SAME[1]

We each,
are like a flower.
Difference is,
we observe
a flower's beauty and passing.
And we are,
Our own.

[1] *Unpublished poem "Same" written and contributed by Eric Nygren.*

University of Alberta

Refinery Power Distribution Reliability and Interruption

by

Leif Matthew Nygren

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

Electrical and Computer Engineering

Fall 2009
Edmonton, Alberta

Examining Committee

Dr. Don Koval, Electrical and Computer Engineering

Dr. Venkata Dinavahi, Electrical and Computer Engineering

Dr. Andrew Knight, Electrical and Computer Engineering

Dr. Ming Zuo, Mechanical Engineering

Dr. Dil Joseph, Electrical and Computer Engineering

Dedicaiton

This thesis is dedicated to my parents, Eric & Bonnie Nygren, whose wisdom has shaped and forged my perspective.

Abstract

In the refining industry, the cost of a power system interruption is dominated by an associated loss of production. Power distribution within a refinery includes a set of production units within a highly inter-dependent process, where the outage of a single unit affects the production of additional units. This thesis proposes a method to quantify the impact of this cascading effect, called the criticality enhancement function, in which a process reliability model is introduced to link electrical outage cut-sets with lost production. Power system criticality is analyzed using four different approaches to the calculation of annual expected impact from load point interruptions on a case study of the 125,000 barrel-per-day Petro-Canada Edmonton Refinery. This thesis demonstrates how employment of the proposed technique, with its marriage of electrical and process reliability models, enables the most accurate estimation of the impact of power system interruptions.

Acknowledgements

I wish to express my thanks to my supervising professors Dr. Koval and Dr. Dinavahi for their guidance.

Thanks to my wife Andrea, without whom this would *not* have been possible.

Thanks to Randy Parcels, Mike Lyne, and Tom Day for their support, mentorship, and for allowing the use the Petro-Canada Edmonton Refinery as my case study.

Thanks to Phil O'Hara for his mentorship and wisdom.

And thanks to Dr. Milne for his clairvoyance and support throughout my journey.

Contents

List of Tables

List of Figures

Abbreviations

BPU	Barrels per-unit of average refinery production (flow rate)
BPU•H	Barrels per-unit hours of average refinery production (volume)
CAT	Catalytic cracking unit
CCF	Common cause factor
CEF	Criticality enhancement function
CFHTU	Catalytic cracking unit feed hydrotreating unit
CSV	Current state vector
DHTU	Distillate hydrotreating unit
EDD or ED	Edmonton diesel desulphurization
EDMR	Petro-Canada Edmonton refinery
FCCU	Fluid catalytic cracking cnit
HF	Hydro-fluoric
HTU	Hydrotreating unit
IDCV	Input don't care vector
IEEE	Institute of electrical and electronics engineers
ISTM	Input state transition matrix
LPG	Liquefied petroleum gas
MTBF	Mean time between failures
NSV	Next state vector
ODCV	Output don't care vector
OSTM	Output state transition matrix
PCIC	IEEE petroleum and chemical industry subcommittee
SIG or SG	Sulphur in gas
ST	Survival time

Chapter 1 – Introduction

1.1 Motivation & Perspective

As energy demand grows without a sizeable increase in North American refining capacity, existing refineries' production becomes more heavily relied upon to be increasingly both stable and available. In an era where a prolonged interruption of a single refinery can cause a widespread gasoline or diesel shortage, greater attention is being paid to plant reliability. A tangible example of the increased awareness and importance of reliability is the increasingly common use of the title 'Reliability Engineer' throughout the oil & gas industry. A Reliability Engineer is tasked with minimizing the expected cost of unavailability for a given scope, within the constraint of a reasonable budget. For an Electrical Reliability Engineer, to achieve and maintain a reliable power system, the task that arises is how to optimally distribute limited resources, to this end. From the perspective of a Reliability Engineer, motivation for this thesis is to develop a practical optimization solution that more accurately estimates the impact of electrical power system interruptions in a refinery.

There is a common misconception that maximizing availability necessarily minimizes the expected cost of unavailability. This thesis intends to demonstrate that longer outages tend to cascade throughout a refinery. It is hoped that, by studying the effects of electrical cut-sets on a process reliability model, Electrical Reliability Engineers within the oil & gas industry can adopt conclusions that enable an improved optimization of available resources within their power systems.

1.2 Outline of Thesis

This thesis is divided into seven chapters. Chapter #1 sets the stage for subsequent chapters by sharing motivation and perspective, and then provides the necessary background theory required to understand the material in subsequent chapters.

Chapter #2 introduces a problem statement, and then a proposed solution. This chapter outlines a general solution approach, which is demonstrated by a case study in later chapters. Chapter #2 introduces the concept of the 'Criticality Enhancement Function' to assess the impact of power supply on a refinery.

Chapter #3 introduces the reader to the case study with an overview of the Petro-Canada Edmonton Refinery, and then a unit-by-unit process description of production units, as a background for Chapters #4 and Chapter #5.

Chapter #4 presents a detailed study of process modeling and simulation of electrical cut-sets to determine the impact of process outage on other units and refinery production vs. downtime. The results in Chapter #4 form the basis required to compute the criticality enhancement function of each electrical cut-set.

Chapter #5 presents a detailed case study electrical reliability analysis that compares data from using the IEEE spreadsheet methodology and a proposed zone branch style method.

Intermediate reliability data is computed for a target substation scenario, creating an interruption probability mass function demonstration.

Chapter #6 displays the interruption BPU functions for all case studies. This chapter ties together the case study target scenario interruption probability mass function and criticality enhancement function to demonstrate the expected impact of substation interruptions.

Chapter #7 summarizes the case study, and draws relevant conclusions from the preceding chapters, that can be used by other Electrical Reliability Engineers.

1.3 Reliability

1.3.1 Bathtub Curve and the Exponential Function

Over the last century, Reliability Engineering has risen to a place of prominence out of necessity. As technology advances, so too does the complexity of the designs we engineer, and the need for those designs to meet performance expectations.

In the period preceding World War II, the concept of reliability existed mainly in a qualitative sense [1]. During the 1950s, the increasing complexity of electronics design in military applications soon demonstrated the need for quantitative reliability consideration in design and this type of unexpected problem drove research in the area of reliability, which fostered the development of quantitative techniques. The term 'reliability' was defined as "*the probability that a device, equipment, or system would perform its intended function for a specified period of time under given conditions [1].*" This definition is very similar to the widely accepted definition we use today, which is "*the ability of a component or system to perform required functions under stated conditions for a stated period of time [3]*", as stated in the IEEE Gold Book.

The most significant initial steps in the science of Reliability Engineering were taken in the period surrounding world war two. Perhaps the most recognizable aspect of reliability is the 'Bathtub Curve' in Figure 1, which depicts the failure rate of electronic equipment as a function of its operating time. The key to the science of reliability engineering is a fundamental understanding that the bathtub curve actually represents the hazard function for electrical equipment and that, during the useful life period of a piece of equipment, the hazard function has a constant value. The hazard function is the instantaneous probability of failure as a function of time, given that failure has not previously occurred.

The most fundamental and basic concepts of probability and cumulative density functions for reliability engineering are summarized in Table 1, to demonstrate how solution of the hazard function differential equation yields the blessing of exponential distributions, for electrical reliability engineers [1] [3].

The bathtub curve in Figure 1 has three distinct failure regions of operation: 'early failure', 'chance failure' during useful life, and 'wearout'. If we assume that a component is in the chance failure region, then a good approximation during useful life is a constant failure rate λ.

