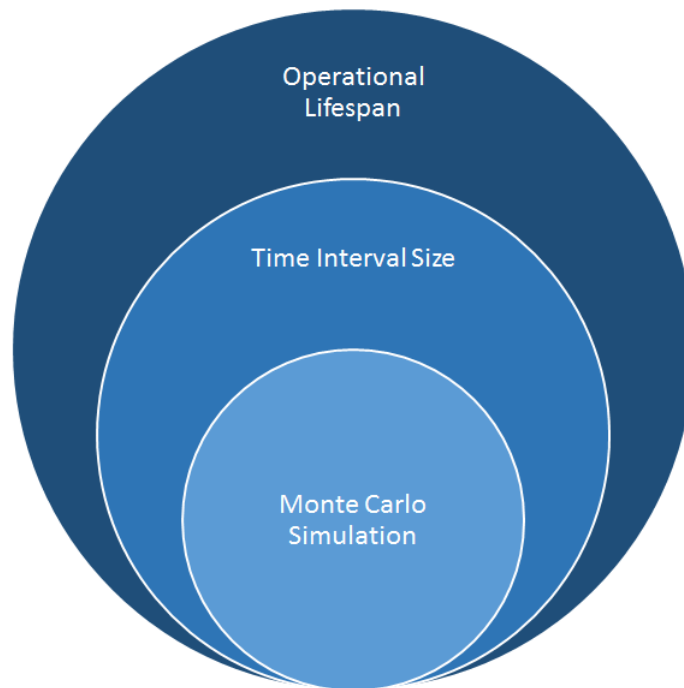


Figure 3.10: Illustration Of Loops In Methodology.

During each time interval, a $DSMR(t)$ (Design Structure Matrix for Rework at year t) is evaluated. It is read as “ $DSMR(t)_{(i,j)}$ is the probability that Task i has to reworked because of a error in Task j .” The assumption of rework caused by device failures is fundamental in

this methodology. Equation (3.2) is used to fill in the $DSMR(t)$. It is more accurate to use this for determining the probability of rework than the $DSMRStart$ because the failure curves of the technologies used to complete the tasks might not start at the same time (see lines 161 through 180 in Appendix A.7).

$$DSMR(t)_{(i,j)} = \frac{1 - DSMRStart_{(i,j)}}{1 + e^{-DSMRRate_{(i,j)}(t - DSMMAT_{(i,j)})}} + DSMRStart_{(i,j)} \quad (3.2)$$

During each Monte Carlo trial, a vector made of the durations, T , and cost, C , is randomly generated from the given distributions of tasks time and cost in which each component represents task order of completion (see lines 190 through 209 in Appendix A.7). Also a matrix that is $n \times n$ called the Redo matrix is made. The Redo matrix is filled with randomly generated numbers from zero to one. In each Monte Carlo trial, the total duration and cost is split into three types of rework (0^{th} order, 1^{st} order, and 2^{nd} order) which will be explained in more detail later. The total duration and cost needed to complete the process is calculated with Eqs. (3.3) and (3.4).

$$T_{total} = T_0 + T_1 + T_2 \quad (3.3)$$

where

T_{total} is total duration of a process,

T_0 is duration of zero order rework,

T_1 is duration of first order rework (considered wasted time),

T_2 is duration of second order rework (considered wasted time).

$$C_{total} = C_0 + C_1 + C_2 \quad (3.4)$$

where

C_{total} is total cost of a process,

C_0 is cost of zero order rework,

C_1 is cost of first order rework (considered wasted money),

C_2 is cost of second order rework (considered wasted money).

3.3.2 Definition of 0th Order Rework

Zeroth order rework of a task is its first ever attempt to complete it. To determine the time and cost spent doing first order rework, simply add the components of the time and cost vectors as shown in Eqs. (3.5) and (3.6) respectively.

$$T_0 = \sum_{i=1}^n T(i) \quad (3.5)$$

where $T(i)$ is a component in the time vector.

$$C_0 = \sum_{i=1}^n C(i) \quad (3.6)$$

where $C(i)$ is a component in the cost vector.

3.3.3 Definition of 1st Order Rework

Figure 3.11 shows an incident of first order rework that can occur while completing the process in Fig. 2.10. What occurs in incidents of first order rework is that after a task is completed, its outputs are inspected and seen as not meeting specifications; then the task in question is repeated such that its outputs are to specifications. With regards to the situation in Fig. 3.11, the following events occurs.

1. Task A is completed.
2. The input specifications of Task C are compared to the outputs of Task A.
3. The outputs of Task A are determined to be not to specifications.
4. Task A is repeated.

5. Task C is completed.

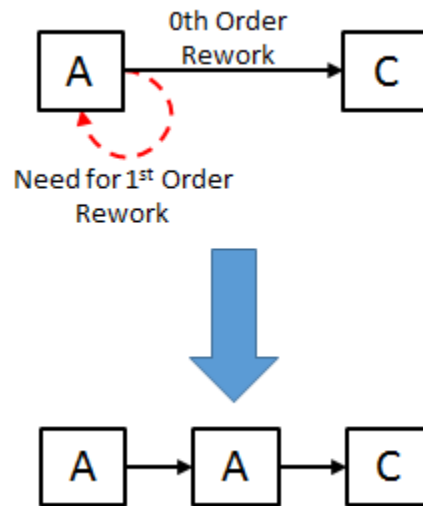


Figure 3.11: An Illustration Of A Situation Involving First Order Rework.

Figure 3.12 contains the flowchart that the software uses to calculate first order rework. To determine if any incidents of first order rework have occurred, the lower halves (where row number is greater than column number) of the $DSMR(t)$ for a given time and the Redo matrix are compared to each other. If an element in the Redo matrix, $Redo_{(r,c)}$ is lower than its corresponding element in the DSMR, $DSMR(t)_{(r,c)}$, an incidence of first order rework has occurred and the task associated with the element's column has to be repeated. To keep track of the number of times a task is repeated because of first order rework, a vector called the FOV (First Order Vector) is used. The vector component represents the task order and the component's value represents the number of times the task is repeated because of first order rework. An example of the FOV's notation is when $FOV(2)$ has a value of five means the second task in the process was repeated five times because of first order rework. To fill in the FOV, just take each component, $FOV(c)$ and determine the number of elements in the

matching column, c in the Redo matrix is lower than the same column in the $DSMR(t)$ that are below the diagonal (see lines 224 through 232 in Appendix A.7). Equations (3.7) and (3.8) are used by the software to determine the time and cost spent on first order rework.

$$T_1 = \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n FOV(i)T(j)RC(k) \quad (3.7)$$

$$C_1 = \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n FOV(i)C(j)RC(k) \quad (3.8)$$

3.3.4 Definition of 2nd Order Rework

Figure 3.13 shows an incidence of second order rework that can occur while completing the process in Fig. 2.10. Second order rework is the worst kind of rework because it involves repeating entire sets of tasks rather than single tasks like in first order rework. What occurs in incidences of second order rework is that the outputs of the last task in a loop are not to specification, but the first task needs input from the last task and all the tasks in the loop have to be repeated so that the last task's output is to specifications. With regards to the situation in Fig. 3.13, the following events occurs.

1. Task E is completed.
2. Task A is completed.
3. Task C is completed.
4. The input specifications of Task F are compared to the outputs of Task C.
5. The outputs of Task C are determined to be not to specifications.
6. Those using the process notice that Task E need inputs from Task C for Task E to be completed correctly.
7. Task E is repeated.
8. Task A is repeated.
9. Task C is repeated.

An assumption of this methodology is that it is possible that PBMs (interactions above a diagonal in a DSMTS) in a process are not always needed but occurs with a certain probability. It is possible that the tasks in a loop can be completed correctly without any rework needed.

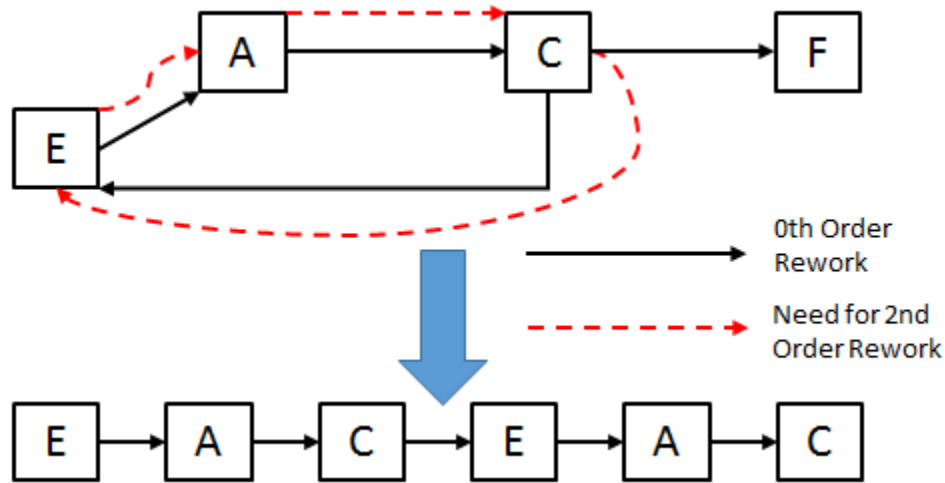


Figure 3.13: An Illustration Of A Situation Involving Second Order Rework.

Figure 3.14 contains the flowchart that the software uses to calculate second order rework. Eqs. (3.9) and (3.10) are used by the software to determine the time and cost spent on second order rework (see lines 237 through 248 in Appendix A.7). To determine if any incidences of second order rework has occurred, the upper halves (where row number is less than column number) of the $DSMR(t)$ for a given time and the Redo matrix are compared to each other. If an element in the Redo matrix, $Redo_{(r,c)}$ is lower than its corresponding element in the DSMR, $DSMR(t)_{(r,c)}$, then an incidence of second order rework has occurred and the task associated with the element's column has to be repeated. This is repeated for each row in the loop master other than the one for standalone tasks, hence the extra summation outside the brackets. While calculating the time and money spent on second order rework, only parts of the loop master rows, time vectors, cost vectors, and RC are needed. This makes the indexes of the sums go from r to c . An example of this is if the loop in Fig. 2.10 has to be reworked, then the index for l is from one to one (the loop master would have two rows, but only one is needed) and the other indexes would be from three to five. The terms with the *embedded* subscript ($T_{embedded}$ and $C_{embedded}$) represent the second order rework of the embedded loops of each loop master row. The index for those summations is for the number of embedded loops each clean loop contains, b .

$$T_2 = \sum_{l=1}^{m-1} \left[\sum_{i=r}^c \sum_{j=r}^c \sum_{k=r}^c LM(l, i)T(j)RC(k) + \sum_{a=1}^b T_{embedded} \right] \quad (3.9)$$

$$C_2 = \sum_{l=1}^{m-1} \left[\sum_{i=r}^c \sum_{j=r}^c \sum_{k=r}^c LM(l, i)C(j)RC(k) + \sum_{a=1}^b C_{embedded} \right] \quad (3.10)$$

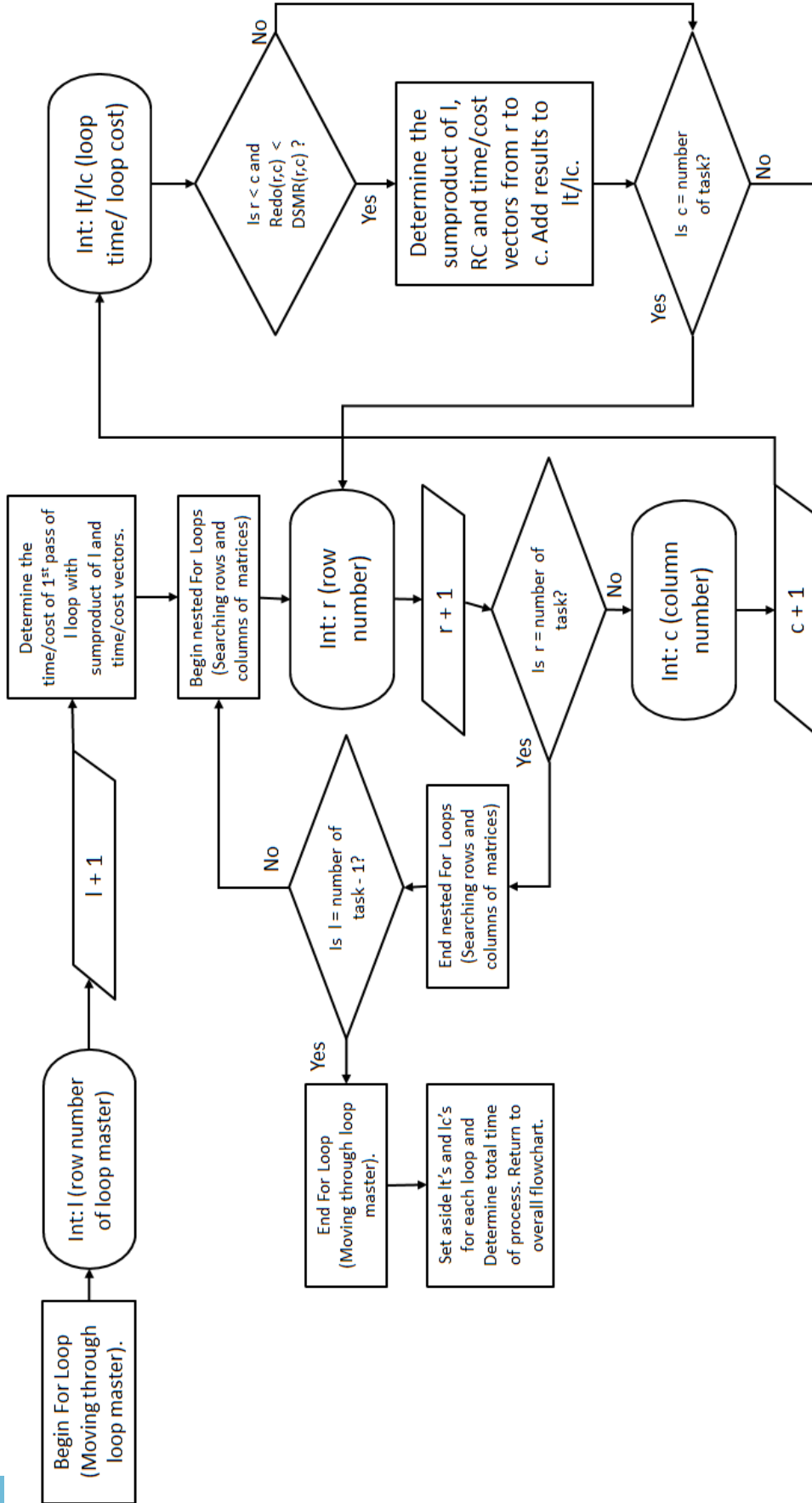


Figure 3.14: Flowchart Of Second Order Rework Calculation.

3.4 Checking If Process Design Becomes Obsolescent During Its Life

As time passes in the simulation, the distribution of the process's duration and cost will move and change shape. If an unwanted majority of the PDF moves outside predetermined duration and/or cost limits, then the process design will become obsolescent during its life and the process should be redesigned.

In the next chapter, a case study will be provided. The case study will first discuss the need for preparations to conduct the simulations and then how to do the simulations themselves.

CHAPTER 4

CASE STUDY AND PROGRAM DEMONSTRATION

For a better understanding of how to implement the methodology to a process and determine whether or not the process's design will become obsolescent during its operational life, a case study will be used. The case study was first started by Rogers [26] where only an optimization considering task sorting was discussed. Later, Obeng [27] used the DSM used by Rogers's case study, assigned properties to the task, and implemented the methodology discussed in the previous chapter with success. The purpose of the case study in this dissertation is to provide a more precise discussion of the case study Obeng [27] made and add some extensions. To be able to implement the methodology, some prior preparation is needed. The first section (Section 4.1) will explain how the task order was optimized with the software presented in the appendix. The second section (Section 4.2) will discuss how the loop master was assembled for the case study. In the third section (Section 4.3), a discussion of how the methodology was implemented to create a single data point for a simulation. This section will show the task information needed to conduct the simulations and the Appendix will show how these are made into inputs for the software made to automate the simulations. The fourth section (Section 4.4) will also show what happens if obsolescence is included and neglected. The fifth section (Section 4.5) will contain a sensitivity analysis. The last section (Section 4.6) will discuss the results of the case study.

4.1 DSM Optimization For Case Study

4.1.1 DSMTS Before Optimization

Figure 4.1 was made by Rogers [26] and contains the DSMTS before it was optimized. Figure A.1 shows how the DSM in Fig. 4.1 is entered into Microsoft Excel so that the software can conduct the optimization, assemble the loop master, and do the simulations.

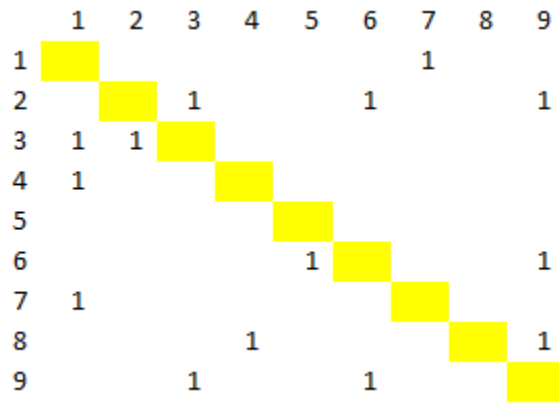


Figure 4.1: Unsolved DSMTS For Case Study. (Made by Rogers [26])

4.1.2 DSMTS After Optimization

Figure 4.2 was made by Obeng [27] and contains the DSMTS after it was optimized and the task order was found acceptable. Because the given optimizer does not always converge to solution given the number of generations allowed to calculate and/or population size, the optimized DSMTS has to be examined and found acceptable before anything can be done. The case study used 100 generations and a population size of 100 individuals. The following criteria can be used in determining if the process order is acceptable.

1. Most starting tasks (tasks that need no inputs) are within the first 25% of the sequence. For example, if a process has 100 tasks, then this task order is not rejected if most starting tasks are within the first 25 slots.
2. Most ending tasks (tasks that give no outputs) are within the last 25% of the sequence. For example, if a process has 100 tasks, then this task order is not rejected if most ending tasks are within the last 25 slots.

The tasks are in an optimized order if both of these criteria are satisfied. Increasing the population size and number of generations can make finding solutions easier if acceptable DSMTS cannot be found. After optimizing the DSMTS for the case study, the score went down from

48 to 30 and the PBM went down from 42.9% to 21.4%. The software outputs many metrics about the process to the Excel file that has the simulation inputs.

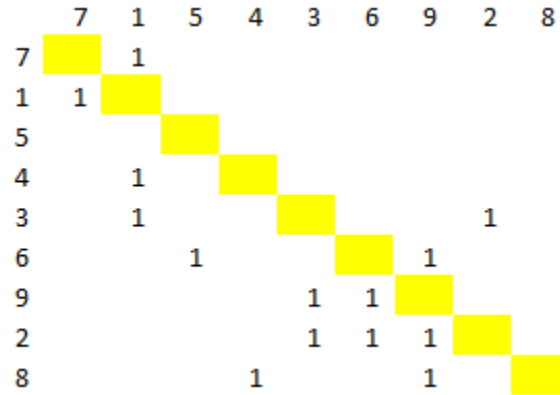


Figure 4.2: Solved DSMTS For Case Study. (Made by Obeng [27])

4.2 Creation of Loop Master For Case Study

4.2.1 Looking For Coupled Pairs For Case Study

The process in the case study has three coupled pairs. They are made of Task 7 and 1 (because $DSMTS_{(1,2)}$ and $DSMTS_{(2,1)}$ both nonzero), Tasks 3 and 2 (because $DSMTS_{(5,8)}$ and $DSMTS_{(8,5)}$ both nonzero), and Tasks 6 and 9 (because $DSMTS_{(6,7)}$ and $DSMTS_{(7,6)}$ both nonzero).

4.2.2 Filling Loop Master Powers of Adjacency Matrix For Case Study

Table 4.1 contains the loop master for this case study after using the powers of adjacency matrix method. As shown, the loop master has not yet been organized. Each row represents a power of the adjacency matrix and the elements represent the power's diagonal. For example, the second power of the adjacency matrix have ones in the diagonals for Tasks 7, 1, 3, 9, 6, and

2 implying that they are two steps from each other.

Table 4.1: Loop Master Filled Out After Using Powers Of Adjacency Matrix Method In Case Study.

Power	7	1	5	4	3	6	9	2	8
1	0	0	0	0	0	0	0	0	0
2	1	1	0	0	1	1	1	1	0
3	0	0	0	0	1	0	1	1	0
4	1	1	0	0	1	1	1	1	0
5	0	0	0	0	1	1	1	1	0
6	1	1	0	0	1	1	1	1	0
7	0	0	0	0	1	1	1	1	0
8	1	1	0	0	1	1	1	1	0
9	0	0	0	0	1	1	1	1	0

4.2.3 Finding Standalone Tasks and Correcting Loop Master For Case Study

Based on the sums of the columns in the loop master in Table 4.1 Tasks 5, 4, and 8 are standalone tasks because they are not part of any loop.

Because the powers of the adjacency matrix method are not perfect, some extra steps have to be taken to ensure that the final edition of the loop master is correct. The first step is to look for rows whose sum is the same as its power. In this case, it is the sixth row. Here, DSMTS locations are made with the column numbers of first and last non zero columns. By looking at $DSMR_{(1,7)}$ and noticing that it is filled with a zero, the sixth row has connected loops and not one loop that has six tasks. That corresponding row and its duplicates in higher powers (rows four and eight) are removed by filling it with zeros.

The second step taken in correcting the loop master is removing rows whose sum is higher than the row's power. Here, the second row is removed for that reason. It has the coupled pairs

entangled. After this point, row number does not represent power of the adjacency matrix. Here, extra rows representing coupled pairs are added to ensure that they are not skipped before determining which loops are embedded. Table 4.2 contains the loop master for the case study after the connected loops are removed and the coupled pairs are added.

Table 4.2: Case Study Loop Master Filled Out After Connected And Duplicate Loops Are Removed.

Row	7	1	5	4	3	6	9	2	8
1	0	0	0	0	1	0	1	1	0
2	0	0	0	0	1	1	1	1	0
3	1	1	0	0	0	0	0	0	0
4	0	0	0	0	1	0	0	1	0
5	0	0	0	0	0	1	1	0	0

4.2.4 Finding Embedded Loops For Case Study

To determine which loops are embedded, each row in the loop master is added to every other. If the resulting vector contains any twos, then one of an embedded loop has been found. The loop with few tasks is the embedded loop. Such a situation in the case study is shown in Table 4.3. The first and second rows of the loop master were added. By the twos in the last row in Table 4.3 representing Tasks 3, 9, and 2, those tasks are embedded in a loop that is made of Tasks 3, 6, 9, and 2. The embedded loop is removed to prevent double counting when calculating second order rework.