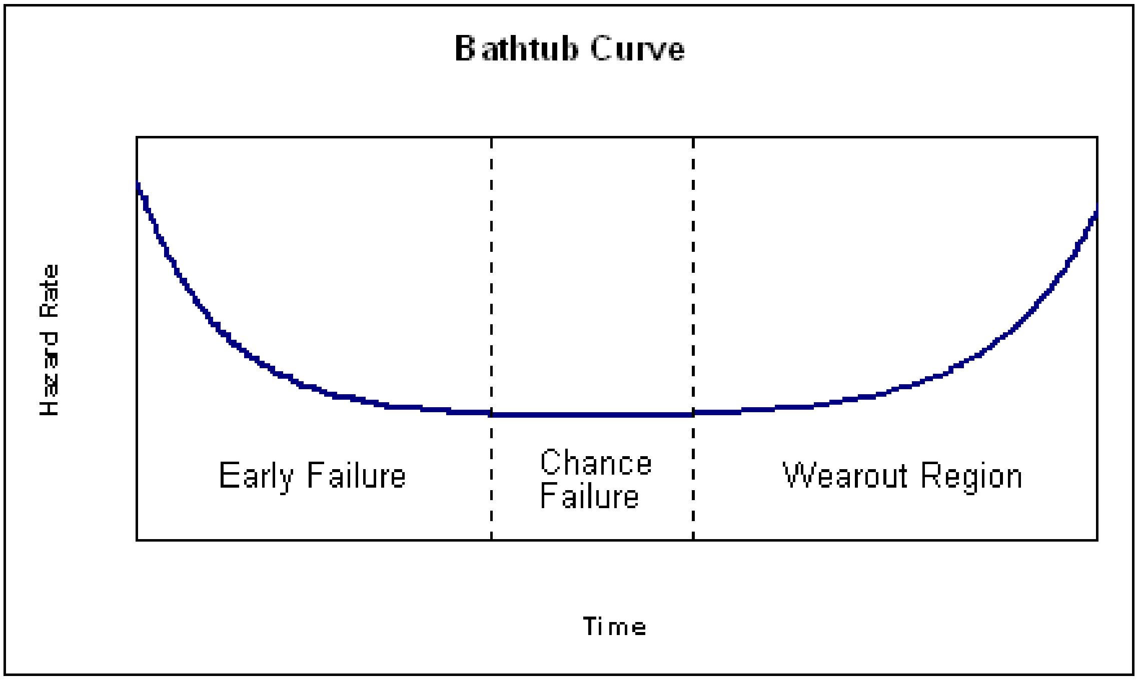


Figure 1: Bathtub Curve

$$h(t) = \frac{f(t)}{1 - \int_0^t f(t)dt} = \lambda \quad \rightarrow \quad f(t) = \lambda\left(1 - \int_0^t f(t)dt\right) \quad \rightarrow \quad \frac{df(t)}{dt} = -\lambda f(t) \qquad (1)$$

The solution of equation (1) yields the basic exponentially distributed results $f(t) = \lambda e^{-\lambda t}$, $F(t) = 1 - e^{-\lambda t}$, and finally $R(t) = e^{-\lambda t}$.

Table 1: Basic Reliability Definitions & Equations

Function or Variable		Definition		Equation
λ	Failure Rate	The approximately constant value of the bathtub curve in the operating time region. Usually given in units of number of failures per year.		λ
$MTBF$	Mean Time Between Failures	The mean exposure time between consecutive failures of a component.		$\frac{1}{\lambda}$
r	Mean Time To Repair	The mean time to repair or replace a component. Units are most useful in years per failure, and it is assumed that there are 8760 hours per year.		r
$f(t)$	Failure pdf	The instantaneous probability that a component will fail.	$\int_0^\infty f(t)dt = 1$	$f(t) = \lambda e^{-\lambda t}$
$F(t)$	Failure cdf	The probability that a component will fail before time 't'	$F(t) = \int_0^t f(t)dt$	$F(t) = 1 - e^{-\lambda t}$
$R(t)$	Reliability Function	The probability that a component will not fail before time 't'	$R(t) = \int_t^\infty f(t)dt$	$R(t) = 1 - F(t)$ $R(t) = e^{-\lambda t}$
$h(t)$	Hazard Function	The instantaneous conditional probability that a component will fail, given that the component has not previously failed.	$h(t) = \frac{f(t)}{\int_t^\infty f(t)dt}$	$h(t) = \lambda$

1.3.2 Availability and Probabilistic vs. Deterministic Modeling

Availability is the most widely used metric, to quantify the reliability of a system. Availability ("A") is the fraction of time that a component or system is expected to be available for service in a given period of time and may be derived from the simple two-state Markov model in Figure 2. In this model, the steady-state probability of transitioning from UP to DOWN is given by the failure rate λ, and the steady-state probability of transitioning from DOWN to UP, is given by the repair rate $\frac{1}{r}$. Using the frequency balance approach, the availability may then be expressed as the probability of being in the UP state [2].

$$P(UP)\cdot\lambda = P(DOWN)\cdot\frac{1}{r} = (1-P(UP))\cdot\frac{1}{r} = \frac{1}{r} - \frac{P(UP)}{r}$$

$$P(UP)\cdot\left(\lambda+\frac{1}{r}\right) = \frac{1}{r} \quad\rightarrow\quad P(UP)\cdot(r\cdot\lambda+1) = 1$$

$$A = P(UP) = \frac{1}{1+\lambda\cdot r} \tag{2}$$

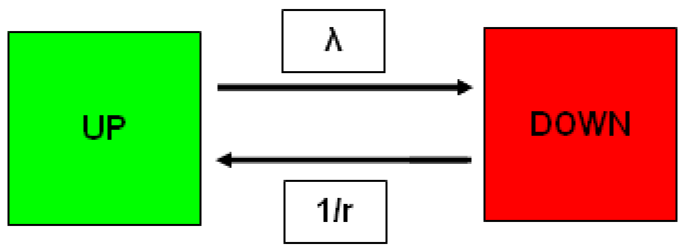


Figure 2: Two State Time Invariant Markov Model – Renewable System

It is often assumed that the employment of a probabilistic model precludes the use of a deterministic model. Successful prediction using a probabilistic model does not necessarily mean that a process exhibits any more or less inherent randomness or unpredictability than a process whose deterministic model is widely employed. It is the opinion of the author that a deterministic model is often abandoned in favor of a simplified probabilistic model, due to lack of specific information, burdensome computation, or possibly a lack of fundamental understanding of the physics behind a predictable event. Take the simple example of a card player enjoying a game of Texas Hold'em. The card player knows only his two hole cards, three flop cards, and one turn card. Based on the cards he knows and the behavior of his opponents, he employs a probabilistic model in an attempt to predict the identity of the river (last) card because he has only this limited information. To the card player, the identity of the river card exhibits randomness. In reality, we could peek at the river card and know that it's the Ace of Hearts – it's determined. Similarly, if we had information pertaining to all the other cards in the deck, we could employ a deterministic model knowing 51 of 52 cards to identify and determine the remaining card. In that sense, a process can be modeled by either a deterministic or probabilistic model, depending on the amount of information available, and the perception of randomness does not preclude determinism. Electrical components or systems seem to exhibit failure rates that look similar to probability distributions with which we are familiar. If, however, we knew vast amounts of information about the materials, construction, and service duty of a particular component, we could employ a deterministic model to more accurately predict the time at which the component will fail. It is important to understand that when a deterministic or probabilistic model can accurately predict an outcome, it doesn't mean that the system is necessarily inherently purely random, or purely deterministic in nature.

1.3.3 Zone-Branch Method

Zone-Branch is a technique used for analyzing the availability of load points in complex networks, which includes the impact of other components' failure and other customers' failures, as well as the impact of unreliable protection-coordination schemes. The Zone Branch algorithm is a reliability model used by industry's leading software packages of today. The zone-branch technique is especially appropriate for the study of electrical systems, because it lends itself well to the modeling of protective devices, which are prevalent in power systems. As an extension of the cut-set method, zone-branch makes use of the assumptions that equipment repair times are generally small, and failure rates are generally infrequent, and hence most component failures are mutually exclusive.

The key to understanding the Zone-Branch technique is the distinction between isolating a branch due to a fault in that branch, and isolating that branch because of a fault in a different branch of the network configuration.

The technique [2] begins by partitioning a power system network into branches within protective zones. Each zone is sequentially numbered and then branches within each zone are sequentially numbered.