Table 4.3: A Found Embedded Loop For Case Study.

Row	7	1	5	4	3	6	9	2	8
1	0	0	0	0	1	0	1	1	0
2	0	0	0	0	1	1	1	1	0
Sum	0	0	0	0	2	1	2	2	0

Table 4.4 shows two loops that are not embedded. The second and third rows were added together. These loops were found to be not connected because the resulting vector does not have any twos.

Table 4.4: Two Loops That Are Not Embedded In Case Study.

Row	7	1	5	4	3	6	9	2	8
2	0	0	0	0	1	1	1	1	0
3	1	1	0	0	0	0	0	0	0
Sum	1	1	0	0	1	1	1	1	0

4.2.5 Final Assembly of Loop Master For Case Study

After taking the loop master from Table 4.4, adding a row for the standalone tasks, and assigning classes to the loops, the final loop master for the case study by Obeng [27] is obtained and shown in Table 4.5. Figure 4.3 contains the digraph for this case study with the clean loops shown.

Table 4.5: Completed Loop Master For Case Study. (Made by Obeng [27])

Task ID	7	1	5	4	3	6	9	2	8
1	0	0	0	0	1	1	1	1	0
Class 2	1	1	0	0	0	0	0	0	0
3	0	0	1	1	0	0	0	0	1

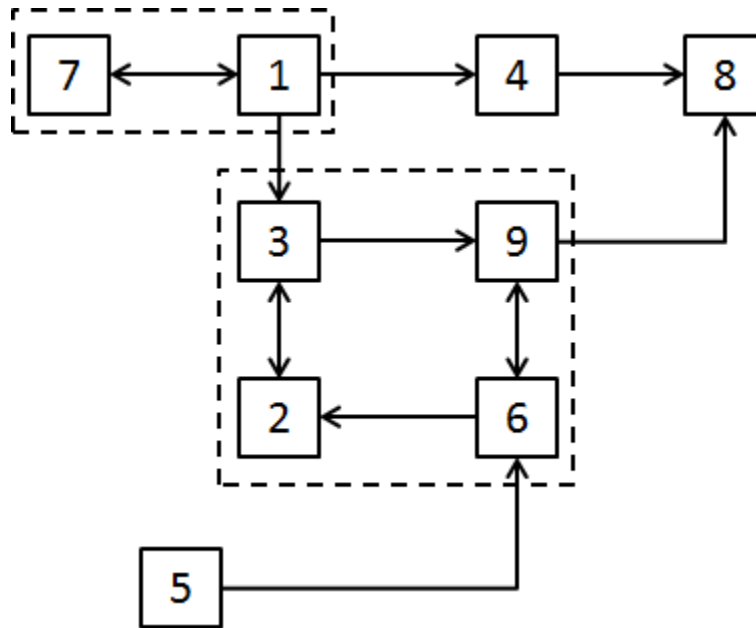


Figure 4.3: Digraph For Case Study With Clean Loops Shown.

4.3 Example of Data Set Creation For Case Study

4.3.1 Task Information and Preparation For Case Study

Tables 4.6 and 4.7 were made by Obeng [27] and contain the duration and cost of each of the tasks respectively. The joint PDFs for the case study will have the total process duration in years.

Table 4.6: Duration Of Individual Tasks In Years. (Made by Obeng [27])

Task	Min(Years)	Expected (Years)	Max (Years)
1	0.074763	0.07668	0.078597
2	0.11502	0.15336	0.17253
3	0.13419	0.1917	0.28755
4	0.01917	0.05751	0.061344
5	0.1917	0.23004	0.30672
6	0.09585	0.11502	0.13419
7	0.017253	0.01917	0.028755
8	0.13419	0.17253	0.193617
9	0.01917	0.03834	0.07668

Table 4.7: Cost Of Individual Tasks In 1000's OF USD. (Made by Obeng [27])

Task	Min	Expected	Max
1	30	40	50
2	50	100	101
3	10	20	22
4	114	150	177
5	25	30	36
6	40	55	90
7	9	10	12
8	25	35	40
9	15	19	20

Table 4.8 was made by Obeng [27] and contains the rework coefficients, growth rate of failure curves and maturity time of tasks in the case study. These parameters are assumed as such in our case study.

Table 4.8: RC'S, Technology Rates, And Maturities Of Tasks For Case Study. (Made by Obeng [27])

Task	RC	Rate	Maturity (Years)
1	20	0.3	10
2	50	1	18
3	80	1.5	15
4	100	0.4	-10
5	10	1.1	5
6	25	0.8	6
7	78	0.25	-2
8	6	1.8	50
9	10	0.75	1

Figures 4.4, 4.5, 4.6 were also made by Obeng [27] contains the DSMRtart, DSMRate, and DSMMAT respectively for the case study.

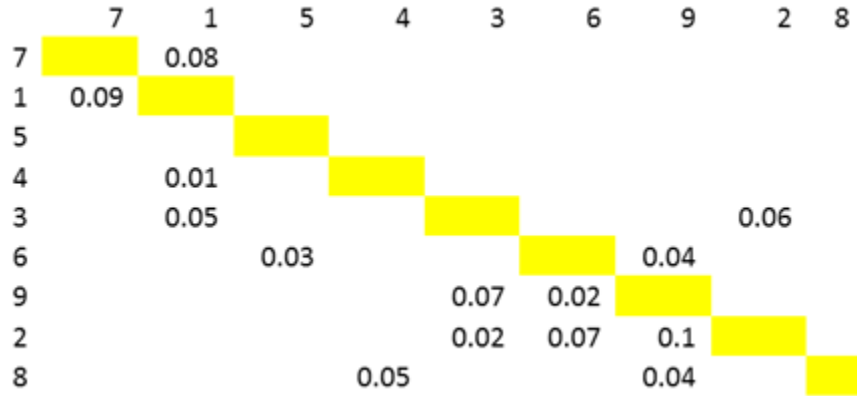


Figure 4.4: DSMRStart For Case Study. (Made by Obeng [27])

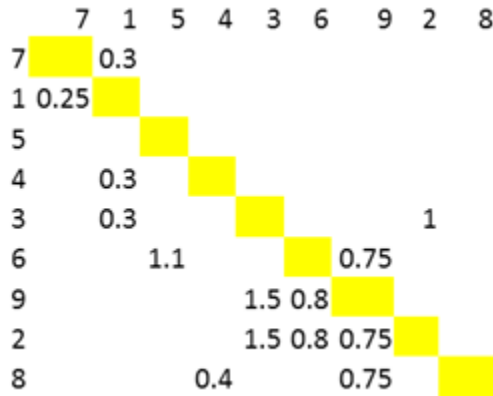


Figure 4.5: DSMRate For Case Study. (Made by Obeng [27])

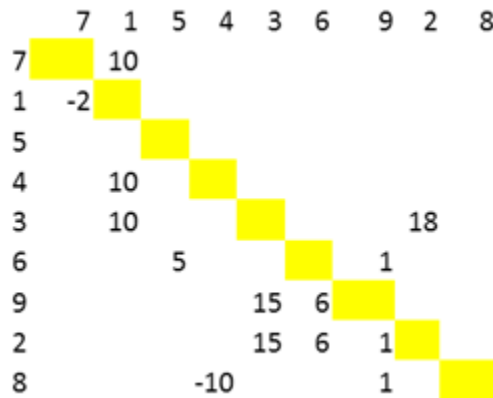


Figure 4.6: DSMMAT For Case Study. (Made by Obeng [27])

Table 4.9 was made by Obeng [27] and contains the time and cost vectors that will be used for this case study. When determining the time and cost of the process, the components of these vectors and the RC shown in Table 4.10 must be arranged to match the order of tasks in the optimized DSMTS.

Table 4.9: Time And Cost Vectors With Labels For Case Study. (Made by Obeng [27])

Task Order	1	2	3	4	5	6	7	8	9
Task Name	7	1	5	4	3	6	9	2	8
Time Vector Component, $T(j)$	0.02	0.077	0.23	0.03	0.25	0.11	0.05	0.115	0.07
Cost Vector Component, $C(j)$	11	33	27	140	21	55	18	75	30

Table 4.10: Rework Coefficient Vector With Labels For Case Study. (Made by Obeng [27])

Task Order	1	2	3	4	5	6	7	8	9
Task Name	7	1	5	4	3	6	9	2	8
Rework Coefficients Vector Component, $RC(k)$ (%)	78	20	10	100	80	25	10	50	6

The data set will be calculated in this case study at the start of the process's life (at year zero). The DSMR(0) (Design Structure Matrix for Rework at year zero) has to be determined. It is more accurate to use this to determine the probability of rework than the DSMRStart because all the technologies used to complete the tasks might not start at the same time. To determine DSMR(0), Eq. (3.2) is evaluated at zero for all non-zero elements and those that are not on the diagonal. Equations (4.1) and (4.2) show a sample calculation for the probability of rework of Task 1 because of mistakes in Task 7 at start of operational life. Figure 4.7 made by Obeng [27] has the entire DSMR(0) that will be used for the case study.

$$DSMR(0)_{(2,1)} = \frac{1 - DSMRStart_{(2,1)}}{1 + e^{-DSMRate_{(2,1)}(0 - DSMMAT_{(2,1)})}} + DSMRStart_{(2,1)} \quad (4.1)$$

$$0.656 = \frac{1 - 0.09}{1 + e^{-0.25(0 - -2)}} + 0.09 \quad (4.2)$$

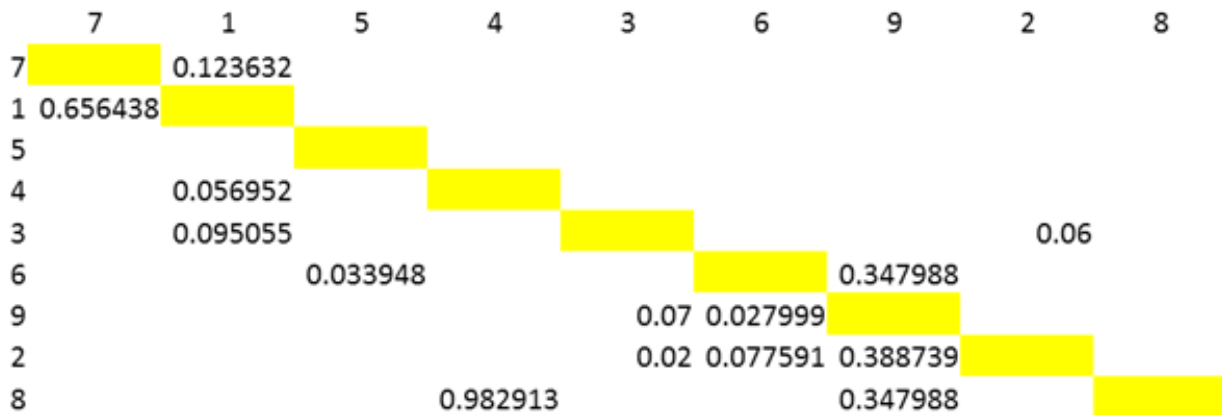


Figure 4.7: Entire DSMR(0) For Case Study. (Made by Obeng [27])

Figure 4.8 by Obeng [27] shows the Redo matrix for this case study. The elements were generated at random. The feedforward interactions to compare are highlighted in blue and the feedback interactions in orange.

4.3.2 Calculation of 0th Order Rework For Case Study

Equations (4.3), (4.4), and (4.5) show the calculations to determine the duration of zeroth order rework for the case study. The index was set from one to nine because the process has nine tasks. To determine the cost of first order rework, replace the time vector with the cost vector to \$410k for the cost of zeroth order rework.

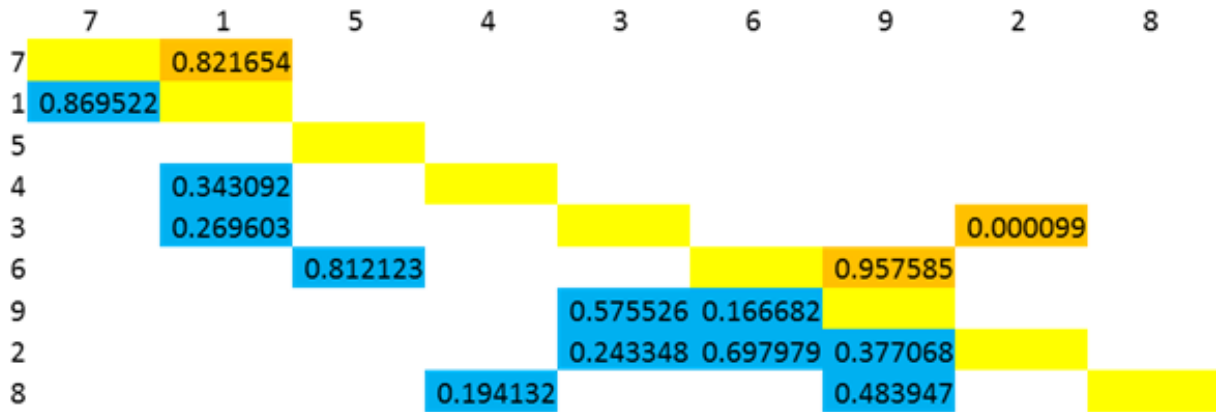


Figure 4.8: Redo Matrix For Case Study. (Made by Obeng [27])

$$T_0 = \sum_{i=1}^9 T(i) \quad (4.3)$$

$$T_0 = 0.02 + 0.077 + 0.23 + 0.03 + 0.25 + 0.11 + 0.05 + 0.115 + 0.07 \quad (4.4)$$

$$T_0 = 0.952 \text{ years} \quad (4.5)$$

4.3.3 Calculation of 1st Order Rework For Case Study

To be able to determine the time and money wasted on first order rework, the First Order Vector (FOV) has to be created. To determine which tasks are repeated due to first order rework, the lower half of DSMR and the lower half of the Redo matrix are compared and if any elements of the Redo matrix are lower than the DSMR, then the tasks associated with those elements' columns have to be reworked. Comparing the bottom rows of the two matrices in Figs. 4.7 and 4.8 respectively shows that Tasks 4 and 9 have to be reworked once. The FOV is shown for the case study in Table 4.11 made by Obeng [27]. No other tasks have to be reworked in terms of the first order.

Table 4.12 by Obeng [27] shows the calculation of time wasted due to first order rework that

Table 4.11: First Order Vector For Case Study. (Made by Obeng [27])

Task Order	1	2	3	4	5	6	7	8	9
Task Name	7	1	5	4	3	6	9	2	8
1st Order Rework Vector Component	0	0	0	1	0	0	1	0	0

uses Eq. (3.7). It is a triple sumproduct calculation that involves the FOV, RC, and time vectors. The sum is in years. Replacing the time vector with the cost vector will show that the money wasted by doing first order rework is \$142k.

Table 4.12: Table Showing Calculation Of Time Wasted By First Order Rework. (Made by Obeng [27])

Task Order	1	2	3	4	5	6	7	8	9	
Task Name	7	1	5	4	3	6	9	2	8	Sum
Vector Component Multiplication	0	0	0	1(1)(0.03)	0	0	1(0.1)(0.05)	0	0	0.035

4.3.4 Calculation of 2nd Order Rework And Total Work For Case Study

To determine which tasks are repeated due to second order rework, the upper half of DSMR and the upper half of the Redo matrix are compared and if any elements of the Redo matrix are lower than the DSMR, then the tasks associated with those elements' columns have to be reworked. It is not the same as for first order rework. The loop master is used to calculate the time and money wasted due to second order rework instead of the FOV. When an incidence of second order rework is found during the comparison, the sumproducts of the loop master row that contains the tasks are involved, the RC, and the time or cost vector. The index is from the row number the incident to the column number of the incident's element as shown in Eq.

(3.9).

An example of an incident of second order rework that can be found by seeing that $Redo_{(5,8)}$ is less than $DSMR(0)_{(5,8)}$. This means that the fifth through eighth tasks in the sequence (Tasks 3, 6, 9, and 2) have to be repeated. Table 4.13 shows the calculation of second order rework. The sum is in years. The terms related to the embedded loops is equal to zero because $Redo_{(6,7)}$ is greater than $DSMR(0)_{(6,7)}$. Replace the T with C and cost of repeating this loop will be \$69.85k.

Table 4.13: Table Showing Calculation Of Time Wasted By Second Order Rework. (Made by Obeng [27])

Task Order Index	5	6	7	8	Sum
Task Name	3	6	9	2	
Vector Component	1(0.8)(0.25)	1(0.25)(0.11)	1(0.1)(0.05)	1(0.5)(0.115)	
Multiplication					

The total duration of the process for the data point is calculated by adding the duration of each order of rework as shown in Eqs. (4.6) and (4.7). The total cost of the process for this data point is \$621.85k.

$$T_{total} = 0.952 + 0.035 + 0.29 \quad (4.6)$$

$$T_{total} = 1.27 \text{ years} \quad (4.7)$$

4.4 Generation of Process Joint Duration/Cost Distribution Plots For Case Study

4.4.1 Process Joint Duration/Cost Distribution Plots Including Obsolescence

For this case study, the bounds of the process's total duration and cost for this case study are assumed to be 1.7 years and \$750k respectively. The process life is 20 years. 10,000 Monte Carlo simulations were conducted to generate each PDF in the case study. Figures 4.9 through 4.17 by Obeng [27] show the DSMR's and resulting PDFs for duration and cost of completing the process. The interval of interest is five years. As the process's life progressed, the duration and cost increased because the probability of rework increased. The process's design would be considered obsolete at the end of life (see Fig. 4.17) because an unwanted majority of the distribution went above the acceptable thresholds. The least likely data points are blue and the most likely data points are dark red.

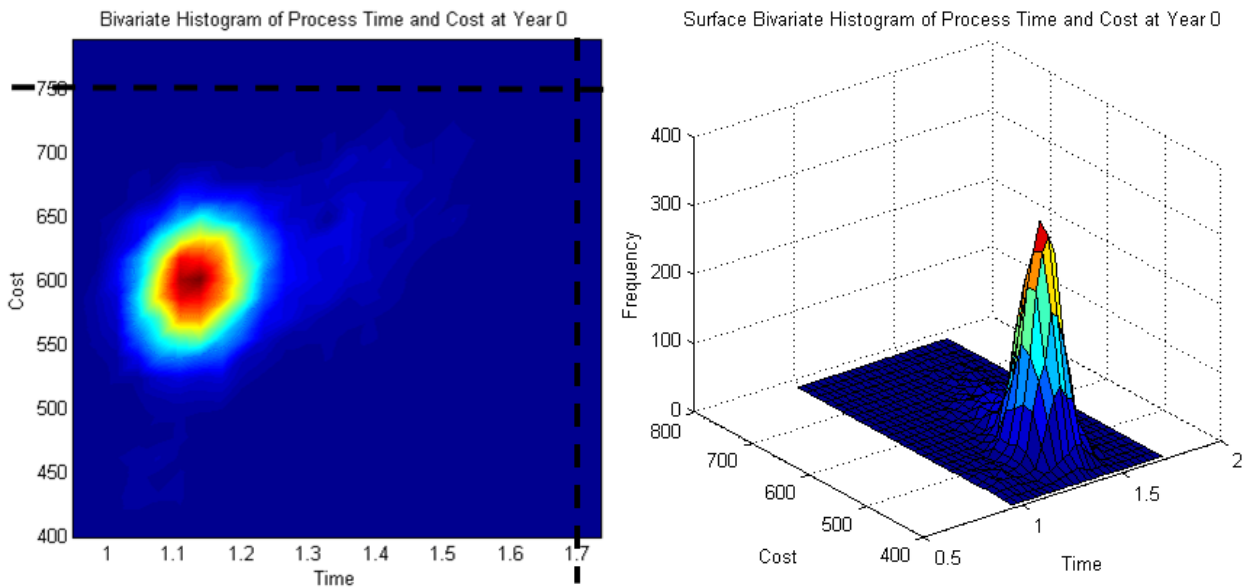


Figure 4.9: Bivariate Histogram With Constraints At Year 0 Of Case Study. (Made by Obeng [27])

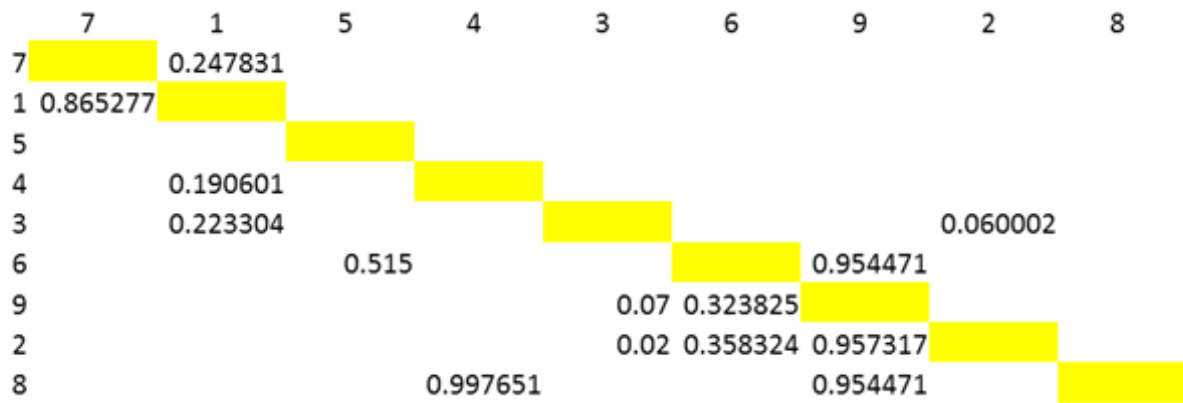


Figure 4.10: DSMR(5) Of Case Study. (Made by Obeng [27])