Mean time to repair and failure rate are then calculated for each branch based only on the components present in a given branch.

Symbols, variables, and relevant equations are here defined:

i	-	The Zone Number
j	-	The Branch Number within a given Zone
$\lambda_{i,j}^{0}$	-	Failure Rate of the j'th Branch of i'th Zone and is an INPUT to the Zone-Branch calculation.
$r_{i,j}^{0}$	-	Mean Time To Repair of the j'th Branch of i'th Zone
$\lambda_{i,j}$	-	Frequency of Interruptions of the j'th Branch of the i'th Zone due to failure in the zone-branch i,j as well as failures of other Branches and the Utility, and is the OUTPUT of the Zone-Branch calculation.
$r_{i,j}$	-	Mean Duration of Interruption of the j'th Branch of the i'th Zone due to failure in the zone-branch i,j as well as failures of other Branches and the Utility
$\lambda r_{i,j}$	-	Mean Annual Downtime of the of the j'th Branch of the i'th Zone due to failure in the zone-branch i,j as well as failures of other Branches and the Utility
$A_{i,j}$	-	Availability of the j'th Branch of the i'th Zone

The results of the zone branch calculation include mean duration of repair and availability:

$$r_{i,j} = \frac{\lambda r_{i,j}}{\lambda_{i,j}} \tag{3}$$

$$A_{i,j} = \frac{1}{1+\lambda r_{i,j}} \tag{4}$$

A recent advance in the Zone-Branch technique is the introduction of the Common Cause Factor (CCF) for dual redundant utility supplies to industrial substations [4]. The CCF is a number between 0.1 and 0.95 that represents the probability of a dual power outage occurring. Failures of parallel utility feeds are not independent in nature, and the CCF is an empirical representation of that non-independence. In an extreme case where the CCF is very high, two utilities would tend to behave more like a single utility, whereas if the CCF is very low, the utilities would tend to behave like independent entities.

Equation (5) represents the equivalent failure rate of two utilities in parallel as a function of the failure rates and availabilities of the constituent parallel utilities, as well as the common cause factor.

$$\lambda_{Ut}^{0} = \lambda_{Ut_1}^{0} + \lambda_{Ut_2}^{0} - \lambda_{Ut_1}^{0} A_{Ut_1}^{0} - \lambda_{Ut_2}^{0} A_{Ut_2}^{0} + \max\left(\lambda_{Ut_1}^{0}, \lambda_{Ut_2}^{0}\right) \cdot CCF_{\lambda_{Ut_1}^{0}, \lambda_{Ut_2}^{0}} \tag{5}$$

λ_{Ut}^{0}	Failure Rate of two 'redundant' Utilities represented as one equivalent Utility
$\lambda_{Ut_x}^{0}$	Failure Rate of the x'th Utility
$A_{Ut_x}^{0}$	Annual Down Time Fraction of the x'th Utility
$CCF_{\lambda_{Ut_1}^{0}, \lambda_{Ut_2}^{0}}$	Common Coupling factor between Utility 1 and Utility 2

1.4. Consequence of Downtime

Wacker & Billinton [6] conducted a great deal of research in the 1980s regarding the cost of residential, commercial, and industrial interruptions, and created a customer damage function to demonstrate the non-linear nature of how outage duration affects financial impact. Their customer damage function demonstrated an exponential cost with respect to interruption duration.

The IEEE Gold Book has also published data from industry surveys regarding the cost of customer interruptions. In addition to publishing mean downtime per failure, the Gold Book also suggests the parameter of *"plant restart time [3]"*. Although mean values have been tabulated for various costs versus time, the Gold Book notes that *"The reader is again cautioned that such general data should be used only for order of magnitude evaluations where data specific to the system being studied is not available [3]."* This caution statement speaks to the wide variance of cost between industrial sectors and facilities and sets the stage for more detailed modeling of the impact of outages on industrial processes.

Thus far, research involving the cost of downtime to industry has treated each facility or unit as an independent entity. This thesis examines units within a refinery as entities that are dependent on each other, to study the way in which an electrical interruption of a subset of refinery units may cause a cascading outage throughout the entire refinery.

Chapter 2 - Refinery Power Distribution Reliability and Interruption

2.1 Problem Statement

To estimate the expected consequence of electrical outages within a refinery, reliability analysis must involve an approach that includes the cascading effect of unit interruptions. To publish the results of such an investigation, data must be presented in a manor that is useful to other facilities, while respecting the confidentiality of its source.

Reliability Engineers are tasked with improving the reliability of their facilities, and often recommend the dispersion of resources to allow for targeted improvements within their facilities. Such improvements could be maintenance activities, or projects that add redundancy or upgrade to more robust components. To optimize the allocation of resources, the Engineer must focus on areas where improving reliability will lessen the expected impact of interruptions - this requires a clear understanding of the impact of interruptions, and how to relate impact and reliability metrics.

2.1.1 Cascading Impact

To any company whose business involves the transmission and distribution of electricity, customers are facilities which, for the most part, are independent of each other's production; i.e. the interruption of one customer does not generally affect other customers who are still receiving power. To a refinery, distribution of electrical energy also has many 'customers' which are unit substations. Each substation serves one or more process units which are each highly dependent on the states of other units, and an outage of one or more units tends to produce a cascading effect within the entire refinery. If power to a given substation is interrupted, power may be interrupted to one or more process units and the combination of interrupted units may form a process cut-set to other units. The IEEE defines a 'cut-set' as a *"set of components whose failure alone will cause system failure [3]"* For our application within a refinery, we can define a 'process cut-set' to be a set of refinery process units whose interruption will cause one or more other process units within the refinery to eventually become interrupted. Units upstream may require the interrupted units to receive flow and may also become interrupted. Units downstream may require the interrupted units to contribute flow and may also become interrupted. If the cut-set produced by substation interruption interrupts a unit that is crucial to the refinery, production in the entire refinery may become interrupted. This cascading effect amplifies the consequence of substation interruptions and enhances the criticality of electrical reliability within a refinery.

Consider the example refinery process in Figure 3 with process units labeled as plants 1 through 5. Plant 4 will have a throughput that is a fraction of the total refinery production. An interruption of Substation C interrupts Plant 4. Plants 2 and 3 are upstream of Plant 4 and may only be able to run for a limited time without sending product to plant 4. If Plant 2 and 3 are interrupted, Plants 1 and 5 will certainly be interrupted and the outage caused by a single substation has then cascaded throughout the entire refinery. Although the nameplate (rated) capacity of Plant 4 is only a fraction of the total refinery throughput, the result of the electrical interruption at Substation C is a total refinery outage.

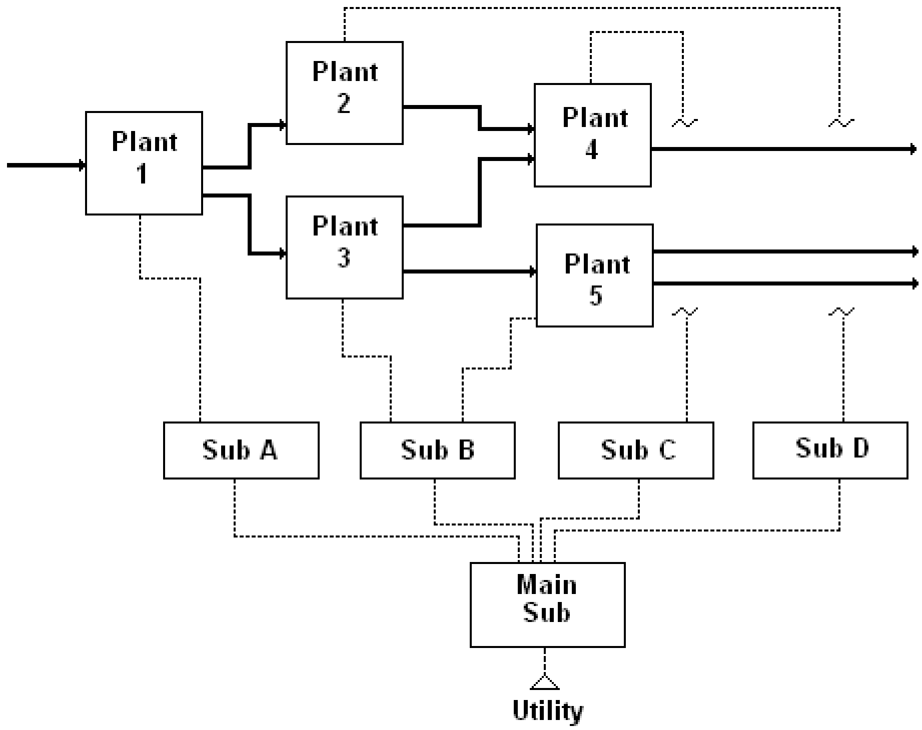


Figure 3: Dependent Process Cascade Example

Without a means of quantifying the cascading effect of substation interruption, the treatment of substations as independent customers tends to underestimate the effects of electrical interruption on smaller units and may downplay the importance of maintenance or reliability improvement to a company's bottom line.

2.1.2 Hindrance to Data Publication

There is a scarcity of published data available regarding the cost of electrical interruption in the oil & gas industry. Cost data, when expressed in dollars, suffers from inflation and commodity price changes and is usually subject to confidentiality. If data from an old study is taken without adjusting for inflation, the tendency is to underestimate cost. If commodity prices or other economic factors change since the data was collected, the published figures would tend to misrepresent current costs. The oil & gas industry is very competitive and confidentiality of costs of interruptions also tends to suppress the publication of useful data. As such, relevant data regarding the cost of electrical interruptions to a refinery may not be publicly available.

2.1.3 Reliability Indices

From data available on the cost of electrical interruptions to other industries, it is clear that cost is not a linear function of time. However, reliability indices such as availability or annual expected down time are presented as averaged data. The duration of an individual interruption determines the impact and the *cost of the average expected interruption* and is likely very different than the a*verage cost of all expected interruption*.

Many different distributions of interruption data can have the same average or expected value, so the relationship between an interruption distribution and an availability metric is *not* one-to-one, making availability an ambiguous measure. When data is averaged, the underlying distribution is lost. As an illustration of this point, consider Figure 4 below. The probability mass functions displayed are for Uniform and Gaussian discrete random variables. While they share a common mean value of 10.5, their distributions are strikingly different.

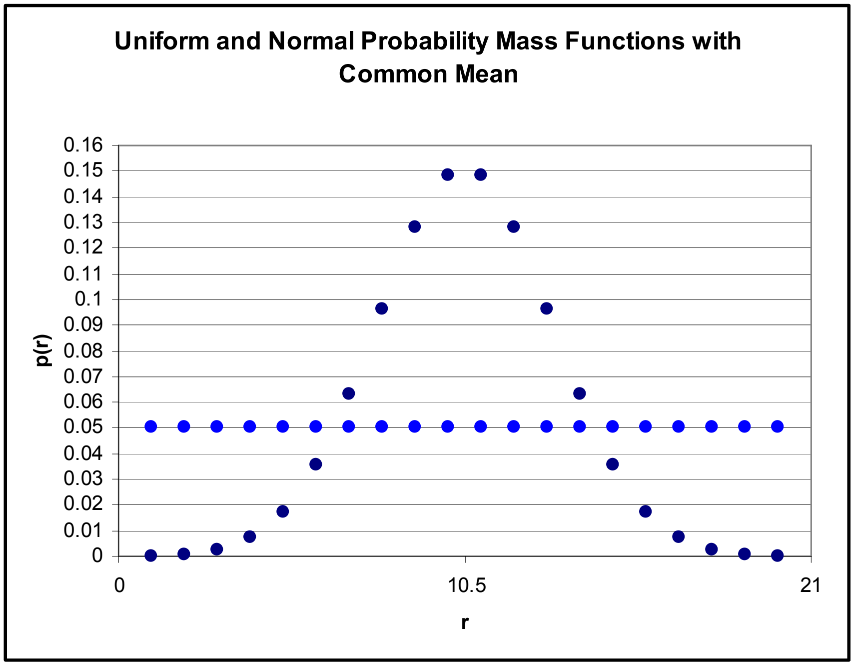


Figure 4: Common Mean Probability Mass Functions

When the underlying distribution is lost, calculation of the impact of interruptions can be inaccurate. This is due to the linearity of expectation. Consider a function g that determines the impact (cost) of interruptions. Given a discrete interruption distribution $p(r)$, its mean value can be calculated as its expected value $E\{r\}$. This thesis argues that, because a cost function g is non-linear, the expected cost of interruptions $g(E\{r\}) \neq E\{g(r)\}$, and that the latter is a more accurate representation of expected impact.

2.2 Proposed Solution

It is proposed that the reliability metric of availability from a zone-branch calculation be replaced by the expected frequency of load point interruptions λ, and a random variable **r,** denoting the load point interruption time; the distribution probability mass function of **r** will then enable calculation of the impact of interruptions.

It is proposed that confidential values such as cost in dollars be replaced by a less confidentially sensitive measure of impact in terms of lost product on a per-unit basis.

It is proposed that a process reliability model be created to determine the cascading impact of substation interruption to units within the refining process. The output of this model then allows an understanding of the cascading nature of process interruption within a refinery.

It is proposed that the functions $CEF(t)$ denote 'Criticality Enhancement Function' of time.

It is proposed that the random variable **y** denote the impact of interruptions in bpu•h. Based on output from the process reliability model, $CEF(t)$ will allow a mapping of the random variable **r** mass points into the interruption domain, creating a distribution of the random variable **y**. The expected impact of an interruption is then the expected value of **y** as $E\{y\}$ and data is readily available to compute a variance $VAR\{y\}$ and a cumulative density function. As such, the random variable **y** is a cascade-inclusive measure of the non-confidential cost of electrical interruptions on a refining process.

2.2.1 The Impact 'Cost' of Interruptions

As a solution to the confidentiality and constancy concerns regarding the publishing of costs in dollars, it is proposed that discussion of cost in dollars be replaced by impact of the opportunity cost in barrels of product. To further protect potential data sources and to present results in a scaleable form, it would be more useful to calculate flow on a per-unit basis of the total rated flow of a refinery.

It is proposed that the introduction of a new unit "**bpu**" denote "**b**arrels-**p**er-**u**nit of refinery average flow. Product volume would then be expressed in ***bpu•h***, denoting 'barrels-per-unit-hours of refinery average flow', where 'h' stands for 'hours'. By expressing flow in bpu, another refinery of a different size could reasonably assume that, if a similar given production unit is out-of-service, they may have a similar bpu of opportunity cost from lost production.

For example, if a given refinery's average flow were 120,000 barrels-day, 1 bpu would represent 120 kbpd. If the total refinery flow were interrupted for 2 hours, the volume of lost production (impact) would be 2 bpu•h which would equate to:

$$2 \quad bpu \cdot h = (2 \quad hours) \cdot \left(\frac{1 \quad day}{24 \quad hours} \right) \cdot \left(\frac{120{,}000 \quad barrels}{day} \right) = 10{,}000 \quad barrels$$

This represents 10,000 barrels of lost production as an impact.

2.2.2 Process Modeling

To quantify the consequence of electrical power system interruptions to one or more process units within a refinery, a process reliability model must be created to simulate a cascading outage.

A refinery may be thought of as a set of process units. Each unit has a name such as "Plant 2 – Naphtha Hydrotreater". Each process unit modifies one or more hydrocarbon streams; these streams may come from other process units within the refinery or from refinery feed stock that is shipped from another facility. After the unit has modified its hydrocarbon stream(s), it may send finished product(s) to market and/or send hydrocarbon stream(s) to one or more process units within the refinery. Finished products may include such goods as gasoline, diesel, naphtha, coke, butane, or propane, to name a few. Between interconnected process units, there may be 'tankage' which is a physical tank to store hydrocarbon. The terms 'stream' and 'flow' are frequently used interchangeably; however, flow generally indicates direction to or from a given unit.