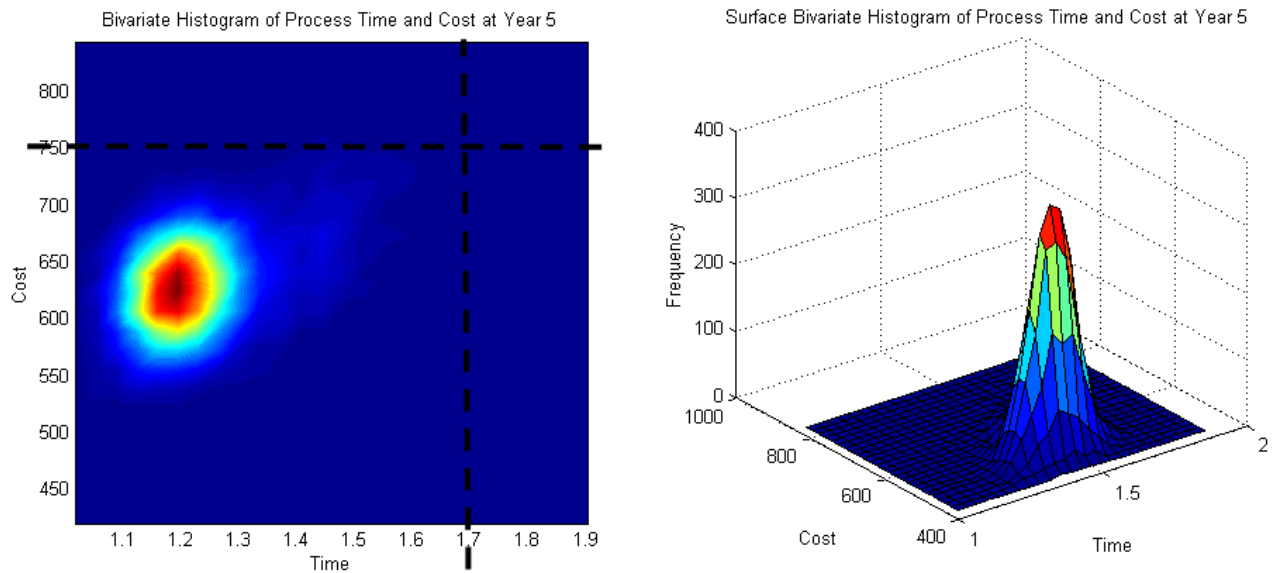


Figure 4.11: Bivariate Histogram With Constraints At Year 5 Of Case Study. (Made by Obeng [27])

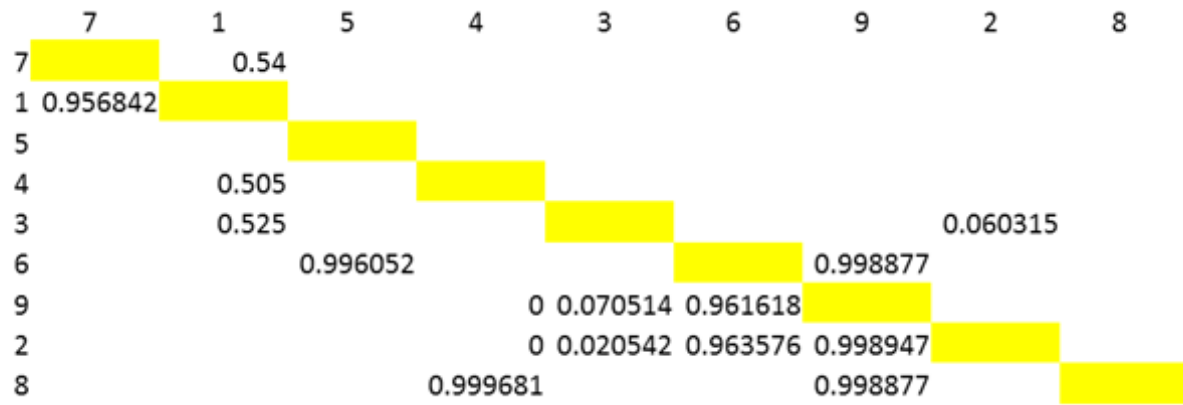


Figure 4.12: DSMR(10) Of Case Study. (Made by Obeng [27])

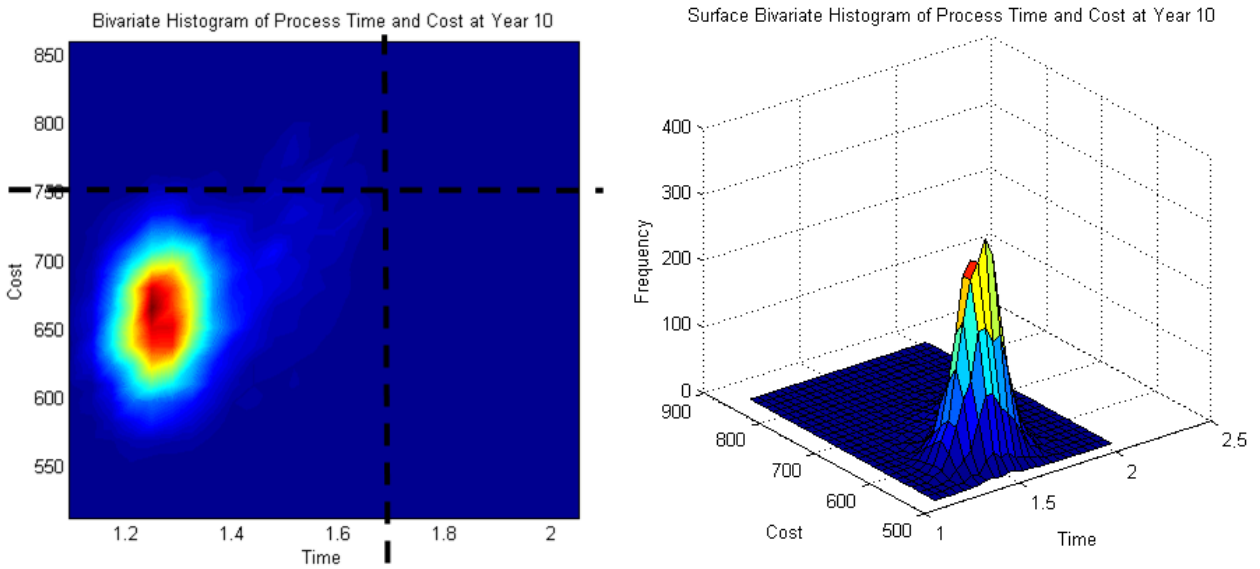


Figure 4.13: Bivariate Histogram With Constraints At Year 10 Of Case Study. (Made by Obeng [27])

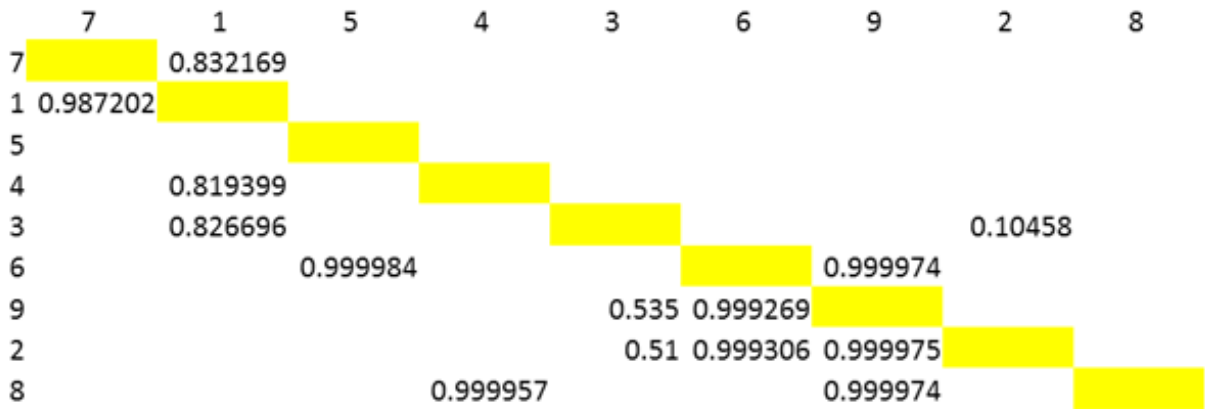


Figure 4.14: DSMR(15) Of Case Study. (Made by Obeng [27])

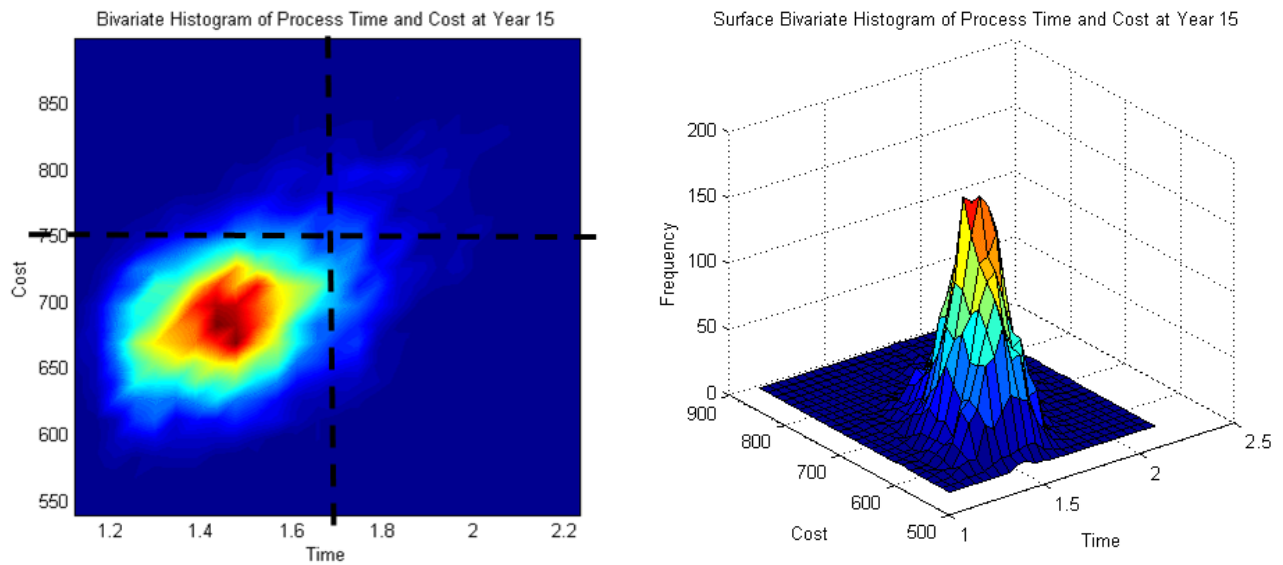


Figure 4.15: Bivariate Histogram With Constraints At Year 15 Of Case Study. (Made by Obeng [27])

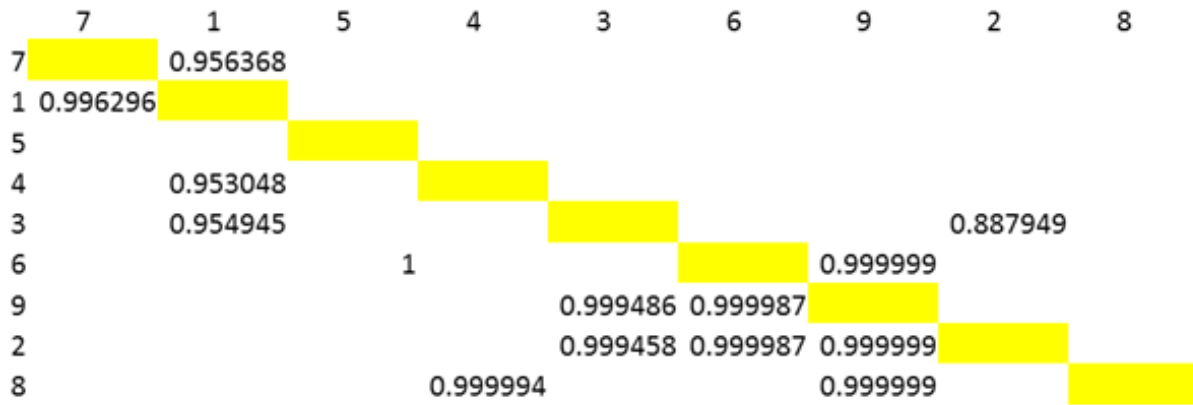


Figure 4.16: DSMR(20) Of Case Study. (Made by Obeng [27])

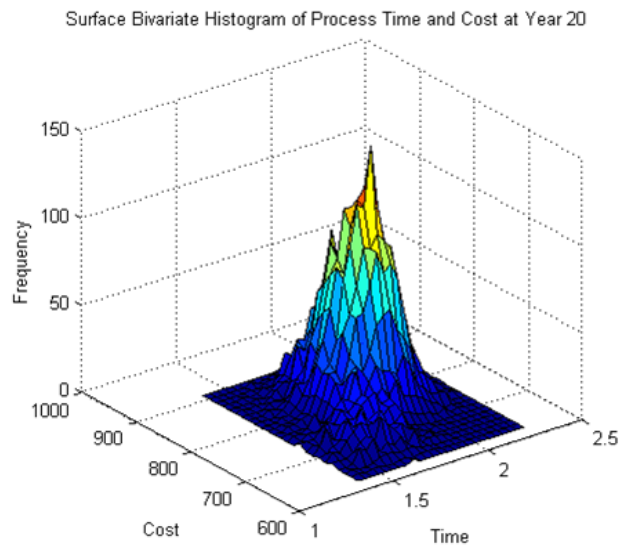
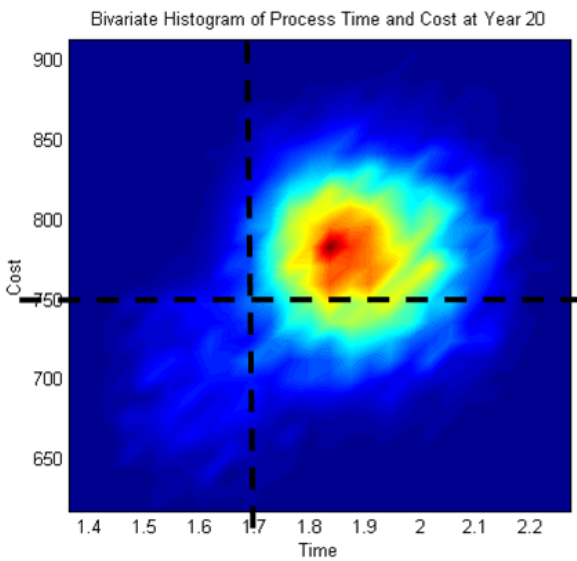


Figure 4.17: Bivariate Histogram With Constraints At Year 20 Of Case Study. (Made by Obeng [27])

4.4.2 Process Joint Duration/Cost Distribution Plots Not Considering Obsolescence

To simulate what the process's duration and cost PDFs would look like if device obsolescence was neglected and considering only device mortality, shifts in failure curves were used. To create the failure curve shifts, the technology rates from Table 4.8 were divided by three and the maturities were increased by 25%. Figures 4.18 to 4.27 by Obeng [27] show the DSMRs for each time interval and their respective duration and cost PDFs.

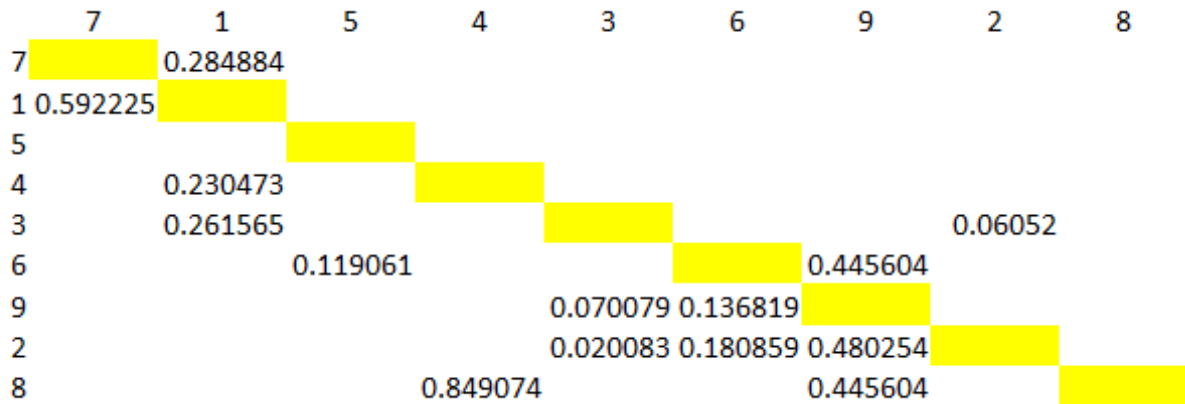
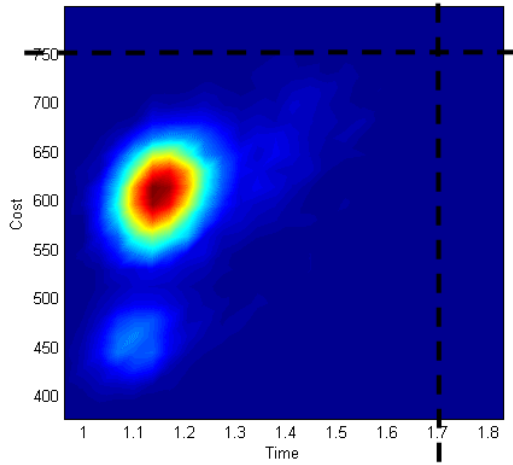


Figure 4.18: DSMR(0) Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

Bivariate Histogram of Process Time and Cost Excluding Obsolescence at Year 0



Surface Bivariate Histogram of Process Time and Cost Excluding Obsolescence at Year 0

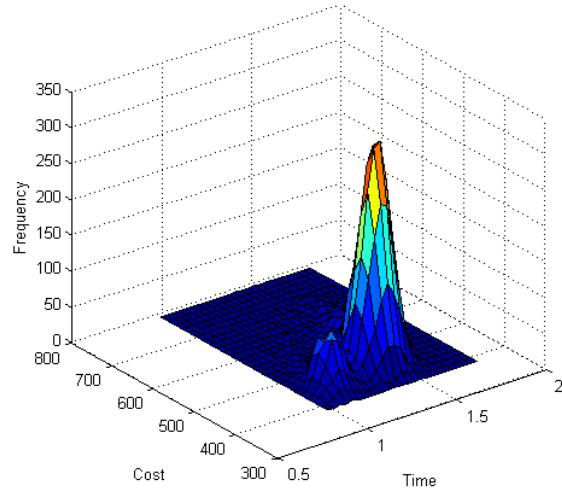


Figure 4.19: Bivariate Histogram With Constraints At Year 0 Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

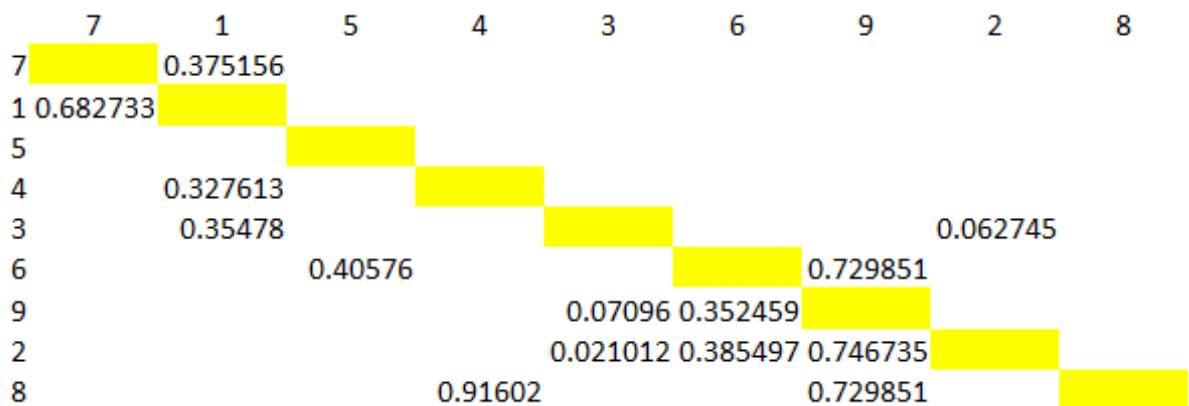


Figure 4.20: DSMR(5) Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

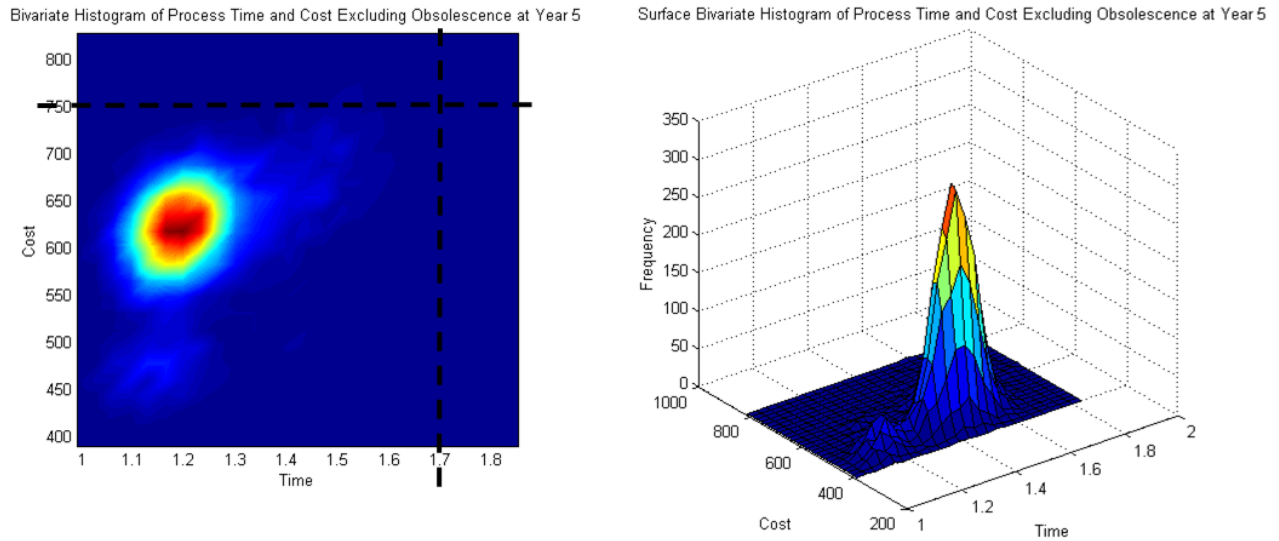


Figure 4.21: Bivariate Histogram With Constraints At Year 5 Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