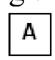
If an electrical substation within a refinery is interrupted, the set of refinery process units it serves will become interrupted. If that set of interrupted units creates a cut-set for one or more other units within the refinery, the interruption will eventually cascade and one or more additional units will be added to the set of interrupted units. The first goal of the proposed process model is to predict such a cascade to determine *what* units will become interrupted *when* as a function of the initially interrupted set of units. Let us define 'state' as it pertains to a refinery or a given process unit. An individual process unit can have two states, namely DOWN or UP. Let us define DOWN as a unit that is interrupted and UP as a unit that is *not* interrupted. The state of the refinery may then be thought of as a vector containing the state of each of its constituent process units; then a given refinery state is a distinct combination of process unit states such that a refinery with N production units has 2^N possible states. During a cascading interruption, a refinery will transition from one state to another as a function of time. At each refinery state throughout the transition, the fraction of interrupted refinery production (*bpu*) may be calculated. Define 'survival time' as the amount of time the refinery can spend in a given state during a cascading outage.

Process units within a refinery tend to rely upon each other's hydrocarbon streams to remain UP. The key to modeling a refinery process is to determine on a unit-by-unit basis exactly how each unit depends upon the state of each other unit within the refinery, which is called the 'process dependency' of a unit. Each unit will have a process dependency that involves all the units to or from which the given unit receives or sends a hydrocarbon stream. The process dependency of each process unit is individually modeled as a table of refinery states and process unit survival times. Define 'inputs' as the set of units that send a hydrocarbon stream to a given unit. Define ‘outputs’ as the set of units that receive a hydrocarbon stream from a given unit. Separate (independent) unit dependencies are constructed for each unit’s inputs and outputs.

The proposed process model and its associated cascading outage calculation algorithm are built upon the following axioms.

<u>Axioms</u>:

1. Process units that are in a down state, remain in a down state throughout the cascading interruption.
2. A process unit must transition into the down state if either its input or output state transition matrix has a zero survival time corresponding to the current refinery configuration.
3. The process unit(s), whose input or output survival time, in the current configuration, is the smallest, determines the refinery survival time in the current refinery state.

The process model itself is derived from a block flow diagram, depicting the refinery process units, hydrocarbon streams between units (flows), tankage, finished product hydrocarbon streams, and feed stock.
The basic block for a process unit is a square, containing the abbreviated unit name. For example, a unit named ‘Plant A’ would use the symbol 

. Each unit may produce finished product that it sends out of the refinery and the finished product stream is terminated by a tap symbol . Some units receive feed stock from other facilities and the feed stock streams are represented by a pump jack symbol . If a hydrocarbon stream between two plants is interrupted because one of the plants is down, the remaining plant can still survive, however ‘the clock is ticking’. At a reduced throughput, the remaining unit is designed to survive (produce) for a period of time until it runs out of hydrocarbon stream from tankage, or an environmental limit is reached, or another process constraint such as catalyst, or other prevents further production. Each hydrocarbon stream between units may then be thought of as having a ‘half-full’ tank (even though in some cases it’s not really a tank at all). The symbol for intermediate tankage is a tank .

The most basic process where plant A sends product to plant B is shown in Figure 5. In this case, plant A receives feedstock, produces finished product, and sends a stream to plant B. Plant B receives a stream from plant A and produces finished product. The refinery state is {A, B} = {UP, UP}.

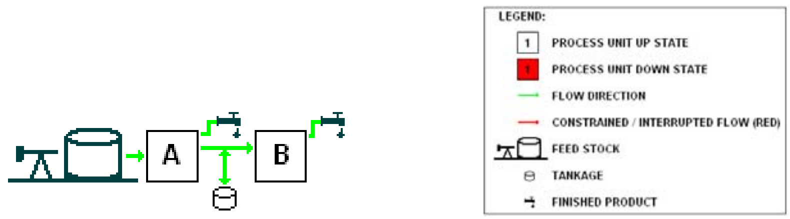


Figure 5: Simple Process Model

If the substation serving plant A is interrupted, the process cut-set created is {plant A} and (hydrocarbon) streams *to* and *from* plant A, as well as the *finished product* from plant A are interrupted. The remaining unit is plant B, which still produces finished product, at a reduced rate, until there is no more tankage. During the period of time in which the refinery state is {A, B} = {DOWN, UP}. The model in Figure 5 is then reduced to the model in Figure 6.

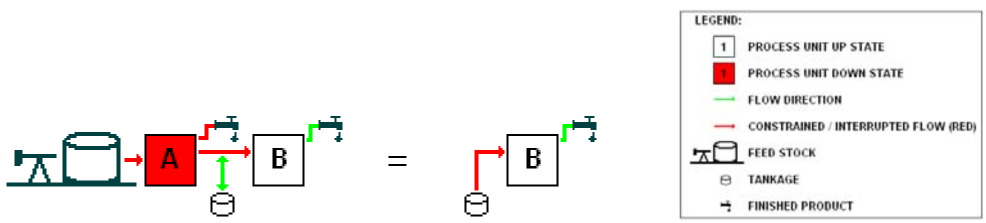


Figure 6: Reduced Process Model with Plant A Down

If, instead, the substation serving plant B is interrupted, the process cut-set created is {plant B} and the stream to plant B, as well as the finished product from plant B are interrupted. The remaining unit is plant A and still produces finished product, at a reduced rate, until it runs out of intermediate tankage. During the period of time in which the refinery state is {A, B} = {UP, DOWN}. The model in Figure 5 is then reduced to the model in Figure 7.

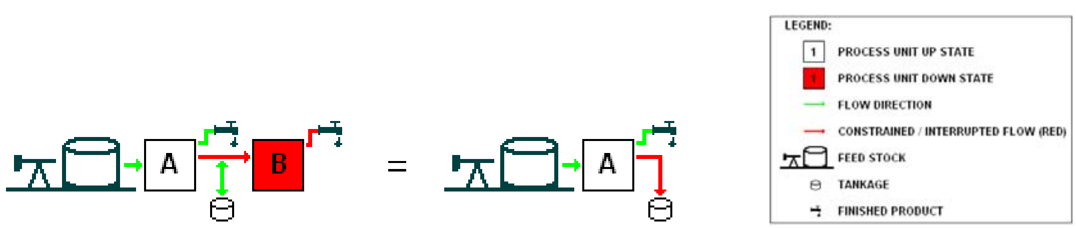


Figure 7: Reduced Process Model with Plant B Down

The proposed process model includes an algorithm which determines how long each successive combination of unit service states can survive, then determines the next stable configuration. This is illustrated with the following example.

EXAMPLE OF THE CASCADING INTERRUPTION ALGORITHM

Consider the process model in Figure 8 for a refinery with five process units, named "Plant 1" through "Plant 5", respectively.

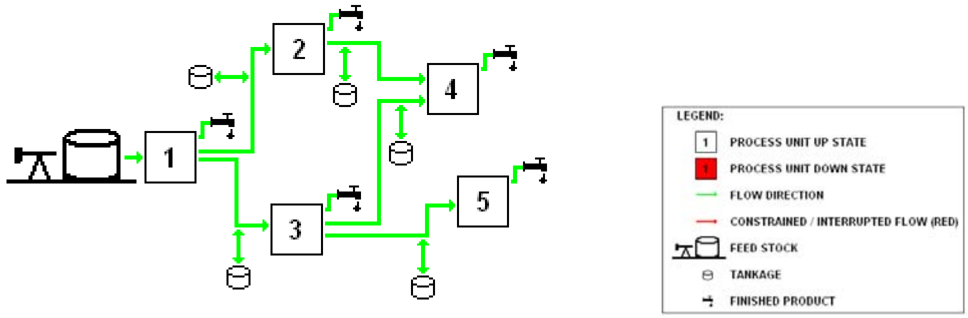


Figure 8: Example Refinery Process Model

In this example refinery, Plant 1 receives feed stock from another facility, processes this hydrocarbon stream, sends some finished product to market, and sends a hydrocarbon streams to Plant 2 and Plant 3. Plant 2 receives a hydrocarbon stream (stream) from Plant 1, processes it, sends some finished product to market, and sends a stream to Plant 4. Plant 3 receives a stream from Plant 1, processes it, sends some finished product to market, then sends a stream to Plant 4 and Plant 5. Plant 4 receives streams from Plant 3 and Plant 2, processes them, sends finished product to market. Plant 5 receives a stream from Plant 3, processes it, then sends finished product to market.