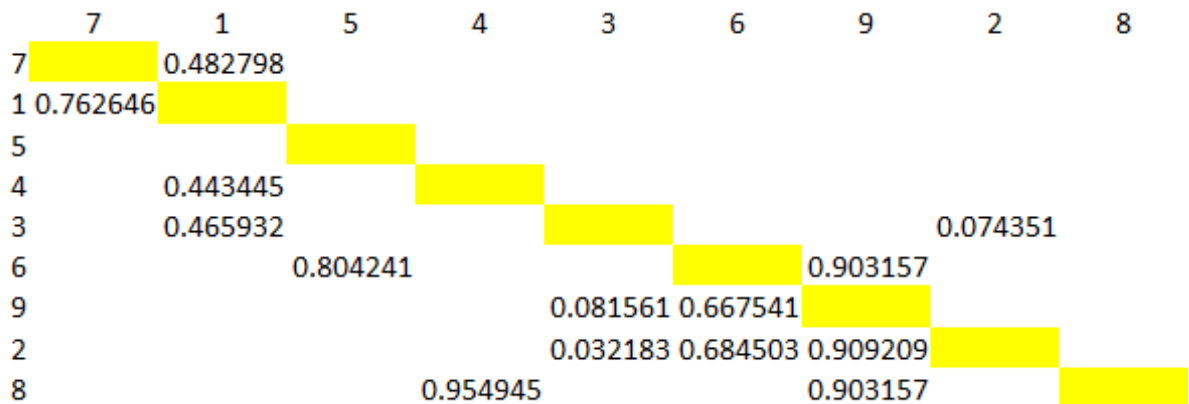


Figure 4.22: DSMT(10) Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

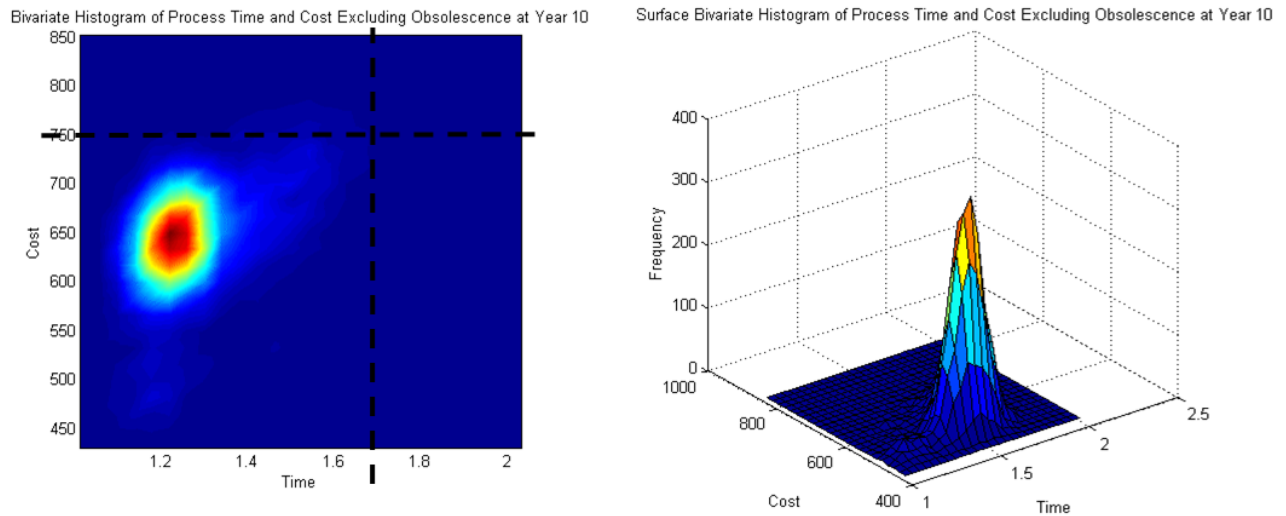


Figure 4.23: Bivariate Histogram With Constraints At Year 10 Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

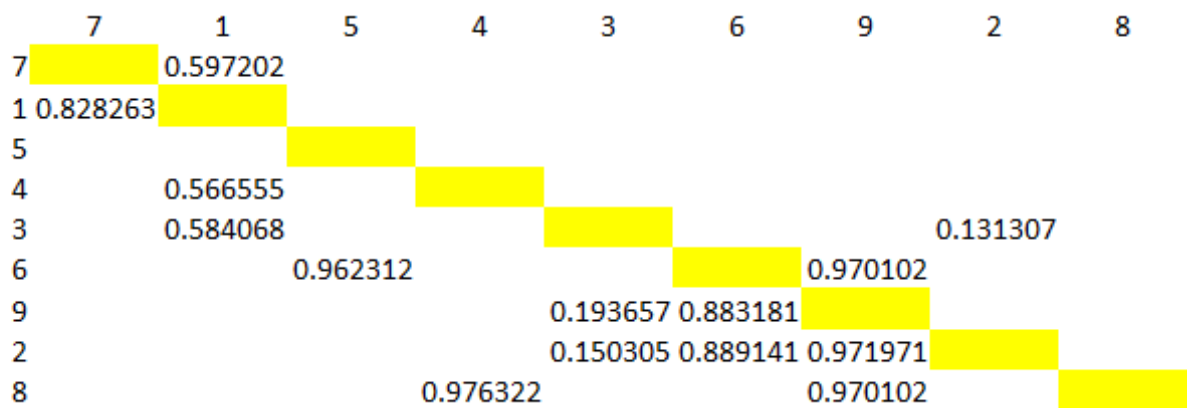


Figure 4.24: DSMR(15) Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

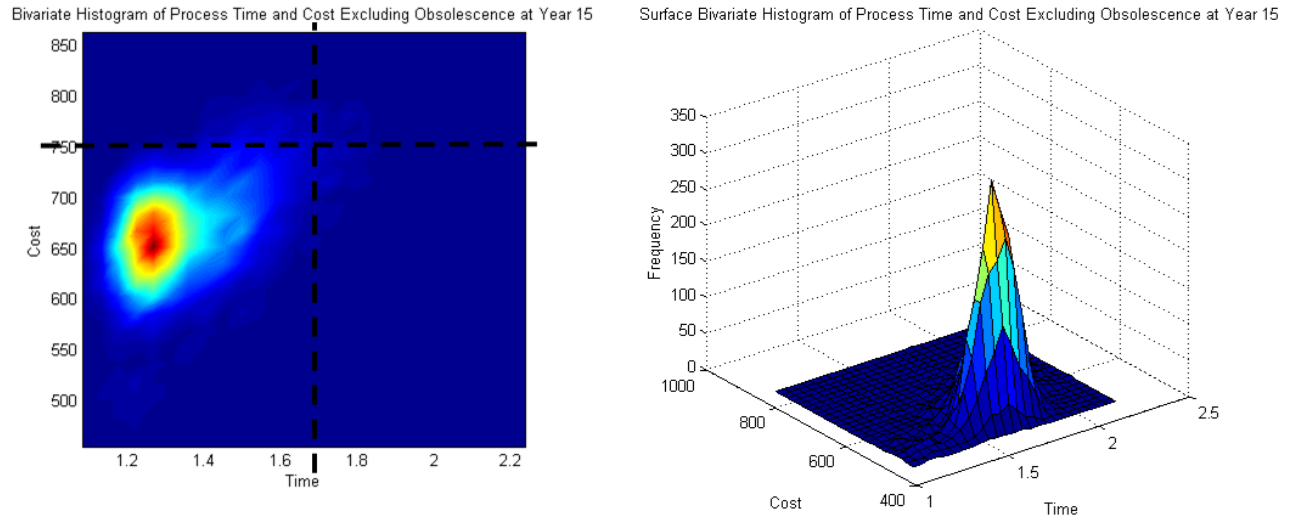


Figure 4.25: Bivariate Histogram With Constraints At Year 15 Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

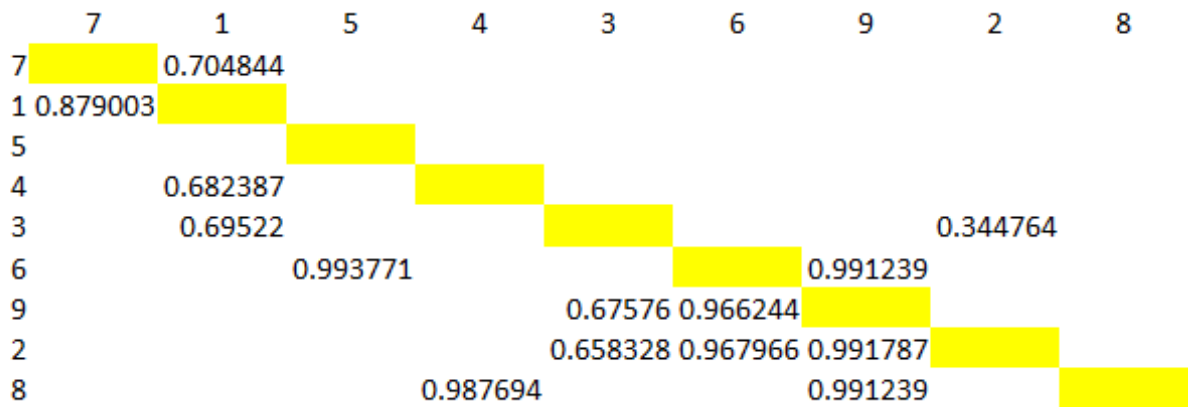
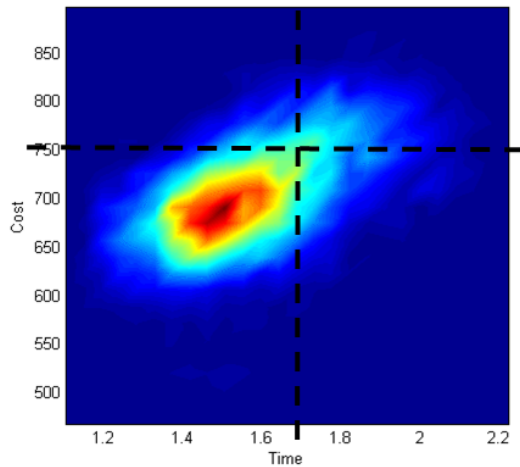


Figure 4.26: DSMR(20) Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

Bivariate Histogram of Process Time and Cost Excluding Obsolescence at Year 20



Surface Bivariate Histogram of Process Time and Cost Excluding Obsolescence at Year 20

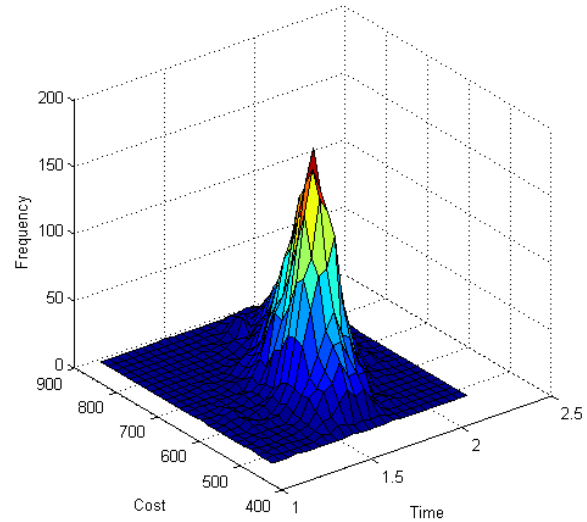


Figure 4.27: Bivariate Histogram With Constraints At Year 20 Of Case Study Not Considering Obsolescence. (Made by Obeng [27])

4.5 Sensitivity Analysis For Case Study

4.5.1 Manipulating Rework Coefficients

Figures 4.28 through 4.32 were created by making intervals from the area of most concern (red and dark red areas) after PDFs made from changing the Rework Coefficients by ± 5 and 10 percent were examined. This was done to prevent clutter from placing multiple plots in a single figure. In these figures, the expected values are coincident with each other.

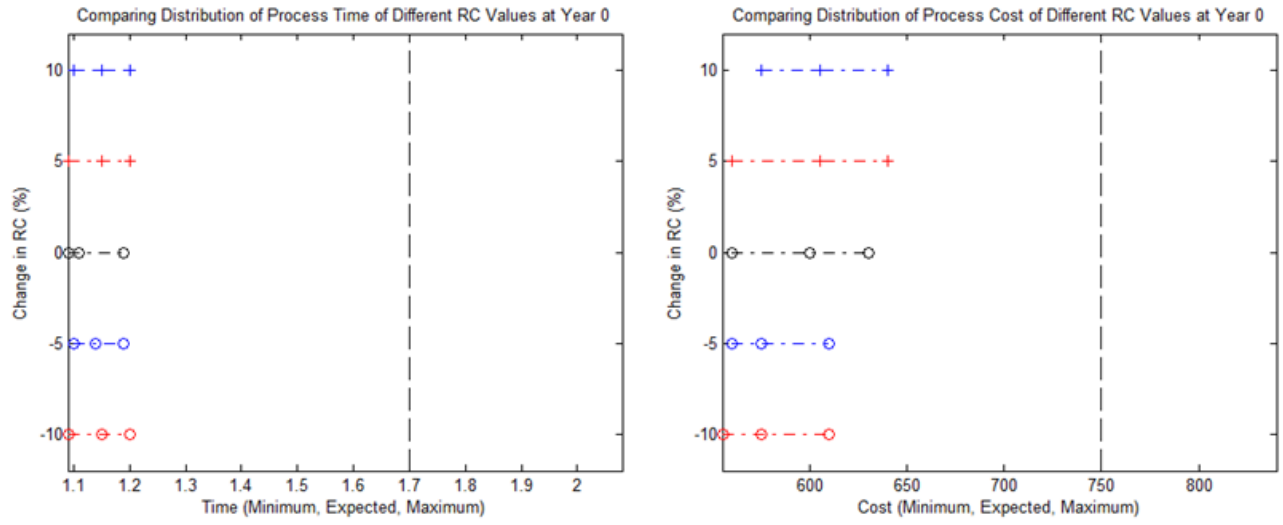


Figure 4.28: A Comparison Of Duration/Cost Distributions Of Different Rework Coefficients At Year 0.

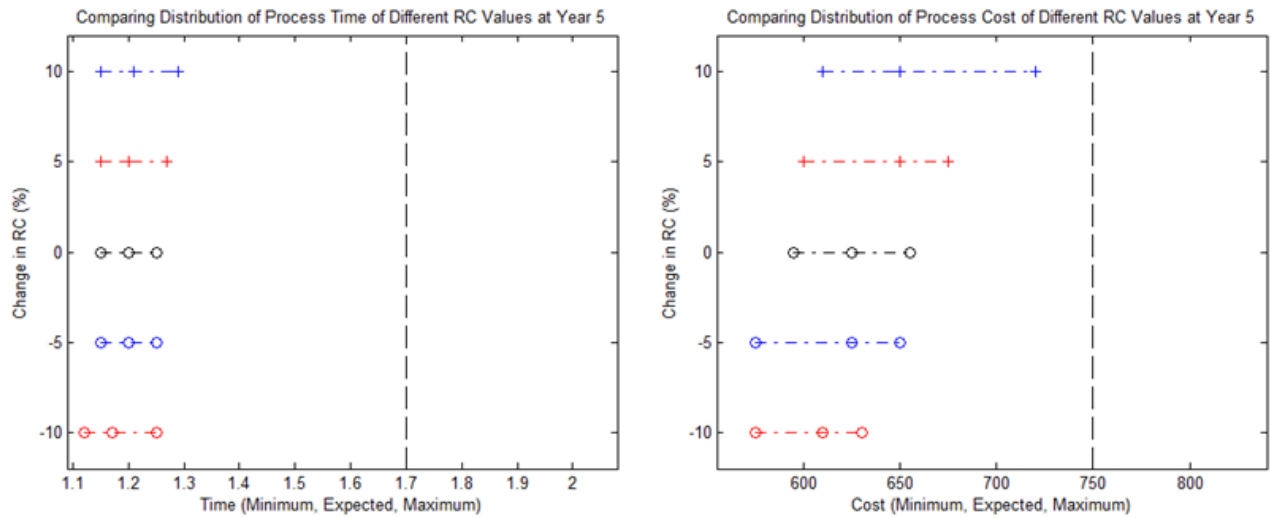


Figure 4.29: A Comparison Of Duration/Cost Distributions Of Different Rework Coefficients At Year 5.

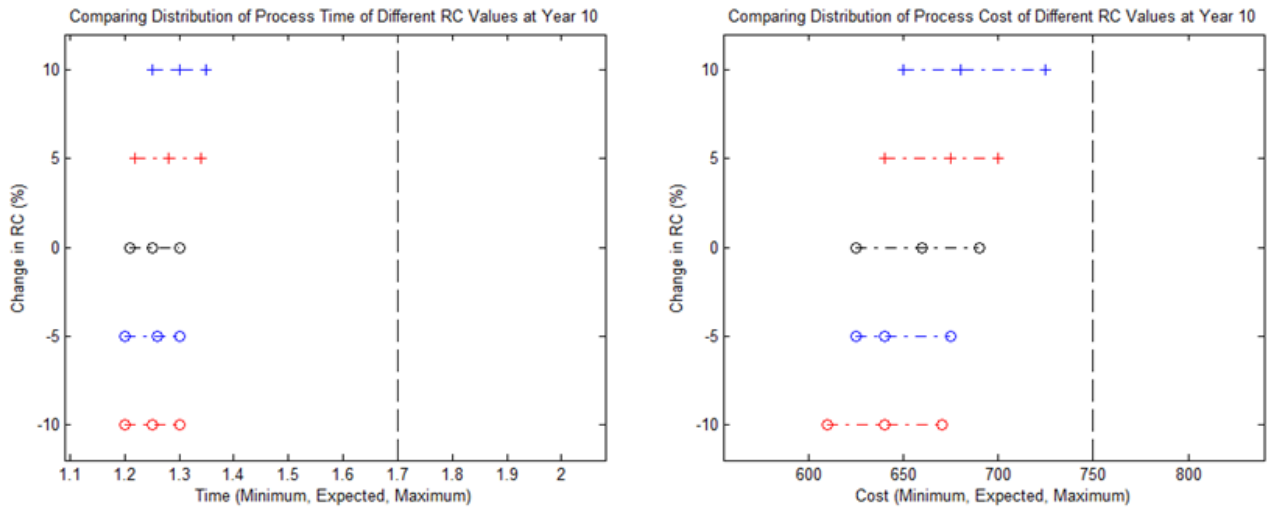


Figure 4.30: A Comparison Of Duration/Cost Distributions Of Different Rework Coefficients At Year 10.

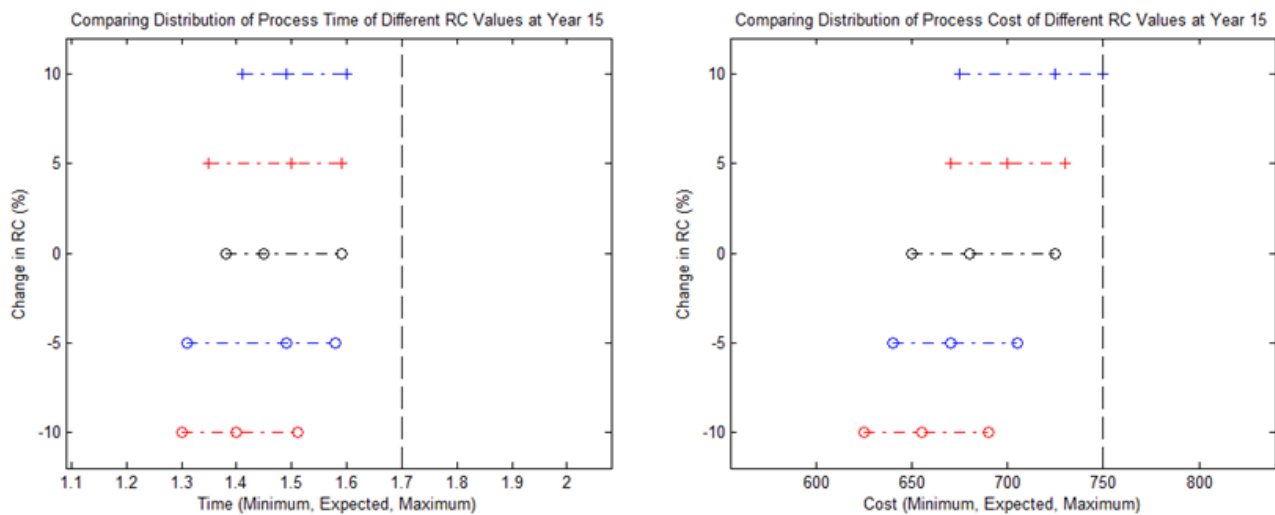


Figure 4.31: A Comparison Of Duration/Cost Distributions Of Different Rework Coefficients At Year 15.

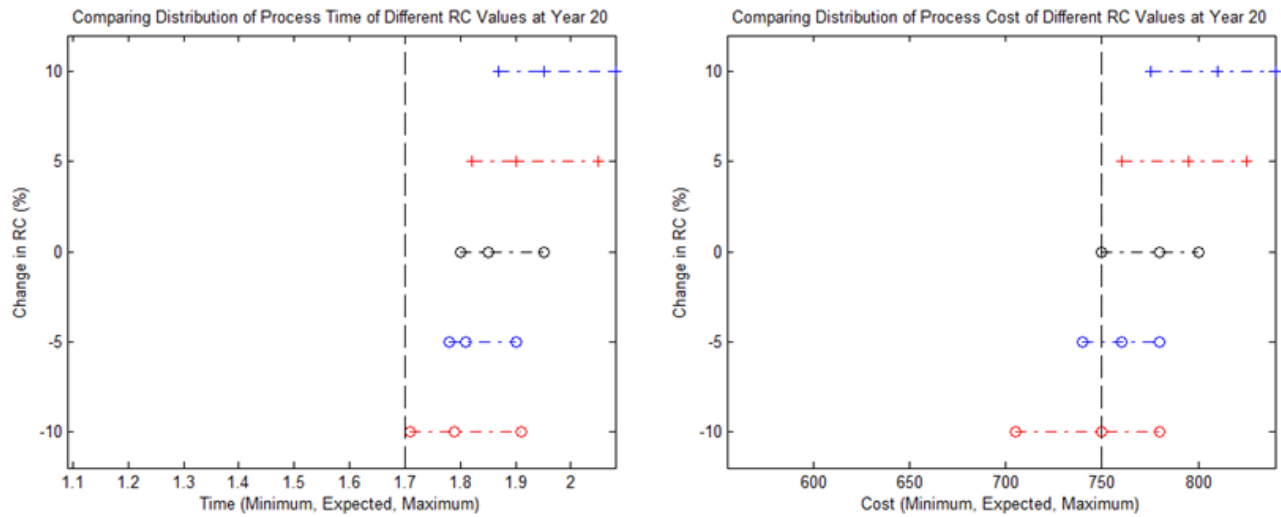


Figure 4.32: A Comparison Of Duration/Cost Distributions Of Different Rework Coefficients At Year 20.

4.5.2 Manipulating Failure Curve Rates

Figures 4.33 through 4.37 were created by making intervals from the area of most concern (red and dark red areas) after PDFs made from changing the rates of the failure curves by \pm 5 and 10 percent were examined.

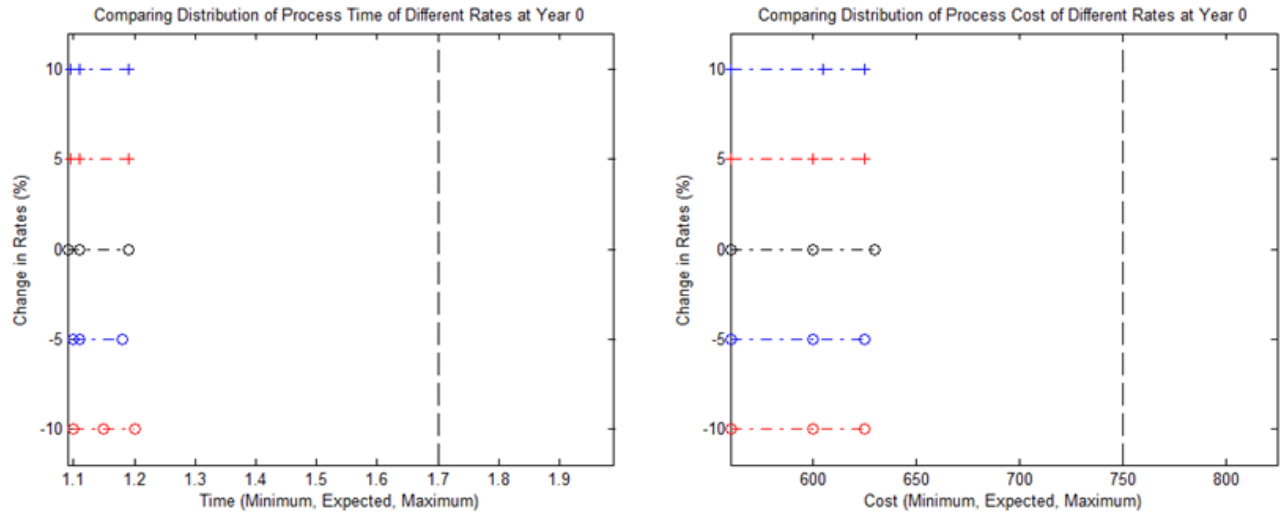


Figure 4.33: A Comparison Of Duration/Cost Distributions Of Different Failure Rates At Year 0.

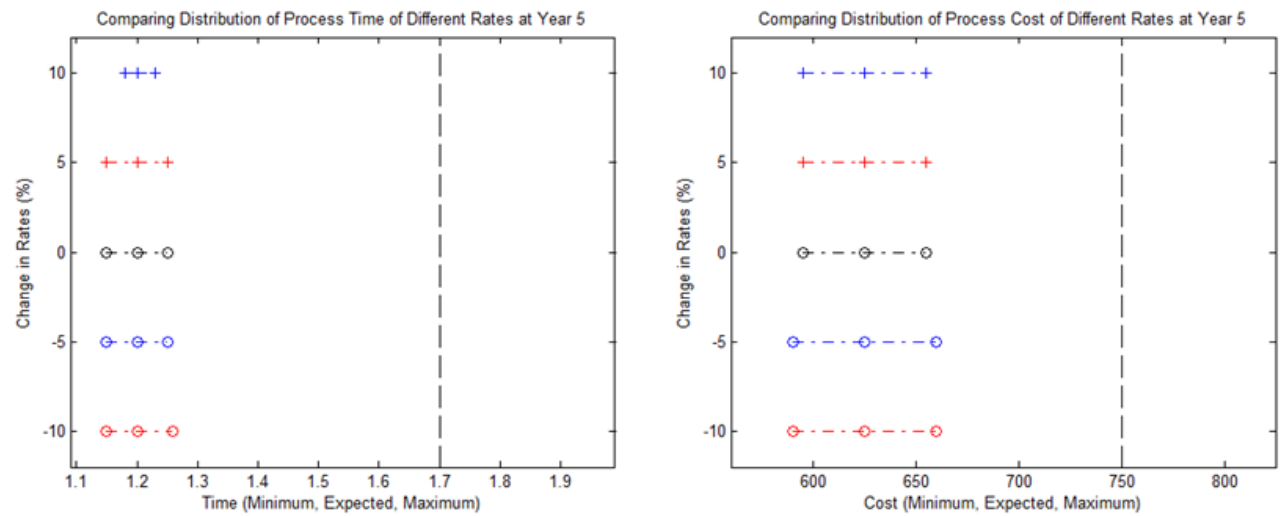


Figure 4.34: A Comparison Of Duration/Cost Distributions Of Different Failure Rates At Year 5.

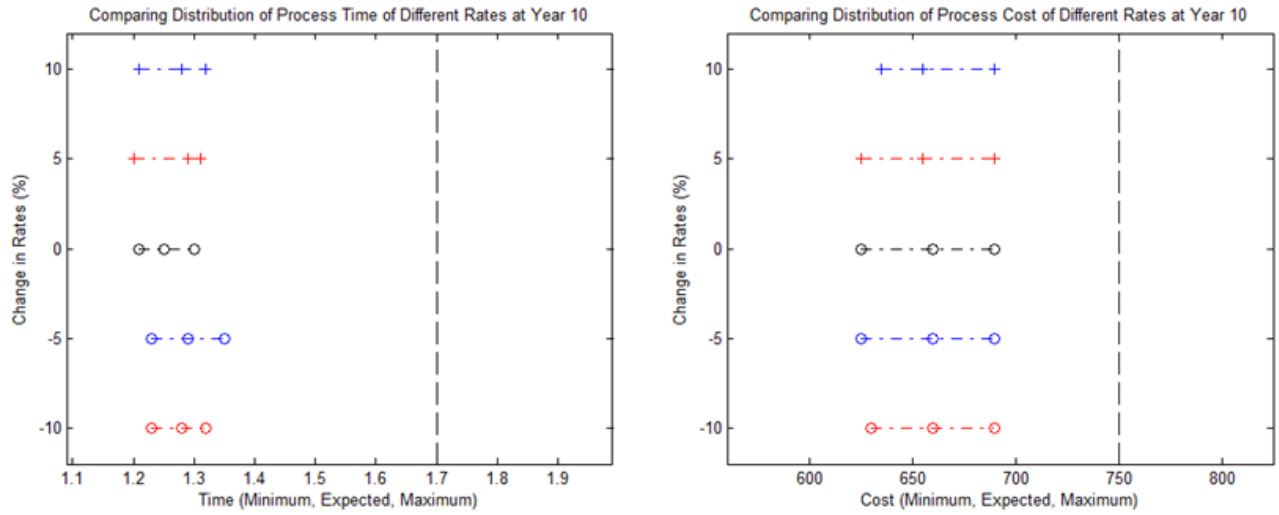


Figure 4.35: A Comparison Of Duration/Cost Distributions Of Different Failure Rates At Year 10.

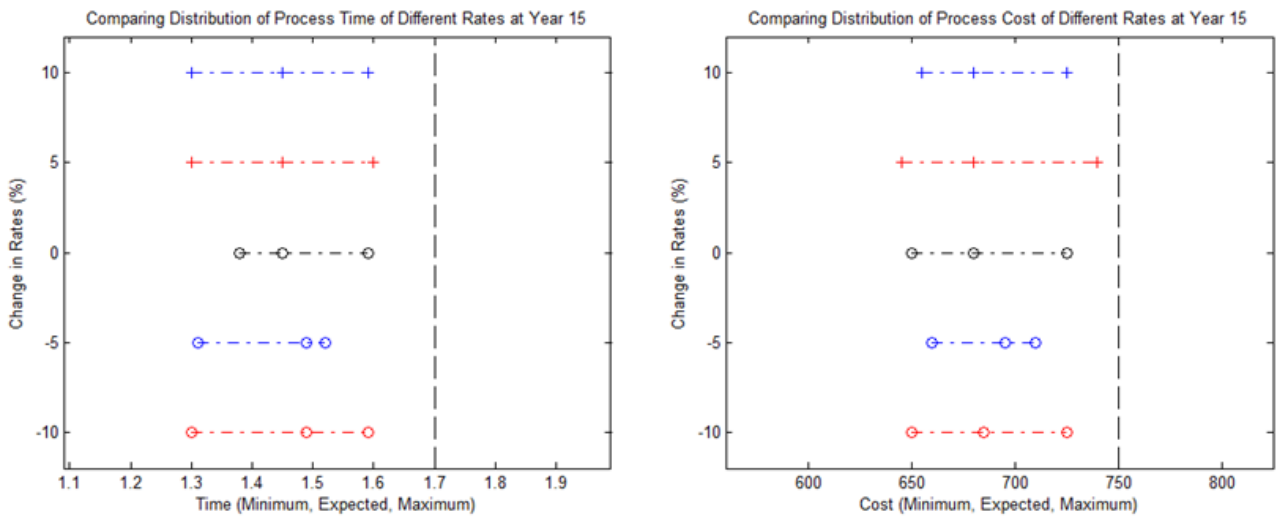


Figure 4.36: A Comparison Of Duration/Cost Distributions Of Different Failure Rates At Year 15.

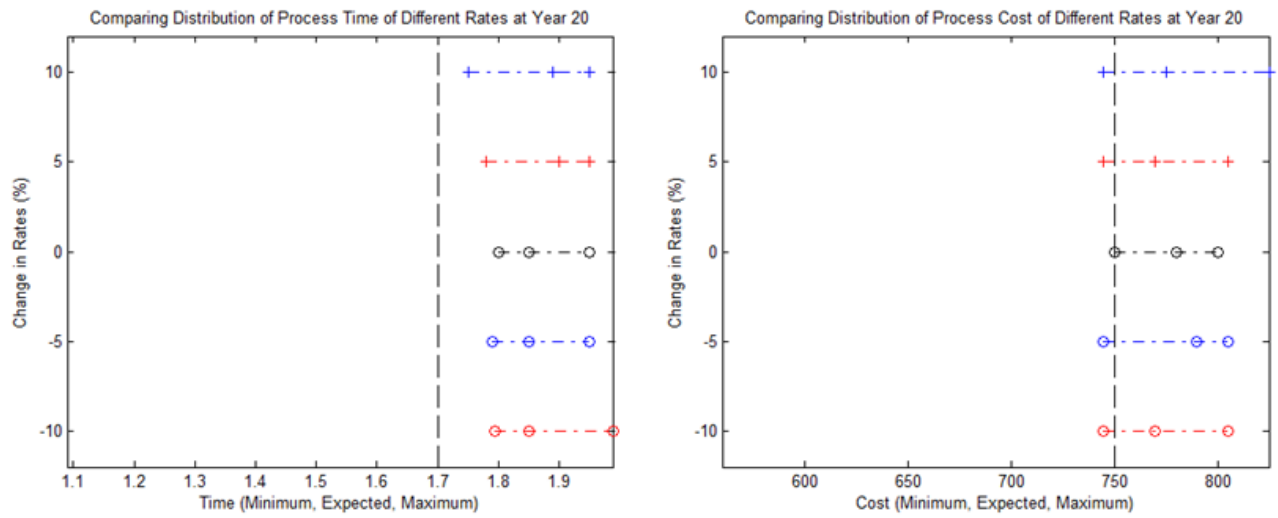


Figure 4.37: A Comparison Of Duration/Cost Distributions Of Different Failure Rates At Year 20.

4.6 Discussion of Results

4.6.1 Comparison of Joint Duration/Cost Distribution

This case study has confirmed the research hypothesis specified in Chapter 1. As time passed, the quality of the interfaces between the tasks in a process degraded as obsolescence affected them. Obsolescence is a kind of failure; it can make the probability of rework higher and, in turn, cause the time and money needed to complete a process to increase. To make comparison of PDFs easier, only the areas of highest frequency were compared. For each scenario, the areas of most concern (shown in Fig. 4.38) were plotted on the same figure to examine how the duration/cost distributions moved over time and changed their shapes.

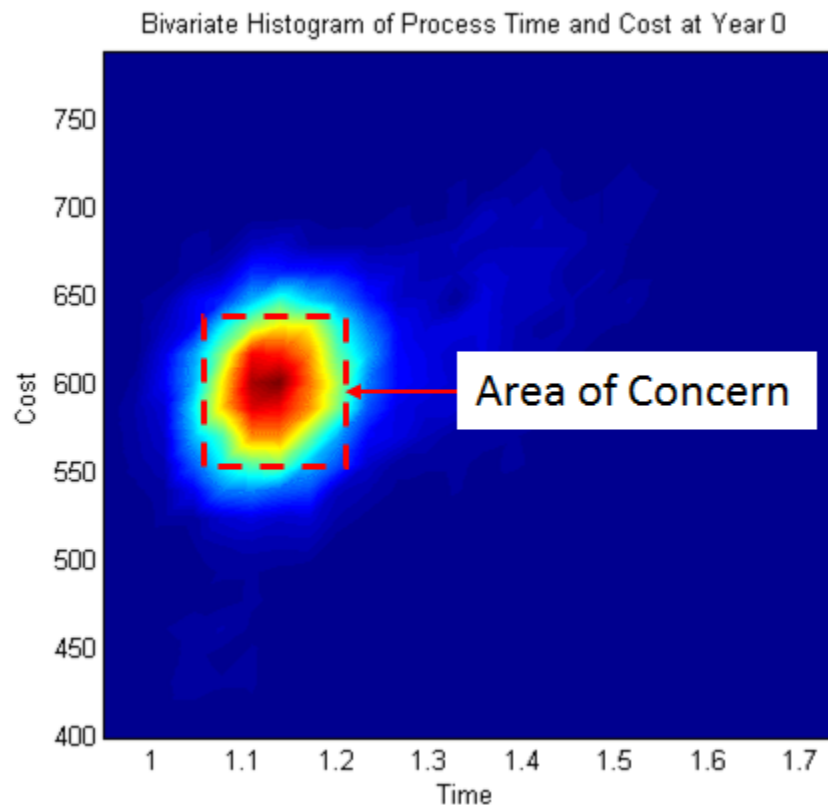


Figure 4.38: Location Of Area Of Concern On Duration/Cost PDF.

Figure 4.39 shows how the joint duration/cost distribution of the process changed as the design ages while considering obsolescence. The circles in the center of each box represented the most likely duration and cost of each distribution. The numbers to the centers are the times (in years) to which the distribution applies. As time passed the distribution showed small cycles of growth and contraction. This was caused by the likelihood of rework of some tasks to be 50%. This caused half of the simulations to include this rework and half to not consider the rework. As time passed, the likelihood of rework of some tasks was more than 50%. This caused a majority of the simulations to include the rework. Figure 4.40 shows how the joint duration/cost distribution of the process changed as the design aged without considering obsolescence. Without considering obsolescence, the expected duration and cost were substantially lower.

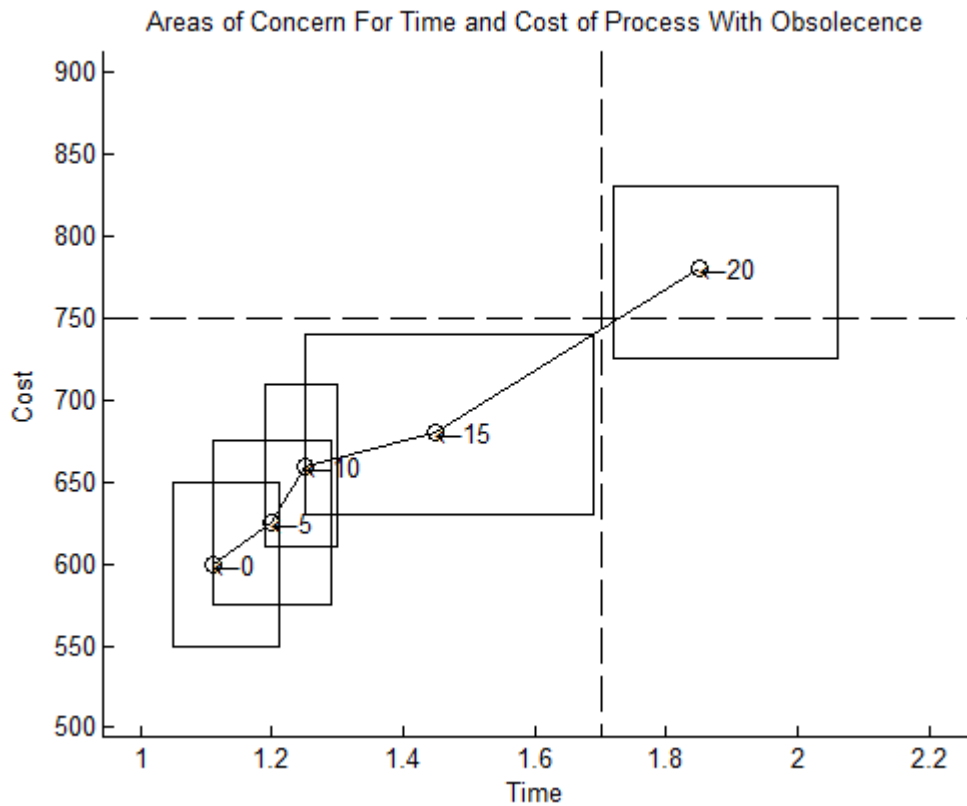


Figure 4.39: Plot Of Areas Of Concern On Duration/Cost Considering Obsolescence.

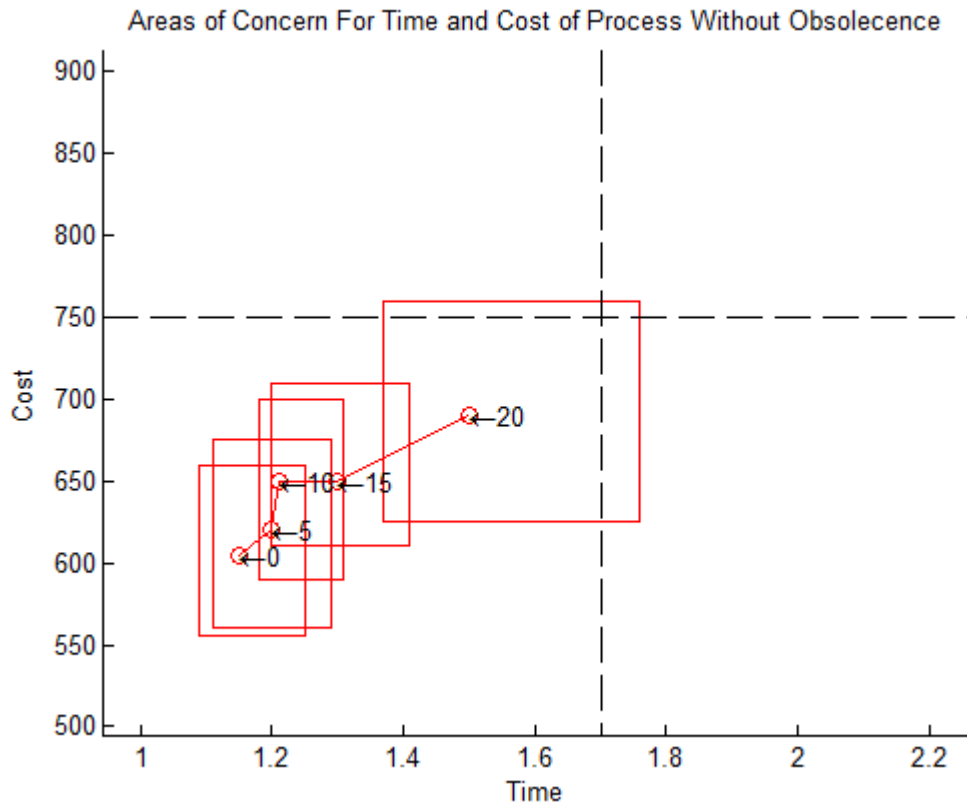


Figure 4.40: Plot Of Areas Of Concern On Duration/Cost Not Considering Obsolescence.

4.6.2 Discussion of Sensitivity Analysis

Increasing the rework coefficients had the greatest effect on the shapes of the distribution. The larger the rework coefficients, the faster the distributions advanced towards the project boundaries in time and cost. Also, the distributions had more volatility. Changing the failure rates had little effect. Just like the rework coefficients, increasing the rates made the distribution advance towards the project boundaries but not as fast as changing rework coefficients. The distributions had little to no volatility in size especially at the beginning of the process's life. In both cases, the distributions looked almost the same as at the start of life with the exception of the distributions involving the 10% increase in RC. Also in all cases, the distributions advanced slowly in the beginning and advanced faster as time passed.

CHAPTER 5

CONCLUSION

The recognition of the influence of obsolescence has caused process planners to consider its effects if they want to monitor the design of a process during its life span. This chapter will present an overview of how to use a common forecasting tool called the growth curve and a powerful systems engineering tool known as the DSM to model the obsolescence of a complex system in the first section, Section 5.1. The second section, Section 5.2 will provide suggestions for future work.

5.1 Contributions of This Dissertation

5.1.1 Outline of Tools Used to Develop Methodology

Growth curves are a common type of curve used by technological forecasters to model obsolescence after noticing the similarities between the physical failures of different types of devices. There has been suggestions for using a growth curve to represent the combined probability of failure by obsolescence (a loss in utility) and failure by getting wear and tear. The reason why the s - shaped curve was used to model the failure of interfaces is because this curve is a continuous function and few parameters are needed to define it.

The DSM is a square matrix that is used in process design. The reason why DSM is selected to represent the interfaces between any pairs of tasks in a process is because it is better at representing the feedforward (below the diagonal in this dissertation) and feedback interactions (above the diagonal) present in complex processes compared to Gantt charts or critical path networks. The DSM can also model task interfaces that are not binary to model interfaces with different weights.

5.1.2 Overview of Methodology

Figure 5.1 contains a shortened version of the flowchart in Fig. 3.1. The section in red represents the preparation needed to model the duration and cost of a process. The section in blue represents the creation of the PDFs themselves.