When all units are up, the refinery state is
$\{\ Plant\ \ 1 = UP,\ \ Plant\ \ 2 = UP,\ \ Plant\ \ 3 = UP,\ \ Plant\ \ 4 = UP,\ \ Plant\ \ 5 = UP\ \}$.
This refinery state vector called the 'current state vector' "CSV" and each unit's up or down state is represented by a 0 or 1, respectively. Negative logic is used because it simplifies the code within the algorithm.

The CSV for Figure 8 where all units are UP is:

$$CSV = \{\ 0,\ \ 0,\ \ 0,\ \ 0,\ \ 0\ \} = \{\ UP,\ \ UP,\ \ UP,\ \ UP,\ \ UP\ \}.$$

Define a 'Unit Dependency' as a collection of unit dependent matrices that completely define the behavior of a process unit with respect to all other units within the refinery. A given dependency has two separate (independent) matrices for inputs (other units that send streams to the unit) and outputs (units to which the unit sends streams). The matrix for inputs is called the Input State Transition Matrix (ISTM). This matrix has rows that depict refinery state vectors that are appended by a unit survival time (ST) in hours; the survival time appended to a given state vector in a unit ISTM represents how long the unit can stay UP, given that its inputs are in that state. The survival time (ST) may be thought of as the size of the abstract tankage between two units. Similarly, the matrix for outputs is called the Output State Transition Matrix and has a similar layout.

We will begin with the Unit Dependency for Plant 3, because it is not trivial in this example.

The ISTM and OSTM for Plant 3 are described in Figure 9.

UNIT DEPENDENCY
Plant 3

IDCV				
1	0	0	0	0

ODCV				
0	0	0	1	1

ISTM

Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	ST (h)
0	X	X	X	X	∞
1	X	X	X	X	5

OSTM

Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	ST (h)
X	X	X	0	0	∞
X	X	X	0	1	3
X	X	X	1	0	1
X	X	X	1	1	0

Figure 9: Example Plant 3 Unit Dependency Matrices

Because Plant 2 only receives an input stream from plant 1, the survival time (ST) for Plant 3 input is only a function of Plant 1. There are 2^1 rows in the ISTM that represent the dependence on Plant 1. Plants that the input survival time does not depend upon are marked with an 'X' that means "don't care". By using 'don't care' values, the ISTM does not need to have 2^5 rows to fully describe its dependency. To compare the Current State Vector (CSV) with the rows of the ISTM, the states of ISTM 'don't care' units must be stripped from the CSV. This is accomplished by constructing an Input and Output Don't Care Vector for each plant. The IDCV and ODCV have zeros in the position corresponding to plants in the ISTM or OSTM, respectively, with 'don't care' X values. With the IDCV constructed, performing a logical bitwise AND of the ISV and the IDCV will yield a vector that can be compared to the rows of the ISTM to determine survival time.

A Unit Dependency including the ISTM and OSTM for each unit in this example is provided in Figure 10. The IDCV and ODCV for each unit are not shown for simplicity.

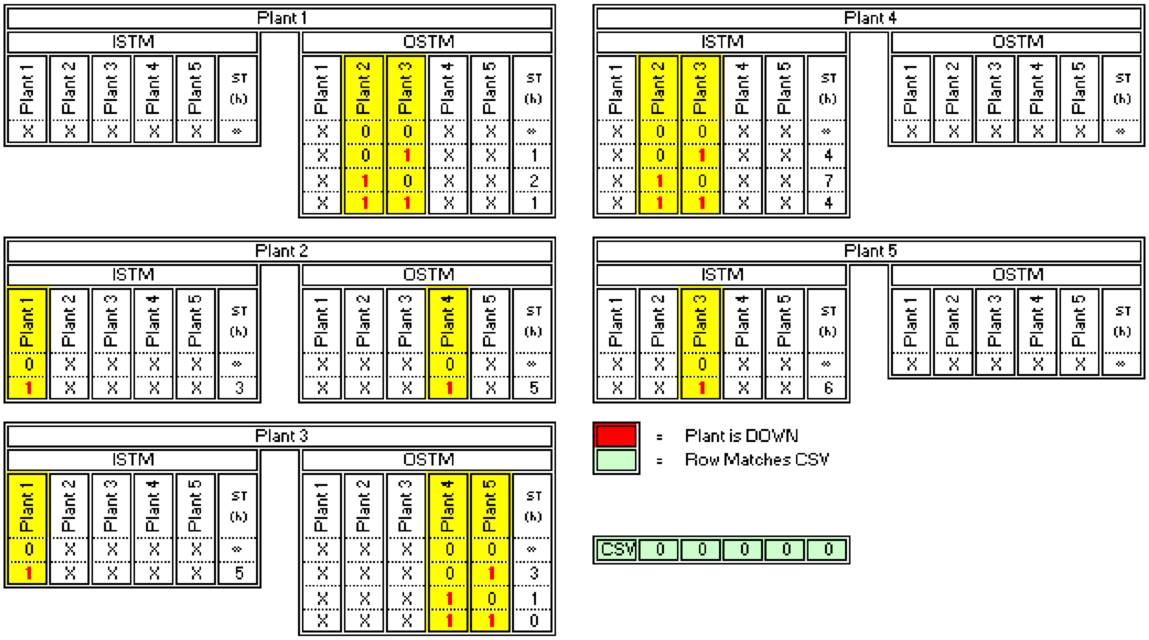


Figure 10: Unit Dependency Matrices – All Units Up

Assume that a substation feeding Plant 3 is interrupted. The set of interrupted units includes {Plant 3} and the refinery current state vector (CSV) is CSV 0 0 1 0 0. The process model for this refinery state is shown in Figure 11.

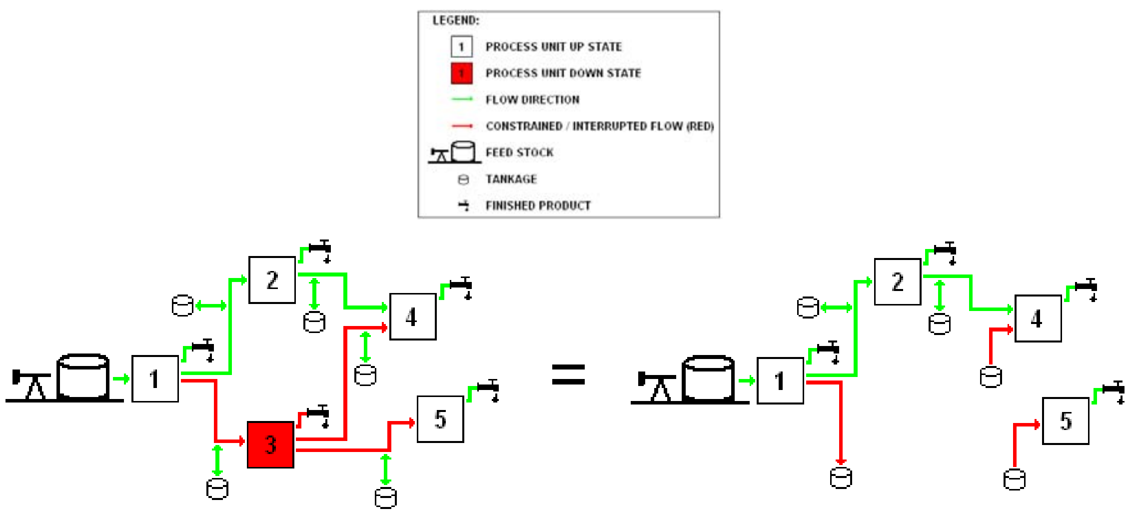


Figure 11: Process Model – Plant 3 Down

When plant 3 is down, the process model replaces the interrupted unit by its intermediate tankage. The cascading interruption calculation algorithm is shown in Figure 12. The CSV is compared with each row in the ISTM and OSTM of each plant that is in the up state. If a row matches the CSV, the corresponding row's survival time (ST) is noted. When all rows have been compared, the smallest survival time ST_min is the amount of time the refinery can survive in the CSV state. At this point in the algorithm, the interrupted flow is calculated in bpu and we'll assume the answer is **0.2 bpu**. It is clear from Figure 12 that the survival time in the current refinery state is 1 hour and that it is limited by the OSTM of Plant 1. ST_min = **1 hour**