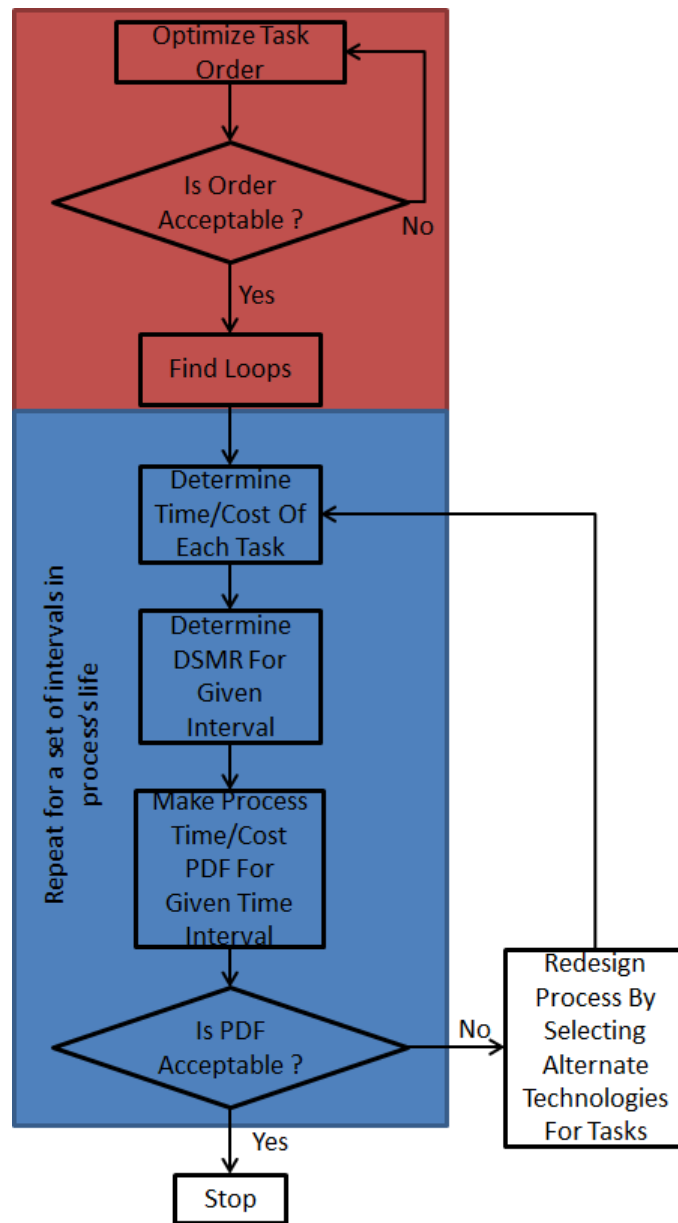


Figure 5.1: A Compact Flowchart Of Methodology.

One of the contributions of this dissertation as shown in the red section is the creation of a loop master which is a tool to keep track of which tasks in a process form loops. Another contribution is the steps involved in making corrections in finding loops to make the powers of adjacency matrix method more effective.

The largest contribution of this dissertation is involved in the blue section which is a DSM - based model (DSMR) in which the state of interactions can be determined at any time in a process's life. To be able to do that, three DSMs (DSMRStart, DSMRate, and DSMMAT) were made from the failure curves of the technologies used to complete the tasks. They are the key inputs for the DSMR. This can be used to determine how obsolescent a process's design is based on how the various technologies used to complete the process becomes obsolescent. The technology used to complete each task used a growth curve made of two failure curves (failure by physical means and by obsolescence). A process's resistance to obsolescence can be determined by examining how joint duration/cost distributions move and change shape as the process's design ages. The methodology discussed in this dissertation is intended for use during the design phase of a process.

5.2 Suggestions for Future Work

5.2.1 Simulation Preparation Improvement

Even with the automation of the methodology through computer programs, a great deal of preparation was needed to create the inputs for the simulations. This can be subject to errors. The biggest concern is in the DSM optimization. The software requires a human to check if the DSMTS is acceptable before anything else can be done because the optimizer might not have been given enough generations and/or population size to converge to an acceptable solution. To help with this, extra code should be added to the optimizer that will determine an appropriate amount of generations and population size before starting the optimization.

5.2.2 Simulation Modifications

Another issue that process designers, planners, and operators have to deal with is the increasing complexity of the process. As an organization uses a process, upgrades are sometimes made to the process's design so that it can keep up its utility. Usually, the upgrades come in the form of add-ons to the number of tasks and/or the equipment used to complete the tasks. Figure 5.2 shows an example of how the tasks are assumed to interface with each other in this dissertation. The task in question (shown in blue in the center) is dependent on a dominant technology and so are its predecessor(s) (shown in red on the left) and its successor(s) (shown in orange on the right).

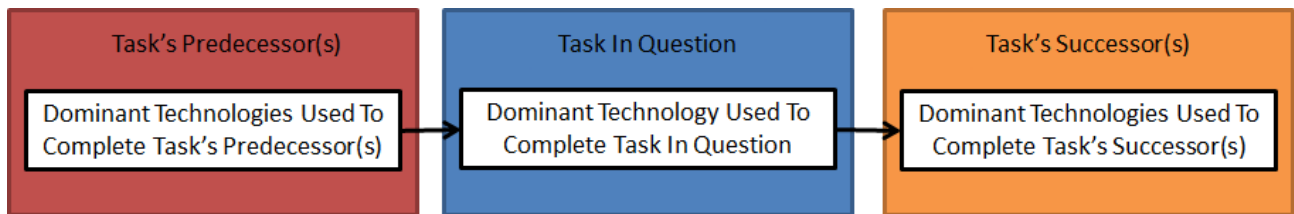


Figure 5.2: This Dissertation's Illustration Of How A Task Interfaces With Its Predecessor(s) And Successor(s).

If a process's design is upgraded with add-ons to the equipment used to complete a task in question, more than one technology might dominate in its completion. Such a situation is illustrated in Fig. 5.3. What happens is that one or more technologies are used to handle inputs from a task's predecessors and one or more technologies are used to create and handle outputs for the task's successors.

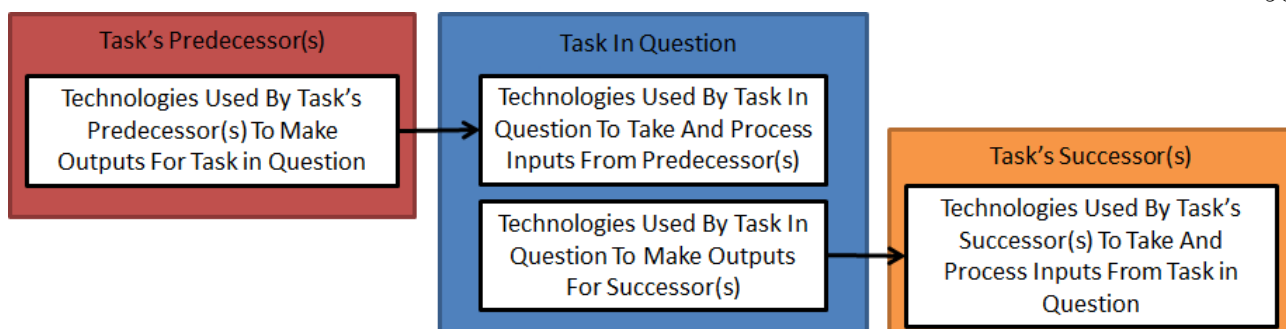


Figure 5.3: A More Complex Illustration Of How A Task Interfaces With Its Predecessor(s) And Successor(s).

If this occurs, expressing the RCs in the form of a vector will not be sufficient for calculating the time and money wasted on rework because the technologies used to complete a task in question are not the same. Here, the RCs will have to be expressed in the form of another DSM such as in a model by Browning and Eppinger [18]. The DSM that they used in calculating rework is read as “the percent of task i has to be reworked because of an error in task j is (i, j) percent.”

Another suggestion for future work may be the method of changing how the rework cycles. In this dissertation, the number of times a task is reworked is based on the number of interactions it has with the other tasks and the probabilities of rework. Incidences of rework only occur once per simulation. In reality, that might not always be true. As processes become more complex, it becomes increasingly difficult to correctly complete tasks. Platanitis, Pop-Iliev, and Barari [28] and Lee, Ong, and Khoo [29] suggested using eigenvalues and eigenvectors of DSMs like the DSMRs in this dissertation to determine the number of times tasks are reworked while Smith and Eppinger [30] suggested using functions that are derived from the development times of coupled pairs in a given process. All of these suggestions may be incorporated in the method advocated in this dissertation.

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APPENDICES

A. Program Codes For Methodology

A.1. Inputs For Program and Extra Notes

Figures A.1 through A.5 show how the needed inputs for the simulation in the case study are made in Excel. The file name that contains all the inputs is shown in codes shown later in the section. The sheet names for each input are underlined and shown in green. If an unsolved DSM considering task precedence is being used, there is no need to add headings, open and execute “starter.m”. The headings in Excel that show element location will be used as the headings in for the DSM. Treat the column headings as the matching number in the English alphabet (A is 1, B is 2, C is 3, etc.). In either case of using unsolved or solved DSM considering task precedence, the DSMRStart must be configured to match the headings in Excel. If a solved DSM considering task precedence is being used, open and execute “skipopt.m”.

	A	B	C	D	E	F	G	H	I
1	0	0	0	0	0	0	1	0	0
2	0	0	1	0	0	1	0	0	1
3	1	1	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	1
7	1	0	0	0	0	0	0	0	0
8	0	0	0	1	0	0	0	0	1
9	0	0	1	0	0	1	0	0	0

given_interact | r_prob | time | cost | rc | rc_no_obsol | ...

Figure A.1: Excel Input For Unsolved DSMTS For Case Study.

	A	B	C	D	E	F	G	H	I	J
1	0	7	1	5	4	3	6	9	2	8
2	7	0	1	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0
4	5	0	0	0	0	0	0	0	0	0
5	4	0	1	0	0	0	0	0	0	0
6	3	0	1	0	0	0	0	0	1	0
7	6	0	0	1	0	0	0	1	0	0
8	9	0	0	0	0	1	1	0	0	0
9	2	0	0	0	0	1	1	1	0	0
10	8	0	0	0	1	0	0	1	0	0

Figure A.2: Excel Input/Output For Solved DSMTS For Case Study.

	A	B	C	D
1	Task	RC	Rate	Maturity
2	1	20	0.3	10
3	2	50	1	18
4	3	80	1.5	15
5	4	100	0.4	-10
6	5	10	1.1	5
7	6	25	0.8	6
8	7	78	0.25	-2
9	8	6	1.8	50
10	9	10	0.75	1

Figure A.3: Excel Input For Rework Coefficient, Rate, And Maturity Of Dominant Technologies Used To Complete Task For Case Study.

	A	B	C	D
1	Task	Min	Expected	Max
2	1	0.074763	0.07668	0.078597
3	2	0.11502	0.15336	0.17253
4	3	0.13419	0.1917	0.28755
5	4	0.01917	0.05751	0.061344
6	5	0.1917	0.23004	0.30672
7	6	0.09585	0.11502	0.13419
8	7	0.017253	0.01917	0.028755
9	8	0.13419	0.17253	0.193617
10	9	0.01917	0.03834	0.07668
11				

time cost ... (+) :

Figure A.4: Excel Input For Duration Of Tasks For Case Study.

	A	B	C	D
1	Task	Min	Expected	Max
2	1	30	40	50
3	2	50	100	101
4	3	10	20	22
5	4	114	150	177
6	5	25	30	36
7	6	40	55	90
8	7	9	10	12
9	8	25	35	40
10	9	15	19	20
11				

time cost rc ... (+)

Figure A.5: Excel Input For Costs Of Tasks For Case Study

	A	B	C	D	E	F	G	H	I
1	0	0	0	0	0	0	0.09	0	0
2	0	0	0.02	0	0	0.07	0	0	0.1
3	0.05	0.06	0	0	0	0	0	0	0
4	0.01	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.03	0	0	0	0.04
7	0.08	0	0	0	0	0	0	0	0
8	0	0	0	0.05	0	0	0	0	0.04
9	0	0	0.07	0	0	0.02	0	0	0
10									

Navigation bar: given_interact | r_prob | time | cost | rc | rc_no_obsol | ... (+) | ⏪

Figure A.6: Excel Input For DSMRStart For Case Study.

A.2. Codes for “starter.m”

```

1% The purpose of the code is to be the starting point.
2% The following steps will be used...
3%     1) Optimize given interaction DSM with "optimizer."
4%     2) Examine the optimized DSM for task precedence. If is
        acceptable ,
5%         go to Step 3, otherwise go back to Step 1.
6%     3) Loops (or circuits) are determined with "circuiter."
7%     4) Simulations are done by "simulator."
8
9 clear all
10 close all
11 clc
12
13 while 1 == 1
14     optimizer %run optimizer
15
16     % Give choice to accept optimized dsm
17     choice = menu('Optimization complete. Is optimized DSM
        acceptable?', 'No', 'Yes');
18
19     if choice == 1
20         continue %redo optimization
21     end
22
23     if choice == 2
24         % Give message to start finding loops

```

```
25     circuiterstart = ['Now looking for loops ...'];
26     disp(circuiterstart)
27     circuiter %run circuiter
28     break
29 end
30 end
```

A.3. Codes for “evaluate.m”

```
1 function [ obf ] = evaluate( triali , trialj )
2 obf = 0; %(objective function of optimizer)
3
4 global info; %from optimizer
5
6% Objective is to minimize feedback by minimizing distance
7% from diagonal.
8 obf = sum(abs((trialj - triali) .* info (:,5)));
9
10 end
```

A.4. Codes for “optimizer.m”

```

1% For lower is better (depend down / provide across) notation
2% Also called IR/FAD (Input is Row/ Feedback Above Diagonal)
   notation
3% Looks at PBM then score. Use To obtain DSMTP
4
5 clear all
6 clc
7
8%% -----Give message to start optimization-----
9 optstart = [ 'Starting Optimization ... '];
10 disp(optstart)
11
12 global best_info;
13 global best_dsm;
14 global best_order;
15 global popi_best;
16 global popj_best;
17 global v;
18 global info;
19 global cir_input;
20
21%% -----Inputs from user -----
22 cir_input = 'rogers_case_study.xlsx'; %file that contains inputs
23 cir_output = 'rogers_case_study.xlsx'; %file that outputs are
   placed
24

```

```

25%% ---Sorting data for optimization--
26 v = (xlsread('cir_input','given_interact')); %read data from excel
      file
27 info = zeros(length(v)^2,6); %intitalize info
28
29 global master;
30 master = 1:length(v):length(v)^2; %used for referance in making
      info matrix
31
32 for m = 1:length(v):length(v)^2
33     for k = 1:1:length(v)
34         loc = find(master==m); %used for referance in making info
              matrix
35         info(m:m+length(v)-1,1) = ones(length(v),1)*loc; %depend (no
              change)
36         info(m:m+length(v)-1,2) = 1:length(v); %provide (no change)
37         info(:,3) = info(:,1); %row(i) (will change during
              optimization)
38         info(:,4) = info(:,2); %column(j) (will change during
              optimization)
39     end
40 end
41
42 for n = 1:length(v)^2
43     info(n,5) = v(info(n,1),info(n,2)); %values from original dsm
44
45     info(n,6) = (abs(info(n,4)-info(n,3))*info(n,5)); %original
              dsm scores

```

```

46 end
47
48 total_moves = sum(info(:,5)); %total moves
49
50 bm = 0; %backtracking moves
51
52 % If a move is above the diagonal, then it is a backtracking move
    .
53 for n = 1:length(v)^2
54     if (info(n,4) > info(n,3)) && (info(n,5) ~= 0)
55         bm = bm+info(n,5);
56     end
57 end
58
59 Original_PBM = (bm/total_moves)*100; % percent backtracking moves
60
61 % Initialing vectors ,
62 triali = zeros(1,length(v)^2)'; %trial for row
63
64 trialj = zeros(1,length(v)^2)'; %trial for column
65
66 gen_max = 100; %generations
67
68 % gen = 1:gen_max; scores = zeros(1,gen_max); %use for
    convergence tracking
69
70 pop_size = 100; %population size
71 popi = zeros(length(v)^2, pop_size); %initialing i's

```



```

72 popj = zeros(length(v)^2, pop_size); %initialing j's
73 cgscore = zeros(1, pop_size); %initialing current generation
    scores of children
74 cgpbm = zeros(1, pop_size); %initialing current generation of
    PBM children
75 lgscore = ones(1, pop_size)*sum(info(:,6)); %last generation score
    of children
76 lgpbm = ones(1, pop_size)*Original_PBM; %last generation PBM of
    children
77 %score of give dsm is staring point for comparsion
78
79 x1 = popi;
80 x2 = popj;
81
82 % Making stating point for population comparision.
83 % If better order cannot be found, then the orginal is given back
    .
84 for i = 1:pop_size
85     x1(:, i) = info(:, 3);
86     x2(:, i) = info(:, 4);
87 end
88
89 %% ___Solving DSM for task precedence___
90 for it = 1:gen_max
91
92
93 for p = 1:pop_size % generate initial test population
94 % _Mutation_

```

```

95     mutmaster = randperm(length(v),length(v))'; %reference for
        mutation
96     for m = 1:length(v):length(v)^2
97         for k = 1:1:length(v)
98             local = mutmaster(find(master==m)); %used for referance in
                making info matrix
99             triali(m:m+length(v)-1) = ones(length(v),1)*local; %triali
100            trialj(m:m+length(v)-1) = mutmaster; %trialj
101         end
102     end
103
104 popi(:,p) = triali;
105 popj(:,p) = trialj;
106
107 end
108
109 % _Evaluating Fitness_
110
111 % PBM
112 score_ref = ones(1,pop_size)*1000; % reference for pbm
        comparsion
113
114 for p = 1:pop_size
115     triali = popi(:,p);
116     trialj = popj(:,p);
117
118     bm = 0;
119     for n = 1:length(v)^2

```

```

120     if (trialj(n) > triali(n)) && (info(n,5) ~= 0)
121         bm = bm+info(n,5);
122     end
123 end
124     cgpbm(p) = (bm/total_moves)*100;
125 end
126
127% Scores
128 for p = 1:pop_size
129     triali = popi(:,p);
130     trialj = popj(:,p);
131
132     [cgscore(p)] = feval('evaluate',triali,trialj); %current
           generation
133 end
134
135% Finding the current generation "elite"
136 [~,cgelite_loc] = find(cgpbm == min(cgpbm));
137
138% Inserting pbms of current generation elite in reference
           locations
139% Matching the scores for easier reference
140 for i = 1:length(cgelite_loc)
141     score_ref(cgelite_loc(i)) = cgscore(cgelite_loc(i));
142
143 end
144
145% Determining the "best"

```

```

146 [~,cgbest_loc] = find(score_ref == min(score_ref)); % best has
        lowest score of elite
147
148% If current generation of children is better than the last, the
        current
149% population is the kept, otherwise keep last generation.
150 if min(cgpbm) < min(lgpbm) && (min(score_ref) < min(lgscore))
151     cgen_best_pbm = min(cgpbm)
152     cgen_best_score = min( score_ref)
153     sample_i = popi(:,cgbest_loc); %duplicates of parents of
        best might exist
154     sample_j = popj(:,cgbest_loc); %only one is needed
155     popi_best = sample_i(:,1); % parents of
156     popj_best = sample_j(:,1); % best children
157     x1 = popi;
158     x2 = popj;
159 else
160     cgscore = lgscore;
161     cgpbm = lgpbm;
162     [~,cgelite_loc] = find(cgpbm == min(cgpbm));
163     score_ref = ones(1,pop_size)*1000;
164     for i = 1:length(cgelite_loc)
165         score_ref(cgelite_loc(i)) = cgscore(cgelite_loc(i));
166     end
167     [~,cgbest_loc] = find(score_ref == min(score_ref));
168     sample_i = x1(:,cgbest_loc); %duplicates of parents of best
        might exist
169     sample_j = x2(:,cgbest_loc); %only one is needed

```

```

170     popi_best = sample_i(:,1); % parents of
171     popj_best = sample_j(:,1); % best children
172     cgen_best_pbm = min(cgpbm)
173     cgen_best_score = min( score_ref)
174 end
175 lgscore = cgscore;
176 lgpbm = cgpbm;
177
178 end
179
180 %% -----Making dsm from info -----
181
182 best_info = zeros(length(v)+1,length(v)+1);
183
184 best_dsm = zeros(length(v),length(v));
185
186 org_order = 1:length(v);
187
188 best_order = zeros(length(v),1);
189
190% Determine order from the population
191% Example if popj_best is [4 1 2 3]
192% then do task 1 forth , task 2 first , task 3 second , and task 4
    third
193 for i = 1:length(v)
194     [r,~] = find(popj_best(1:length(v)) == i);
195     best_order(i) = r;
196 end

```

```

197
198% Filling in column headings
199 best_info(1,2:1+length(v)) = best_order(:,1);
200
201% Filling in row headings
202 best_info(2:1+length(v),1) = best_order(:,1)';
203
204% Filling dsm
205 for coord = 1:length(v)^2
206
207     best_dsm(popi_best(coord),popj_best(coord)) = info(coord,5);
208
209 end
210
211% Inserting best_dsm into best_info
212 best_info(2:end,2:end) = best_dsm;
213
214% Display best order
215 best_order
216
217% Display starting and ending scores and PBMs
218 score_start = sum(info(:,6))
219 Original_PBM
220
221 score_end = cgen_best_score
222 Ending_PBM = cgen_best_pbm
223

```

```
224%% Export starting and ending scores , PBMs, and optimized DSM to
      excel
225 xlswrite(cir_output , score_start , 'score_start')
226 xlswrite(cir_output , Original_PBM , 'Original_PBM')
227
228 xlswrite(cir_output , score_end , 'score_end')
229 xlswrite(cir_output , Ending_PBM , 'Ending_PBM')
230
231% Export optimal dsm to excel
232 xlswrite(cir_output , best_info , 'optimized_DSM')
233% Warning! Make sure that the Excel sheet is not existant and
      file is
234% closed before the program is executed.
```

A.5. Codes for “skipopt.m”

```

1% This code is used for finding loops and doing simulations of
   time and
2% cost given the solved DSM for task precedence and other
   appropriate data.
3
4 clear all
5 close all
6 clc
7
8 global v;
9 global best_info;
10 global best_dsm;
11 global best_order;
12 global master;
13 global popi_best;
14 global popj_best;
15 global cir_input;
16
17
18%% ----Inputs from user-----
19 cir_input = 'rogers_case_study.xlsx'; %file that contains inputs
20 best_info = (xlsread(cir_input, 'optimized_DSM'));
21
22 best_dsm = best_info(2:end,2:end);
23 v = best_dsm;
24 best_order = best_info(2:end,1);

```



```

25 master = 1:length(v):length(v)^2;
26
27%% -----Making popi_best and popj_best-----
28 popi_best = zeros(1,length(v)^2)';
29 popj_best = zeros(1,length(v)^2)';
30
31% Remaking mutmaster
32 mutmaster = zeros(1,length(v))';
33 for i = 1:length(v)
34     mutmaster(i) = find(best_order==i);
35 end
36
37 for m = 1:length(v):length(v)^2
38     for k = 1:length(v)
39         mut = mutmaster(find(master==m));
40         popi_best(m:m+length(v)-1) = ones(length(v),1).*mut;
41         popj_best(m:m+length(v)-1) = mutmaster;
42     end
43 end
44
45%% -----Give message to start finding
         loops-----
46 circuiterstart = ['Now looking for loops ...'];
47 disp(circuiterstart)
48 circuiter %run circuiter

```

A.6. Codes for “circuit.m”

```

1% The purpose of this code is to take a DSM and find the circuits
   (loops).
2
3%% ----Inputs from user-----
4 cir_output = 'rogers_case_study.xlsx'; %file that outputs are
   placed
5
6%% ----Get data from optimizer----
7 global best_info;
8 global best_dsm;
9 global best_order;
10
11%% ----Give data to simulator ----
12 global loop_ref
13 global loop_ref_named
14 global coup_pairs
15 global it_size
16 global loop_master
17
18 [1,~] = size(best_info); %dimensions of best_info
19
20%% ---- Finding Coupled pairs-----
21
22 pair_ref = [];
23 for i = 2:l
24     for j = 2:l

```

```

25     if (best_info(i,j) == best_info(j,i)) && (best_info(i,j) ~=
        0) && (best_info(j,i) ~= 0)
26         pair_ref((i-1),1) = best_info(i,1);
27         pair_ref((i-1),2) = best_info(j,1);
28     end
29 end
30 end
31
32 [l,w] = size(pair_ref);
33 if l ~= 0
34     % Removing entries with zeros
35     pair_ref(~any(pair_ref,2), :) = []; %rows
36     pair_ref(:, ~any(pair_ref,1) ) = []; %columns
37
38     % Finding and sorting duplicates
39     for i = 1:length(pair_ref)
40         sort_ref = pair_ref(i,1); %using first number in row as
            referance .
41         [r,~] = find(sort_ref == pair_ref(:,2)); %find duplicate
            location
42         if r >= i
43             pair_ref(r,1) = pair_ref(r,2);
44             pair_ref(r,2) = pair_ref(i,2);
45         end
46         % The duplicate is made look like original
47     end
48 end
49

```

```

50% Removing duplicates and display
51 coup_pairs = unique(pair_ref, 'rows', 'stable')
52
53% Export list of iterative pairs to excel
54 [pair_size, ~] = size(pair_ref);
55 if pair_size ~= 0
56     xlswrite(cir_output, coup_pairs, 'coup_pairs')
57 end
58%% ---- Finding Iterative loops-----
59
60% Making adjacency matrix
61 a = best_dsm; % starting point for making adjacency matrix
62
63% Make non zero entries one
64 for i = length(best_dsm)
65     for j = length(best_dsm)
66         if a(i, j) ~= 0
67             a(i, j) = 1;
68         end
69     end
70 end
71
72 loop_ref = zeros(length(best_dsm), length(best_dsm));
73% ^^^ Referance for filling in loops. ^^^
74% Also, rows are powers of a and columns are task.
75
76 for i = 2:length(best_dsm) % start at power 2
77     a = best_dsm^i ;

```

```

78
79 % Make non zero entries one in current power of a
80 for j = 1:length(best_dsm) % row
81     for k = 1:length(best_dsm) % column
82         if a(j,k) ~= 0
83             a(j,k) = 1;
84         end
85     end
86 end
87
88 % Search diagonals
89 for j = 1:length(best_dsm)
90     if a(j,j)==1
91         loop_ref((i),j) = 1;
92     end
93 end
94 end
95
96%% ----Sorting data before simulations-----
97
98% Finding standalone tasks
99 stand_alones = zeros(1,length(best_dsm));
100% ^^^ Referance for stand alone tasks. 1 is yes. 0 is no. ^^^
101
102 for i = 1:length(best_dsm)
103     if sum(loop_ref(:,i)) == 0
104         stand_alones(1,i) = 1;
105     end

```

```

106 end
107
108% Removing connected loops and its copies
109 index_ref = 1:length(best_dsm);
110 index_ref = index_ref';
111
112% Overall, a row in loop_ref has connected loops if the sum of a
      row and
113% in row's number do not match. Example row 2 in loop_ref has a
      sum of 6.
114% this means that they are 3 loops of 2, not 1 loop of 6.
      Suspicion can
115% arise if the loop_ref sum and row number match. Example is a
      row
116% with sum of 5 but having a loop of size 2 and another of size
      3.
117
118% For row and sum are equal
119 for i = 3:length(loop_ref)
120     start_indx = 0; %"start in loop"
121     end_indx = 0; %"last in loop"
122     for c = 1:length(best_dsm)
123         if loop_ref(i,c) == 1
124             start_indx = c;
125             break
126         end
127     end
128     for d = length(best_dsm):-1:1

```

```

129         if loop_ref(i,d) == 1
130             end_indx = d;
131             break
132         end
133     end
134     if best_dsm(c,d) == 0 && c < d
135         loop_ref(i,:) = zeros(1,length(best_dsm));
136     end
137 end
138
139 % For sum and row mismatch
140 for i = 2:length(best_dsm)
141     if sum(loop_ref(i,:)) > i
142         loop_ref(i,:) = zeros(1,length(best_dsm));
143     end
144 end
145
146 % If all loops are removed (multiple loops of equal size exist)
147     ...
147 [lc,~] = size(loop_ref);
148 if sum(loop_ref) == 0;
149     % loop_ref = zeros(length(best_dsm),length(best_dsm));
150     k = 1; %row of loop_ref for referance in reconstructing loop
151         master
151     for i = 1:length(best_dsm)
152         for j = 1:length(best_dsm)
153             if (i < j) && best_dsm(i,j) == 1
154                 loop_ref(k,i:j) = ones(1,(j-i+1));

```

```

155             k = k+1;
156         end
157     end
158 end
159 end
160
161 % Adding coupled pairs (if any) to loop_ref
162 [pr,pc] = size(coup_pairs);
163 [r,~] = size(loop_ref);
164
165 if pr ~= 0
166     for i = 1:pr
167         [~,pair_loc1] = find(best_order' == coup_pairs(i,1));
168         [~,pair_loc2] = find(best_order' == coup_pairs(i,2));
169         loop_ref(r+i,pair_loc1) = 1;
170         loop_ref(r+i,pair_loc2) = 1;
171     end
172 end
173
174 loop_ref = unique(loop_ref,'rows','stable');
175
176 % Removing rows with zeros
177 loop_ref2 = loop_ref;
178 loop_ref2(~any(loop_ref,2),:) = [];
179 loop_ref = loop_ref2;
180
181
182 [r,c] = size(loop_ref);

```



```

183
184% Give name to loops
185 loop_ref_named = loop_ref;
186 for i = 1:r
187     loop_ref_named(i,:) = loop_ref(i,:).*best_order';
188 end
189
190%% ----- Removing "embedded" loops -----
191 [r,~] = size(loop_ref);
192
193 row_check = zeros(r,r); %reference for checking
194
195% If the loop in loop_ref_named row, curr_r is part of
    loop_ref_named
196% column new_r, then row_check(curr_r,new_r) is made to be 1.
197
198 for curr_r = 1:r
199     for new_r = 1:r
200         combo = loop_ref(curr_r,:)+loop_ref(new_r,:);
201         meeting = find(combo == 2);
202         [~,inter] = size(meeting);
203         if inter ~= 0 % If any 2's exist, then one loop in
            another
204             sum_curr = sum(loop_ref(curr_r,:));
205             sum_ref = sum(loop_ref(new_r,:));
206             if curr_r == new_r % A row always intersects with
                self.
207                 row_check(curr_r,new_r) = 1;

```

```

208         elseif sum_curr < sum_ref % Loop curr_r inside loop
                new_r.
209         row_check(curr_r , new_r) = 1;
210         end
211     end
212 end
213 end
214
215 % Now the if the sum of a row in the row_check matrix is more
        than one ,
216 % then the loop is part of another and is removed
217 row_check_sum = sum(row_check , 2);
218
219 loop_ref((row_check_sum > 1) , :) = [];
220 loop_ref_named((row_check_sum > 1) , :) = [];
221
222 %% ----Constucting master for loops-----
223
224 [r , ~] = size(loop_ref);
225 it_size = r + 1;
226 % ^^^ Sum of number of loops , coupled pairs , and one for stand
        alone tasks
227
228 loop_master = zeros(it_size , length(best_order));
229
230 % Adding loops
231 loop_master((1:r) , :) = loop_ref((1:r) , :);
232

```

```

233% Adding stand alone tasks
234 loop_master(it_size,:) = stand_alones;
235
236%% -----Making loop master for export-----
237
238 loop_master_ex = zeros(it_size+1,length(v)+1); %loop master for
      export
239 loop_master_ex(1,2:end) = best_order; % Adding column heading
240 loop_master_ex(2:end,2:end) = loop_master; % Adding info
241
242% Adding labels for loop classes. Numbers are for class
243% Class 1 is clean loop with 3 or more tasks
244% Class 2 is clean, coupled pair
245% Class 3 is stand alone task(s)
246 for i = 1:it_size
247     if sum(loop_master(i,:)) >= 3
248         loop_master_ex(i+1,1) = 1;
249     end
250     if sum(loop_master(i,:)) == 2
251         loop_master_ex(i+1,1) = 2;
252     end
253     if i == it_size
254         loop_master_ex(i+1,1) = 3;
255     end
256 end
257
258% Print loop_master_ex
259 loop_master_ex

```

```
260
261% Export name of loop_master to excel
262 xlswrite(cir_output , loop_master_ex , 'loop_master')
263
264% Determining sizes
265 loop_sizes = zeros(it_size ,1);
266
267 for i = 1:it_size
268     loop_sizes(i) = sum(loop_master(i ,:));
269 end
270
271% Print sizes of loops and notice
272 loop_sizes
273
274 notice = 'Note that the last sum is for stand alone tasks.';
275 disp(notice)
276
277% Export name of loop sums to excel
278 xlswrite(cir_output , loop_sizes , 'loop_sizes')
279
280%% ----Give message to simulations-----
281
282 simstart = ['Now starting simulations ...'];
283 disp(simstart)
284 simulator %start simulations
```

A.7. Codes for “simulator.m”

```

1% The purpose of this code is simulate project time and cost.
2
3%% -----User inputs -----
4
5 life_span = 20; %life of project
6
7 int_size = 5; %size of interval for plots
8
9 mc_trial = 10000; %number of runs in each monte carlo simulation
10
11 sim_output = 'Original_DSMRS.xlsx'; %where to put outputs
12
13%% ----Get data from optimizer or skipopt-----
14
15 global best_info;
16 global best_dsm;
17 global best_order;
18 global v
19 global popi_best;
20 global popj_best;
21 global master
22 global cir_input;
23
24%----Get data from circuiter and excel files-----
25
26 global it_size

```

```

27 global loop_master
28
29% Taking loop master from excel
30 loop_master = (xlsread(cir_input , 'loop_master')); %read data from
        excel file
31 loop_master = loop_master(2:end,2:end); %removing headings
32
33% Taking rework prob and impact infomation from excel and
        reoganize
34
35% Probability of rework
36 r_prob = (xlsread(cir_input , 'r_prob')); %read data from excel
        file
37
38% Times
39 time = (xlsread(cir_input , 'time')); %read data from excel file
40
41% Cost
42 cost = (xlsread(cir_input , 'cost')); %read data from excel file
43
44% Rework Coeffiecent , Alpha, and Beta
45 rc = (xlsread(cir_input , 'rc')); %read data from excel file
46
47%% -----Reogranizing given to match optimal -----
48
49% Probability of rework
50 prob_info = zeros(length(v)^2,5); %intitalize info
51

```

```

52 for m = 1:length(v):length(v)^2
53     for k = 1:1:length(v)
54         loc = find(master==m); %used for referance in making info
           matrix
55         prob_info(m:m+length(v)-1,1) = ones(length(v),1)*loc; %
           provide (no change)
56         prob_info(m:m+length(v)-1,2) = 1:length(v); %depend (no
           change)
57         prob_info(:,3) = prob_info(:,1); %row(i) (will change during
           optimization)
58         prob_info(:,4) = prob_info(:,2); %column(j) (will change
           during optimization)
59     end
60 end
61
62 for n = 1:length(v)^2
63     prob_info(n,5) = r_prob(prob_info(n,1),prob_info(n,2)); %
           values from original dsm
64
65 end
66
67 % Inserting better population into info
68 prob_info(:,3) = popi_best;
69 prob_info(:,4) = popj_best;
70
71 new_prob = best_info;
72
73 % Filling dsm

```

```

74 for coord = 1:length(v)^2
75     DSMR_start_info(popi_best(coord), popj_best(coord)) =
        prob_info(coord,5);
76 end
77
78 new_prob(2:end,2:end) = DSMR_start_info;
79
80 %Export DSMR_start (DSM for Rework at time zero of their tech
        releases )
81 xlswrite(sim_output ,new_prob , 'DSMR_start' )
82
83% Reorganizing given time/cost estimates and improvment to match
        optimal
84
85 opt_time = time; %time estimates in optimal order
86
87 opt_cost = cost; %cost estimates in optimal order
88% Column 1 is min. 2 is likely. 3 is max for time and cost.
89
90 opt_rc = rc; %rework estimates in optimal order
91
92 for r = 1:length(v)
93     r_ref = find(best_order == r);
94     opt_time (r_ref,:) = time(r,:);
95     opt_cost (r_ref,:) = cost(r,:);
96     opt_rc (r_ref,:) = rc(r,:);
97 end

```



```

98 rc_horz = opt_rc(:,2)'/100; %want vector to be horizontal
    starting with given
99
100% Making DSMRate(DSM for Rates). Made of rates
101
102 DSMRate = best_info;
103
104 DSMRate_info = best_dsm;
105
106 % Make non zero entries one in DSMRate_info for proper filling
107     for j = 1:length(best_dsm) % row
108         for k = 1:length(best_dsm) % column
109             if DSMRate_info(j,k) ~= 0
110                 DSMRate_info(j,k) = 1;
111             end
112         end
113     end
114
115% Filling in DSMRate
116 for i = 1:length(best_dsm)
117     DSMRate_info(i,:) = DSMRate_info(i,:).*opt_rc(:,3)';
118 end
119
120 DSMRate(2:end,2:end) = DSMRate_info;
121
122 xlswrite(sim_output,DSMRate,'DSMRate')
123
124% Making DSMMAT(DSM for Maturity). Made of inflection points

```

```

125
126DSMMAT = best_info;
127
128DSMMAT_info = best_dsm;
129
130 % Make non zero entries one in DSMO_info for proper filling
131     for j = 1:length(best_dsm) % row
132         for k = 1:length(best_dsm) % column
133             if DSMMAT_info(j,k) ~= 0
134                 DSMMAT_info(j,k) = 1;
135             end
136         end
137     end
138
139% Filling in DSMMAT
140 for i = 1:length(best_dsm)
141     DSMMAT_info(i,:) = DSMMAT_info(i,:) .* opt_rc(:,4)';
142 end
143
144DSMMAT(2:end,2:end) = DSMMAT_info;
145
146 xlswrite(sim_output,DSMMAT,'DSMMAT')
147
148%% -----Monte Carlo Simulaion Runs-----
149
150% Make time and cost vectors
151 mc_time_v = zeros(mc_trial,length(v)); % want time vectors
        horizontal

```

```

152 mc_cost_v = zeros(mc_trial,length(v)); % want cost vectors
        horizontal
153
154 mc_master = zeros(mc_trial,3); %master for time and cost
        simulation
155% ^^^ Column 1 is simulation. column 2 is time. column 3 is cost
        ^^^.
156
157 for curr_time = 0:int_size:life_span %for each time interval
158
159     curr_DSMR_info = best_dsm; %current dsm for rework
160
161     % Evaluating current dsm for rework
162     for i = 1:length(v)
163         for j = 1:length(v)
164             if best_dsm(i,j) ~= 0
165                 ll = DSMR_start_info(i,j);
166                 %^^ Lower limit (ll) is starting p(rework) ^^
167
168                 a = DSMRate_info(i,j);
169                 %^^ Alpha is rate of obsolescence from DSMRate ^^
170
171                 t = curr_time; %time is time in project life
172
173                 b = DSMMAT_info(i,j);
174                 % ^^When maturity of tasks's tech (beta) occurs
                    ^^
175

```

175

```

176         curr_DSMR_info(i,j) = ll + ((1-ll)./(1+exp(-a*(t-
           b)))));
177         %^^ Based on logistics curve ^^
178     end
179 end
180 end
181
182 % Getting current DSMR for display in Excel file
183 curr_DSMR = best_info;
184 curr_DSMR(2:end,2:end) = curr_DSMR_info;
185
186 time4export = num2str(curr_time);
187 xlswrite(sim_output ,curr_DSMR ,time4export)
188
189 for sim = 1:mc_trial
190     % Filling in time and cost vectors
191     for i = 1:length(v)
192         % Time
193         min_t = opt_time(i,2); %min estimate
194         likely_t = opt_time(i,3); %likely estimate
195         max_t = opt_time(i,4); %max estimate
196
197         % Cost
198         min_c = opt_cost(i,2); %min estimate
199         likely_c = opt_cost(i,3); %likely estimate
200         max_c = opt_cost(i,4); %max estimate
201
202         % Spread of distributions

```

```

203     spd_t = makedist('Triangular','a',min_t,'b',likely_t,'c',
                    max_t); %time
204     spd_c = makedist('Triangular','a',min_c,'b',likely_c,'c',
                    max_c); %cost
205
206     % Make random number from given spreads
207     mc_time_v(sim,i) = random(spd_t,1,1);
208     mc_cost_v(sim,i) = random(spd_c,1,1);
209     end
210
211     % Fill trial master
212     redo = rand(length(v),length(v)); %probability of rework
                    indicator
213     loop_t = zeros(it_size-1,1); %time for set of loops
214     loop_c = zeros(it_size-1,1); %cost for set of loops
215     mc_t_curr = mc_time_v(sim,:); %current time from monte carlo
                    list
216     mc_c_curr = mc_cost_v(sim,:); %current cost from monte carlo
                    list
217     order1_mult = zeros(1,length(v)); %for multiples of 1st order
                    rework
218
219     % Determining time and cost 0th order rework
220     order0_time = sum(mc_t_curr); %first pass time
221     order0_cost = sum(mc_c_curr); %first pass cost
222
223     % Determining time and cost 1st order rework
224     for r = 1:length(v) %going through rework dsm

```

```

225     for c = 1:length(v)
226         if (r > c) && (redo(r,c) < curr_DSMR_info(r,c))
227             % If redo is less than given probablity and is a
                forword
228             % moving move, only single tasks have to be
                repeated.
229             order1_mult(1,c) = order1_mult(1,c)+1;
230         end
231     end
232 end
233 order1_time = sum(order1_mult.*mc_t_curr.*rc_horz);
234 order1_cost = sum(order1_mult.*mc_c_curr.*rc_horz);
235
236 % Determining time and cost of 2nd order rework
237 for i = 1:(it_size-1)
238     for r = 1:length(v) %going through rework dsm
239         for c = 1:length(v) %r = row, c = column
240             if (r < c) && (redo(r,c) < curr_DSMR_info(r,c))
241                 % If redo is less than given probablity and
                    is a
242                 % backtracking move, rework of an entire loop
                    has to
243                 % be done.
244                 loop_t(i) = loop_t(i) + sum(loop_master(i,r:c)
                    .*mc_t_curr(r:c).*rc_horz(r:c));
245                 loop_c(i) = loop_c(i) + sum(loop_master(i,r:c)
                    .*mc_c_curr(r:c).*rc_horz(r:c));
246     end

```

```

247         end
248     end
249     order2_t_tot = sum(loop_t); %total loop 2nd order rework
        time
250     order2_c_tot = sum(loop_c); %total loop 2nd order rework
        cost
251 end
252 mc_master(sim,1) = sim; %simulation number
253 mc_master(sim,2) = order0_time+order1_time+order2_t_tot; %
        total process time
254 mc_master(sim,3) = order0_cost+order1_cost+order2_c_tot; %
        total process cost
255
256 end
257
258 %__Make bivariate histograms__
259
260 % 2D
261 figure
262 data = [mc_master(:,2),mc_master(:,3)];
263 hist3(data)
264
265 n = hist3(data,[25 25]); %Bin size for time and cost is 25
266 n1 = n';
267 n1(size(n,1) + 1, size(n,2) + 1) = 0;
268
269 xb = linspace(min(data(:,1)),max(data(:,1)),size(n,1)+1);
270 yb = linspace(min(data(:,2)),max(data(:,2)),size(n,1)+1);

```

```

271
272 h = pcolor(xb,yb,n1);
273
274 title(['Bivariate Histogram of Process Time and Cost at Year ',
        num2str(curr_time)])
275 xlabel('Time');
276 ylabel('Cost');
277 %colorbar %adds colarbar
278 shading interp % makes line go away
279
280 % 3D
281 figure
282 [n,c] = hist3(data,[25 25]); %Bin size for time and cost is 25
283 surf(c{1}, c{2}, n);
284 title(['Surface Bivariate Histogram of Process Time and Cost at
        Year ', num2str(curr_time)])
285 xlabel('Time');
286 ylabel('Cost');
287 zlabel('Frequency');
288 %colorbar
289
290 end
291
292 %% Give message showing simulations are complete
293 simend = ['Simulations are complete.'];
294 disp(simend)

```


B. Extra Code Used For Dissertation

B.1. Extra Notes For Using Code That Plots Distribution Motion

Figure A.7 show how to enter the distribution bounds into Excel.

	A	B	C	D	E	F	G
1	year	low time	expected time	high time	low cost	expected cost	high cost
2	0	1.05	1.11	1.21	550	600	650
3	5	1.11	1.2	1.29	575	625	675
4	10	1.19	1.25	1.3	610	660	710
5	15	1.25	1.45	1.69	630	680	740
6	20	1.72	1.85	2.06	725	780	830
7							

FIGURE A.7: Excel Input For Distribution Bounds.

B.2. Code For Plotting Distribution Motion

```

1% The purpose of this code is plot the bounds of time/cost
   distribution
2% as time passes in the form of lines (one for duration and
   another for
3% cost). This code is important to the work, but is not linked to
   other
4% codes. Suggest integrating this code into the simulator for
   faster and
5% more efficient processing.
6
7 clear all
8 close all
9 clc
10
11%% -- Data Collection and User Inputs ---
12
13% Time and cost bounds of process during life
14 time_bound = 1.7;
15 cost_bound = 750;
16
17% Excel data
18 data_loc = 'dist_bounds.xlsx'; %location of data (manually
   gathered)
19
20% Data for first case will come in the following form ...
21% Column 1 is year.