Figure 12: Unit Dependency Matrices – Plant 3 Down

To then decide which unit or units transition into the down state next, the ISTM and OSTM matrices are updated for each unit that is in the up state. If an ISTM, for example, of a unit that is in the up state, has a row that matches the CSV when the 'don't care' terms are applied, a ceiling is applied to the remaining terms in the ISTM matrix of ST=ST-ST_min, such that no row can have a larger survival time than the row matching the CSV. The reason this is done because the survival time of a unit should never increase as additional units go down. It is also done with the understanding that ST_min is the smallest ST of all the units who have an ISTM or OSTM row that matches the CSV. As such, no unit will ever have a negative survival time value. It is also important to understand that, because units do not transition into the up state during a cascading interruption, applying the ceiling to all ISTM or OSTM rows is an algorithm shortcut that applies this cap to some rows that will not match the CSV for the remainder of the cascade, as well as the subset that could match the CSV in future states during a cascading interruption: i.e. the Plant 1 OSTM row [X 1 0 X X] will never be used in the remainder of this example because unit 3 is already down, so changing its ST does not matter. This is shown in Figure 13.

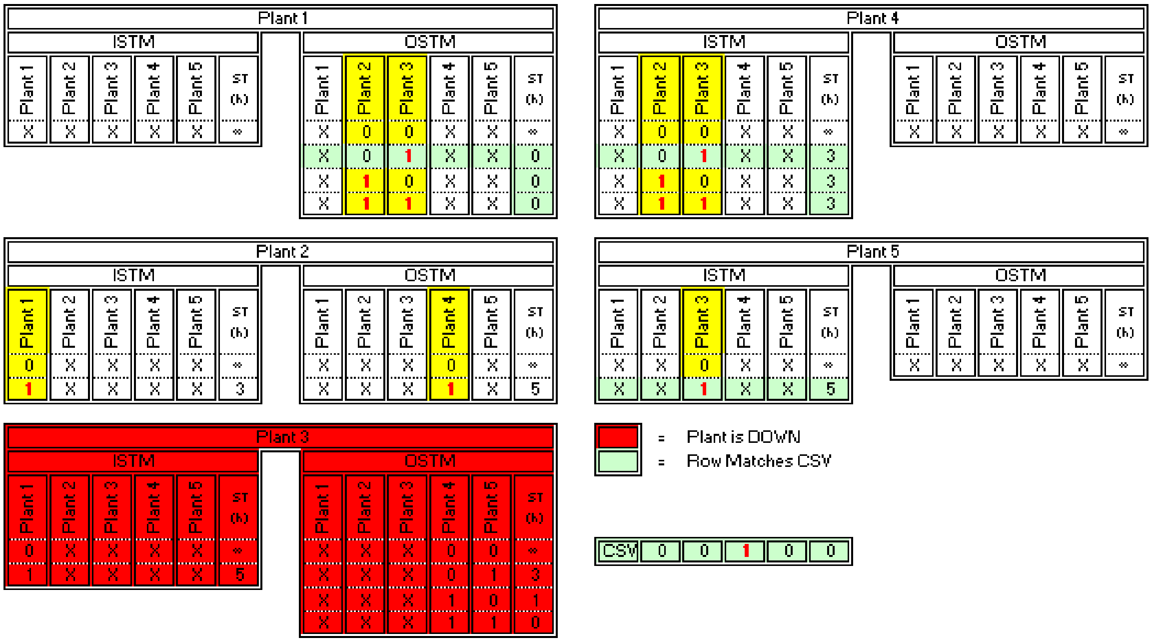


Figure 13: Unit Dependency Matrices – Plant 3 Down & Updated Survival Times

If a plant's ISTM or OSTM contains a row that matches the CSV and now has a 0 survival time, this plant goes down and the CSV is updated for the next iteration. Since Plant 1 now has a 0 hours survival time in its OSTM, it must transition into the down state. The CSV is then updated to include the interruption of Plant 1 and becomes [CSV | 1 | 0 | 1 | 0 | 0]. The process model is updated and shown in Figure 14. Since the CSV is updated, it can again be compared with the Unit Dependency Matrices.

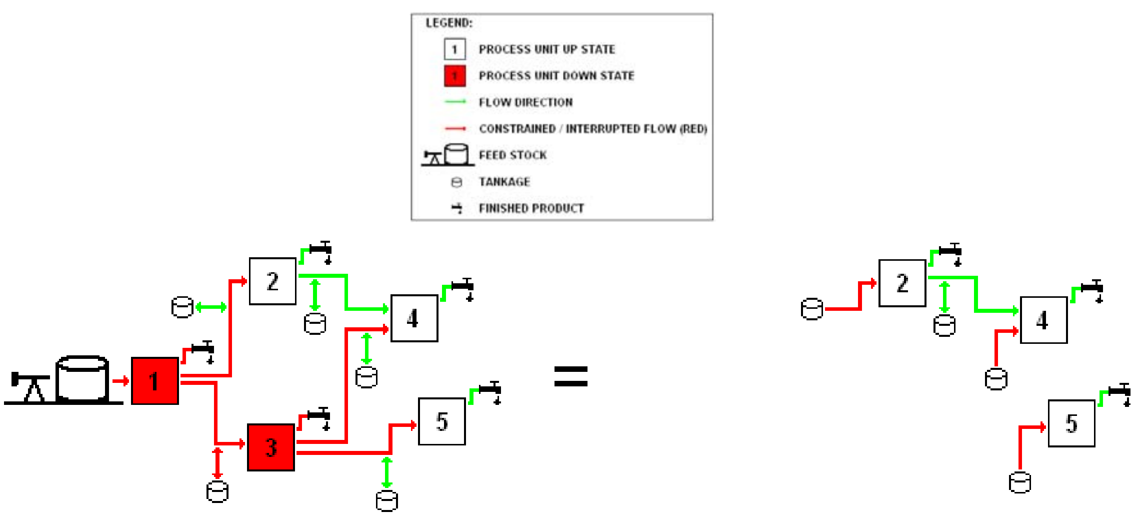


Figure 14: Process Model – Plant 3, 1 Down

Figure 15: Unit Dependency Matrices – Plant 3, 1 Down

Clearly the smallest ST in ISTM and OSTM rows, that match the CSV in Figure 15, is 3 hours. **ST_min = 3 hours** and is subtracted from the appropriate rows the CSV, then appropriate additional rows have the ceiling applied. The result is shown in Figure 16. The interrupted flow is calculated in bpu and we'll assume this result is **0.6 bpu**.

Figure 16: Unit Dependency Matrices – Plant 3, 1 Down & Updated Survival Times

From Figure 16, it is clear that Plant 2 and Plant 4 will both transition into the down state. The CSV is updated to become CSV 1 1 1 1 0. The process model is updated to reflect the updated CSV and is shown in Figure 17.