```

```

22% Column 2 is low time.
23% Column 3 is expected time (location of most concentration).
24% Column 4 is high time.
25% Column 5 is low cost.
26% Column 6 is expected cost (location of most concentration).
27% Column 7 is high cost.
28
29 original = (xlsread(data_loc, 'original')); %good design, with
      obsolescence
30 no_obsol = (xlsread(data_loc, 'no_obsol')); %good design, no
      obsolescence
31
32% Data for RC and rate cases will come in the following form ...
33% Column 1 is % change.
34% Column 2 is low time.
35% Column 3 is expected time (location of most concentration).
36% Column 4 is high time.
37% Column 5 is low cost.
38% Column 6 is expected cost (location of most concentration).
39% Column 7 is high cost.
40
41 rc_0 = (xlsread(data_loc, 'rc_0')); %changing rc year 0
42 rc_5 = (xlsread(data_loc, 'rc_5')); %changing rc year 5
43 rc_10 = (xlsread(data_loc, 'rc_10')); %changing rc year 10
44 rc_15 = (xlsread(data_loc, 'rc_15')); %changing rc year 15
45 rc_20 = (xlsread(data_loc, 'rc_20')); %changing rc year 20
46
47 rates_0 = (xlsread(data_loc, 'rates_0')); %changing rates year 0

```

```

48 rates_5 = (xlsread(data_loc , 'rates_5 ')); %changing rates year 5
49 rates_10 = (xlsread(data_loc , 'rates_10 ')); %changing rates year
    10
50 rates_15 = (xlsread(data_loc , 'rates_15 ')); %changing rates year
    15
51 rates_20 = (xlsread(data_loc , 'rates_20 ')); %changing rates year
    20
52
53
54%% ___Data Processing For Original Vs No Obsolecence___
55
56% Finding size of data
57 data_size = size(original); %size of data (years , 7)
58
59% Original data
60 ot_bounds = original(:,4) - original(:,2); %difference in lower
    and
61 oc_bounds = original(:,7) - original(:,5); %upper bounds for time
    and cost
62
63% No Obsolecence Data
64 not_bounds = no_obsol(:,4) - no_obsol(:,2); %difference in lower
    and
65 noc_bounds = no_obsol(:,7) - no_obsol(:,5); %upper bounds for
    time and cost
66
67% Plotting original bounds
68 for t = 1:data_size(1)

```

```

69     low_ot = original(t,2);
70     ot_diff = ot_bounds(t);
71     low_oc = original(t,5);
72     oc_diff = oc_bounds(t);
73
74     rectangle('position',[low_ot, low_oc, ot_diff, oc_diff])
75     hold on
76 end
77
78 % Plotting original expected values
79 plot(original(:,3),original(:,6),'k-o')
80
81 for t = 1:data_size(1) %adding labels
82     o_label1 = '\leftarrow ';
83     o_label2 = num2str(original(t,1));
84     o_label = strcat(o_label1,o_label2);
85     text(original(t,3),original(t,6),o_label)
86 end
87
88 % Making proper axis bounds (Have to do only once)
89 ll_time = min(original(1,2),no_obsol(1,2)); %lower limit for time
90 ul_time = max(original(end,4),no_obsol(end,4)); %upper limit for
    time
91 ll_time = ll_time - ll_time*.1; %want axis bounds to be slightly
    larger than
92 ul_time = ul_time + ul_time*.1; %distribution bounds
93
94 ll_cost = min(original(1,5),no_obsol(1,5)); %lower limit for cost

```

```

95 ul_cost = max(original(end,7),no_obsol(end,7)); %upper limit for
    cost
96 ll_cost = ll_cost - ll_cost*.1; %want axis bounds to be slighty
    larger than
97 ul_cost = ul_cost + ul_cost*.1; %distribution bounds
98
99 axis([ll_time ,ul_time ,ll_cost ,ul_cost ])
100
101% Adding time/cost bounds (A-B is time bound. C-D is cost bound)
102A = [time_bound ,time_bound]; %(x1 ,x2)
103B = [ul_cost ,time_bound]; %(y1 ,y2)
104hold on
105 line(A,B, 'Color', 'k', 'LineStyle', '—')
106
107C = [0 ,ul_time]; %(x1 ,x2)
108D = [cost_bound ,cost_bound]; %(y1 ,y2)
109hold on
110 line(C,D, 'Color', 'k', 'LineStyle', '—')
111
112% Adding labels to plot
113 title('Areas of Concern For Time and Cost of Process With
    Obsolecence')
114 xlabel('Time');
115 ylabel('Cost');
116
117% Plotting no obsolecence bounds
118 figure
119

```

```

120 for t = 1:data_size(1)
121     low_not = no_obsol(t,2);
122     not_diff = not_bounds(t);
123     low_noc = no_obsol(t,5);
124     noc_diff = noc_bounds(t);
125
126     rectangle('position',[low_not, low_noc, not_diff, noc_diff],
                'EdgeColor','r')
127     hold on
128 end
129
130 % Plotting no obsolescence expected values
131 plot(no_obsol(:,3),no_obsol(:,6),'r-o')
132
133 for t = 1:data_size(1) %adding labels
134     no_label1 = '\leftarrow ';
135     no_label2 = num2str(no_obsol(t,1));
136     no_label = strcat(no_label1,no_label2);
137     text(no_obsol(t,3),no_obsol(t,6),no_label)
138 end
139
140 axis([ll_time,ul_time,ll_cost,ul_cost])
141
142 % Adding time/cost bounds (A-B is time bound. C-D is cost bound)
143 hold on
144 line(A,B,'Color','k','LineStyle','—')
145
146 hold on

```

```

147 line(C,D, 'Color', 'k', 'LineStyle', '—')
148
149% Adding labels to plot
150 title('Areas of Concern For Time and Cost of Process Without
        Obsolescence')
151 xlabel('Time');
152 ylabel('Cost');
153
154%% --Data Processing For Original Vs Changing RCs--
155
156 plotstyle = {'-or', '-ob', '-ok', '-+r', '-+b'}; %colors
157
158% Determining plot bounds. Want to keep plot bounds constant to
        watch the
159% distribution bounds "creep" as obsolescence sets in.
160 plot_time_min = min(rc_0(:,2)); %lower bound of x-axis of all
        time plots
161 plot_time_max = max(rc_20(:,4)); %upper bound of x-axis of all
        time plots
162 plot_cost_min = min(rc_0(:,5)); %lower bound of x-axis of all
        cost plots
163 plot_cost_max = max(rc_20(:,7)); %upper bound of x-axis of all
        cost plots
164
165 y_min = min(rc_0(:,1))*1.2;
166 y_max = max(rc_0(:,1))*1.2;
167
168 [l,~] = size(rc_0); %want number of lines.

```



```

169
170% Year 0
171 figure %(for duration)
172 for dur = 1:1:1
173     t_xs = rc_0(dur,2:4); %x-coordinates of line
174     t_ys = ones(1,3)*rc_0(dur,1); %y-coordinates of line
175     plot(t_xs,t_ys,plotstyle{dur});
176     hold on
177 end
178 axis([plot_time_min,plot_time_max,y_min,y_max]);
179 xlabel('Time (Minimum, Expected, Maximum)')
180 ylabel('Change in RC (%)')
181 title('Comparing Distribution of Process Time of Different RC
        Values at Year 0')
182 time_lim_bott = [time_bound,time_bound]; %bottom of line for
        duration bound
183 time_lim_top = [y_min,y_max]; %top of line for duration bound
184 line(time_lim_bott,time_lim_top,'Color','k','LineStyle','—')
185
186 figure %(for cost)
187 for cost = 1:1:1
188     c_xs = rc_0(cost,5:7); %x-coordinates of line
189     c_ys = ones(1,3)*rc_0(cost,1); %y-coordinates of line
190     plot(c_xs,c_ys,plotstyle{cost});
191     hold on
192 end
193 axis([plot_cost_min,plot_cost_max,y_min,y_max]);
194 xlabel('Cost (Minimum, Expected, Maximum)')

```

```

195 ylabel('Change in RC (%)')
196 title('Comparing Distribution of Process Cost of Different RC
        Values at Year 0')
197 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
        duration bound
198 cost_lim_top = [y_min , y_max]; %top of line for duration bound
199 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
200
201 % Year 5
202 figure %(for duration)
203 for dur = 1:1:1
204     t_xs = rc_5(dur , 2:4); %x-coordinates of line
205     t_ys = ones(1,3)*rc_5(dur , 1); %y-coordinates of line
206     plot(t_xs , t_ys , plotstyle{dur});
207     hold on
208 end
209 axis([plot_time_min , plot_time_max , y_min , y_max]);
210 xlabel('Time (Minimum, Expected, Maximum)')
211 ylabel('Change in RC (%)')
212 title('Comparing Distribution of Process Time of Different RC
        Values at Year 5')
213 time_lim_bott = [time_bound , time_bound]; %bottom of line for
        duration bound
214 time_lim_top = [y_min , y_max]; %top of line for duration bound
215 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
216
217 figure %(for cost)
218 for cost = 1:1:1

```

```

219     c_xs = rc_5(cost,5:7); %x-coordinates of line
220     c_ys = ones(1,3)*rc_5(cost,1); %y-coordinates of line
221     plot(c_xs,c_ys,plotstyle{cost});
222     hold on
223 end
224 axis([plot_cost_min,plot_cost_max,y_min,y_max]);
225 xlabel('Cost (Minimum, Expected, Maximum)')
226 ylabel('Change in RC (%)')
227 title('Comparing Distribution of Process Cost of Different RC
        Values at Year 5')
228 cost_lim_bott = [cost_bound,cost_bound]; %bottom of line for
        duration bound
229 cost_lim_top = [y_min,y_max]; %top of line for duration bound
230 line(cost_lim_bott,cost_lim_top,'Color','k','LineStyle','—')
231
232 % Year 10
233 figure %(for duration)
234 for dur = 1:1:1
235     t_xs = rc_10(dur,2:4); %x-coordinates of line
236     t_ys = ones(1,3)*rc_10(dur,1); %y-coordinates of line
237     plot(t_xs,t_ys,plotstyle{dur});
238     hold on
239 end
240 axis([plot_time_min,plot_time_max,y_min,y_max]);
241 xlabel('Time (Minimum, Expected, Maximum)')
242 ylabel('Change in RC (%)')
243 title('Comparing Distribution of Process Time of Different RC
        Values at Year 10')

```

```

244 time_lim_bott = [time_bound ,time_bound]; %bottom of line for
      duration bound
245 time_lim_top = [y_min ,y_max]; %top of line for duration bound
246 line(time_lim_bott ,time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
247
248 figure %(for cost)
249 for cost = 1:1:1
250     c_xs = rc_10(cost ,5:7); %x-coordinates of line
251     c_ys = ones(1,3)*rc_10(cost ,1); %y-coordinates of line
252     plot(c_xs ,c_ys ,plotstyle{cost});
253     hold on
254 end
255 axis([plot_cost_min ,plot_cost_max ,y_min ,y_max]);
256 xlabel('Cost (Minimum, Expected, Maximum)')
257 ylabel('Change in RC (%)')
258 title('Comparing Distribution of Process Cost of Different RC
      Values at Year 10')
259 cost_lim_bott = [cost_bound ,cost_bound]; %bottom of line for
      duration bound
260 cost_lim_top = [y_min ,y_max]; %top of line for duration bound
261 line(cost_lim_bott ,cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
262
263 % Year 15
264 figure %(for duration)
265 for dur = 1:1:1
266     t_xs = rc_15(dur ,2:4); %x-coordinates of line
267     t_ys = ones(1,3)*rc_15(dur ,1); %y-coordinates of line
268     plot(t_xs ,t_ys ,plotstyle{dur});

```

```

269     hold on
270 end
271 axis ([plot_time_min , plot_time_max , y_min , y_max]);
272 xlabel('Time (Minimum, Expected, Maximum)')
273 ylabel('Change in RC (%)')
274 title('Comparing Distribution of Process Time of Different RC
        Values at Year 15')
275 time_lim_bott = [time_bound , time_bound]; %bottom of line for
        duration bound
276 time_lim_top = [y_min , y_max]; %top of line for duration bound
277 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
278
279 figure %(for cost)
280 for cost = 1:1:1
281     c_xs = rc_15(cost , 5:7); %x-coordinates of line
282     c_ys = ones(1,3)*rc_15(cost , 1); %y-coordinates of line
283     plot(c_xs , c_ys , plotstyle{cost});
284     hold on
285 end
286 axis ([plot_cost_min , plot_cost_max , y_min , y_max]);
287 xlabel('Cost (Minimum, Expected, Maximum)')
288 ylabel('Change in RC (%)')
289 title('Comparing Distribution of Process Cost of Different RC
        Values at Year 15')
290 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
        duration bound
291 cost_lim_top = [y_min , y_max]; %top of line for duration bound
292 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')

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293
294% Year 20
295 figure %(for duration)
296 for dur = 1:1:1
297     t_xs = rc_20(dur,2:4); %x-coordinates of line
298     t_ys = ones(1,3)*rc_20(dur,1); %y-coordinates of line
299     plot(t_xs , t_ys , plotstyle{dur});
300     hold on
301 end
302 axis([plot_time_min , plot_time_max , y_min , y_max]);
303 xlabel('Time (Minimum, Expected, Maximum)')
304 ylabel('Change in RC (%)')
305 title('Comparing Distribution of Process Time of Different RC
        Values at Year 20')
306 time_lim_bott = [time_bound , time_bound]; %bottom of line for
        duration bound
307 time_lim_top = [y_min , y_max]; %top of line for duration bound
308 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
309
310 figure %(for cost)
311 for cost = 1:1:1
312     c_xs = rc_20(cost , 5:7); %x-coordinates of line
313     c_ys = ones(1,3)*rc_20(cost , 1); %y-coordinates of line
314     plot(c_xs , c_ys , plotstyle{cost});
315     hold on
316 end
317 axis([plot_cost_min , plot_cost_max , y_min , y_max]);
318 xlabel('Cost (Minimum, Expected, Maximum)')

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319 ylabel('Change in RC (%)')
320 title('Comparing Distribution of Process Cost of Different RC
        Values at Year 20')
321 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
        duration bound
322 cost_lim_top = [y_min , y_max]; %top of line for duration bound
323 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
324
325%% __Data Processing For Original Vs Changing Rates__
326
327 plotstyle = {'-or' , '-ob' , '-ok' , '-+r' , '-+b'}; %colors
328
329% Determining plot bounds. Want to keep plot bounds constant to
        watch the
330% distribution bounds "creep" as obsolescence sets in.
331 plot_time_min = min(rates_0(:,2)); %lower bound of x-axis of all
        time plots
332 plot_time_max = max(rates_20(:,4)); %upper bound of x-axis of all
        time plots
333 plot_cost_min = min(rates_0(:,5)); %lower bound of x-axis of all
        cost plots
334 plot_cost_max = max(rates_20(:,7)); %upper bound of x-axis of all
        cost plots
335
336 y_min = min(rates_0(:,1)) * 1.2;
337 y_max = max(rates_0(:,1)) * 1.2;
338
339 [1, ~] = size(rates_0); %want number of lines.

```

```

340
341% Year 0
342 figure %(for duration)
343 for dur = 1:1:1
344     t_xs = rates_0(dur,2:4); %x-coordinates of line
345     t_ys = ones(1,3)*rates_0(dur,1); %y-coordinates of line
346     plot(t_xs , t_ys , plotstyle{dur});
347     hold on
348 end
349 axis ([plot_time_min , plot_time_max , y_min , y_max]);
350 xlabel('Time (Minimum, Expected, Maximum)')
351 ylabel('Change in Rates (%)')
352 title('Comparing Distribution of Process Time of Different Rates
        at Year 0')
353 time_lim_bott = [time_bound , time_bound]; %bottom of line for
        duration bound
354 time_lim_top = [y_min , y_max]; %top of line for duration bound
355 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
356
357 figure %(for cost)
358 for cost = 1:1:1
359     c_xs = rates_0(cost , 5:7); %x-coordinates of line
360     c_ys = ones(1,3)*rates_0(cost , 1); %y-coordinates of line
361     plot(c_xs , c_ys , plotstyle{cost});
362     hold on
363 end
364 axis ([plot_cost_min , plot_cost_max , y_min , y_max]);
365 xlabel('Cost (Minimum, Expected, Maximum)')

```



```

366 ylabel('Change in Rates (%)')
367 title('Comparing Distribution of Process Cost of Different Rates
        at Year 0')
368 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
        duration bound
369 cost_lim_top = [y_min , y_max]; %top of line for duration bound
370 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
371
372 % Year 5
373 figure %(for duration)
374 for dur = 1:1:1
375     t_xs = rates_5(dur , 2:4); %x-coordinates of line
376     t_ys = ones(1 , 3) * rates_5(dur , 1); %y-coordinates of line
377     plot(t_xs , t_ys , plotstyle{dur});
378     hold on
379 end
380 axis([plot_time_min , plot_time_max , y_min , y_max]);
381 xlabel('Time (Minimum, Expected, Maximum)')
382 ylabel('Change in Rates (%)')
383 title('Comparing Distribution of Process Time of Different Rates
        at Year 5')
384 time_lim_bott = [time_bound , time_bound]; %bottom of line for
        duration bound
385 time_lim_top = [y_min , y_max]; %top of line for duration bound
386 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
387
388 figure %(for cost)
389 for cost = 1:1:1

```

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390     c_xs = rates_5(cost,5:7); %x-coordinates of line
391     c_ys = ones(1,3)*rates_5(cost,1); %y-coordinates of line
392     plot(c_xs,c_ys,plotstyle{cost});
393     hold on
394 end
395 axis([plot_cost_min,plot_cost_max,y_min,y_max]);
396 xlabel('Cost (Minimum, Expected, Maximum)')
397 ylabel('Change in Rates (%)')
398 title('Comparing Distribution of Process Cost of Different Rates
        at Year 5')
399 cost_lim_bott = [cost_bound,cost_bound]; %bottom of line for
        duration bound
400 cost_lim_top = [y_min,y_max]; %top of line for duration bound
401 line(cost_lim_bott,cost_lim_top,'Color','k','LineStyle','—')
402
403 % Year 10
404 figure %(for duration)
405 for dur = 1:1:1
406     t_xs = rates_10(dur,2:4); %x-coordinates of line
407     t_ys = ones(1,3)*rates_10(dur,1); %y-coordinates of line
408     plot(t_xs,t_ys,plotstyle{dur});
409     hold on
410 end
411 axis([plot_time_min,plot_time_max,y_min,y_max]);
412 xlabel('Time (Minimum, Expected, Maximum)')
413 ylabel('Change in Rates (%)')
414 title('Comparing Distribution of Process Time of Different Rates
        at Year 10')

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415 time_lim_bott = [time_bound ,time_bound]; %bottom of line for
      duration bound
416 time_lim_top = [y_min ,y_max]; %top of line for duration bound
417 line (time_lim_bott ,time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
418
419 figure %(for cost)
420 for cost = 1:1:1
421     c_xs = rates_10 (cost ,5:7); %x-coordinates of line
422     c_ys = ones (1,3)*rates_10 (cost ,1); %y-coordinates of line
423     plot (c_xs ,c_ys ,plotstyle {cost });
424     hold on
425 end
426 axis ([plot_cost_min ,plot_cost_max ,y_min ,y_max]);
427 xlabel ('Cost (Minimum, Expected, Maximum)')
428 ylabel ('Change in Rates (%)')
429 title ('Comparing Distribution of Process Cost of Different Rates
      at Year 10')
430 cost_lim_bott = [cost_bound ,cost_bound]; %bottom of line for
      duration bound
431 cost_lim_top = [y_min ,y_max]; %top of line for duration bound
432 line (cost_lim_bott ,cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
433
434 % Year 15
435 figure %(for duration)
436 for dur = 1:1:1
437     t_xs = rates_15 (dur ,2:4); %x-coordinates of line
438     t_ys = ones (1,3)*rates_15 (dur ,1); %y-coordinates of line
439     plot (t_xs ,t_ys ,plotstyle {dur });

```

```

440     hold on
441 end
442 axis ([plot_time_min , plot_time_max , y_min , y_max]);
443 xlabel('Time (Minimum, Expected, Maximum)')
444 ylabel('Change in Rates (%)')
445 title('Comparing Distribution of Process Time of Different Rates
         at Year 15')
446 time_lim_bott = [time_bound , time_bound]; %bottom of line for
         duration bound
447 time_lim_top = [y_min , y_max]; %top of line for duration bound
448 line(time_lim_bott , time_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
449
450 figure %(for cost)
451 for cost = 1:1:1
452     c_xs = rates_15(cost , 5:7); %x-coordinates of line
453     c_ys = ones(1,3)*rates_15(cost , 1); %y-coordinates of line
454     plot(c_xs , c_ys , plotstyle{cost});
455     hold on
456 end
457 axis ([plot_cost_min , plot_cost_max , y_min , y_max]);
458 xlabel('Cost (Minimum, Expected, Maximum)')
459 ylabel('Change in Rates (%)')
460 title('Comparing Distribution of Process Cost of Different Rates
         at Year 15')
461 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
         duration bound
462 cost_lim_top = [y_min , y_max]; %top of line for duration bound
463 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')

```

```

464
465 % Year 20
466 figure %(for duration)
467 for dur = 1:1:1
468     t_xs = rates_20(dur,2:4); %x-coordinates of line
469     t_ys = ones(1,3)*rates_20(dur,1); %y-coordinates of line
470     plot(t_xs, t_ys, plotstyle{dur});
471     hold on
472 end
473 axis([plot_time_min, plot_time_max, y_min, y_max]);
474 xlabel('Time (Minimum, Expected, Maximum)')
475 ylabel('Change in Rates (%)')
476 title('Comparing Distribution of Process Time of Different Rates
         at Year 20')
477 time_lim_bott = [time_bound, time_bound]; %bottom of line for
         duration bound
478 time_lim_top = [y_min, y_max]; %top of line for duration bound
479 line(time_lim_bott, time_lim_top, 'Color', 'k', 'LineStyle', '—')
480
481 figure %(for cost)
482 for cost = 1:1:1
483     c_xs = rates_20(cost,5:7); %x-coordinates of line
484     c_ys = ones(1,3)*rates_20(cost,1); %y-coordinates of line
485     plot(c_xs, c_ys, plotstyle{cost});
486     hold on
487 end
488 axis([plot_cost_min, plot_cost_max, y_min, y_max]);
489 xlabel('Cost (Minimum, Expected, Maximum)')

```

```
490 ylabel('Change in Rates (%)')
491 title('Comparing Distribution of Process Cost of Different Rates
        at Year 20')
492 cost_lim_bott = [cost_bound , cost_bound]; %bottom of line for
        duration bound
493 cost_lim_top = [y_min , y_max]; %top of line for duration bound
494 line(cost_lim_bott , cost_lim_top , 'Color' , 'k' , 'LineStyle' , '—')
```

VITA

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Currently working at Old Dominion University as a graduate research assistant (areas: life cycle and naval engineering). Currently researching process planning methods while considering obsolescence. Did past work on a project sponsored by the Naval Engineering Education Consortium (NEEC). Was on a research team that developed models for the life cycle cost of naval systems. Taught an engineering graphics class at Thomas Nelson Community College.

Publications:

Obeng, G. K., Bao, H. P., 2016, "Design Structure Matrix with Consideration of Technological Obsolescence for Managing Complex Engineering Projects, Advanced Technology Symposium 2016, Villanova, Pennsylvania.

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The word processor for this dissertation was Texmaker, a form of L^AT_EX.