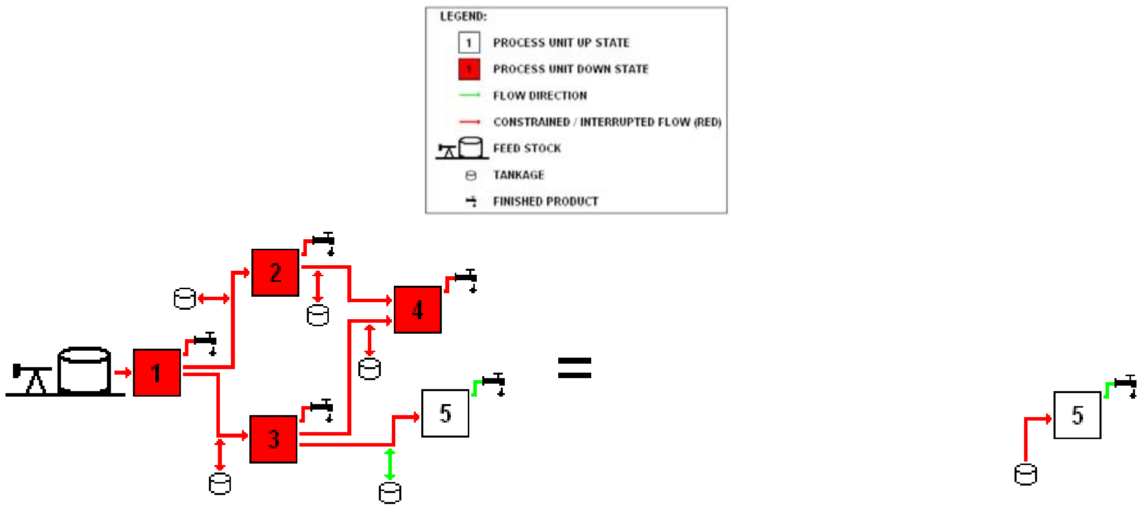


Figure 17: Process Model – Plant 1, 2, 3, 4 Down

Since the CSV is updated, it can again be compared with the Unit Dependency. This is shown in Figure 18.

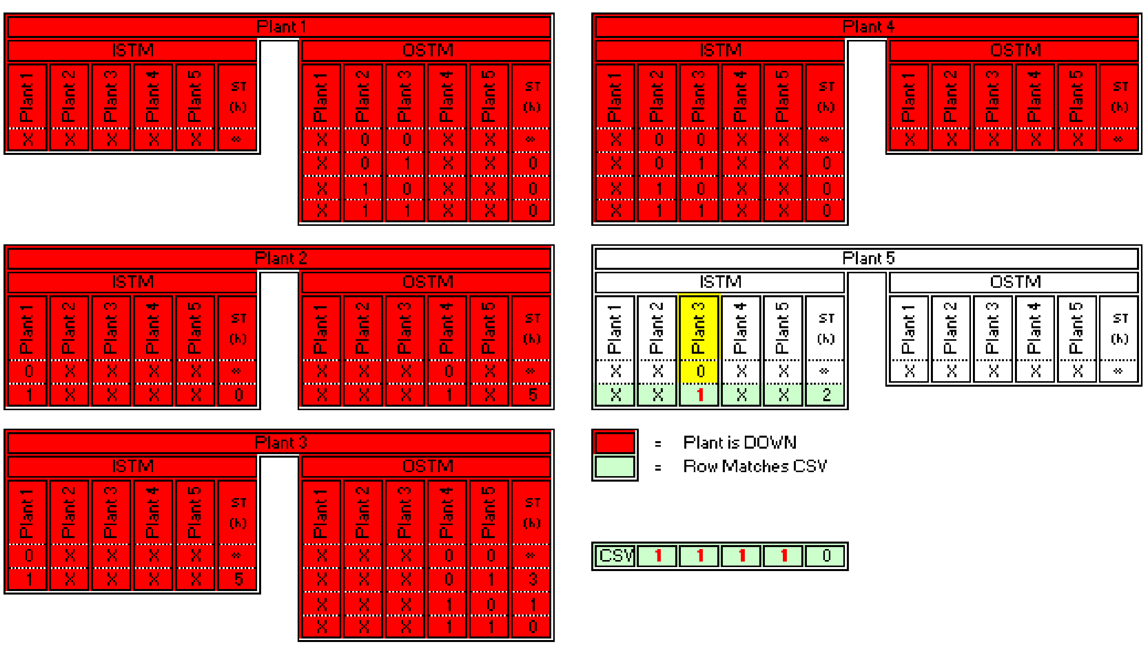


Figure 18: Unit Dependency Matrices – Plant 1, 2, 3, 4, Down

Since only Plant 5 remains, **ST_min = 5 hours** is the survival time listed in the Plant 5 ISTM. The interrupted flow is calculated in bpu and assume the value is **0.8 bpu**. Plant

5 will transition into the down state and the algorithm concludes because there are no units left in the up state. Note that the algorithm would also conclude if there was an infinite survival time, indicating a stable operating configuration.

At the conclusion of the cascading interruption algorithm, the results are displayed in Figure 19.

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Survival Time (hours)	Interrupted Production (bpu)
Initial CSV -->	0	0	1	0	0	1	0.2
CSV after Plant 1 goes down -->	1	0	1	0	0	3	0.6
CSV after Plant 2 & 4 go down -->	1	1	1	1	0	2	0.8
Final CSV after entire refinery is down -->	1	1	1	1	1	∞	1

Figure 19: Cascading Interruption Algorithm Output

The information in Figure 19 shows the survival time and interrupted flow as a function of refinery state. This output can then be the basis for construction of the Criticality Enhancement Function, which is described in the following section 2.2.3.

Chapter 4 of this Thesis includes a detailed process reliability Matlab® model of the Petro-Canada Edmonton Refinery and includes 17 complex process units.

2.2.3 Criticality Enhancement Function

In a refinery, the length of time which a unit may run in the absence of other units is a strong function of available intermediate tankage. As demonstrated in the previous section, interrupted flow is a function of time for a given initial refinery state. The right-most columns in Figure 19 give the increments for an interrupted production function shown in Figure 20.

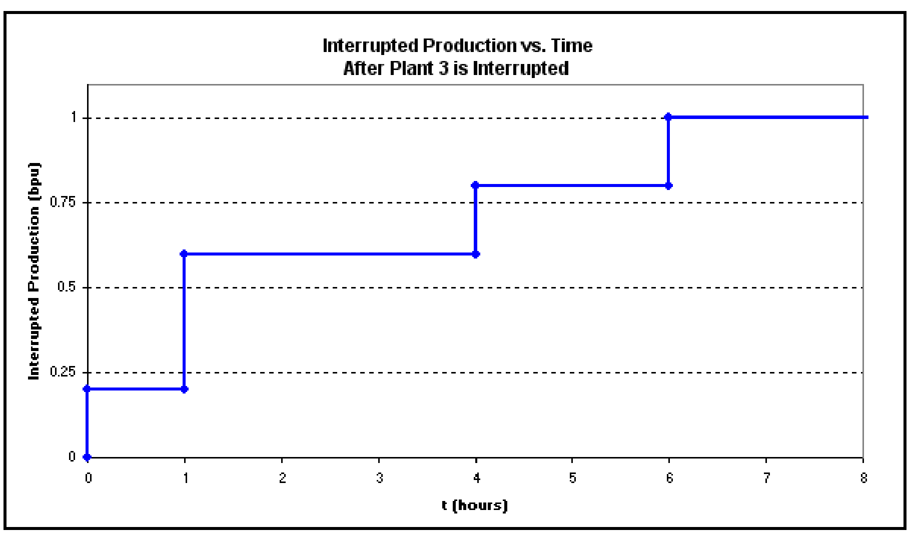


Figure 20: Interrupted Production vs. Time

Figure 20 is the interrupted production function in terms of lost production *rate* (bpu), as a function of repair time and is a step function, because of the constant flow within each discrete operating mode as a function of time. The range of Interrupted Production is [0,1]. The cost impact function in terms of lost *product* as a function of time would be the time integral of the function in Figure 20 as a series of piece-wise linear regions. We will call this the Criticality Enhancement Function "$CEF(t)$". The units of $CEF(t)$ are bpu•h.

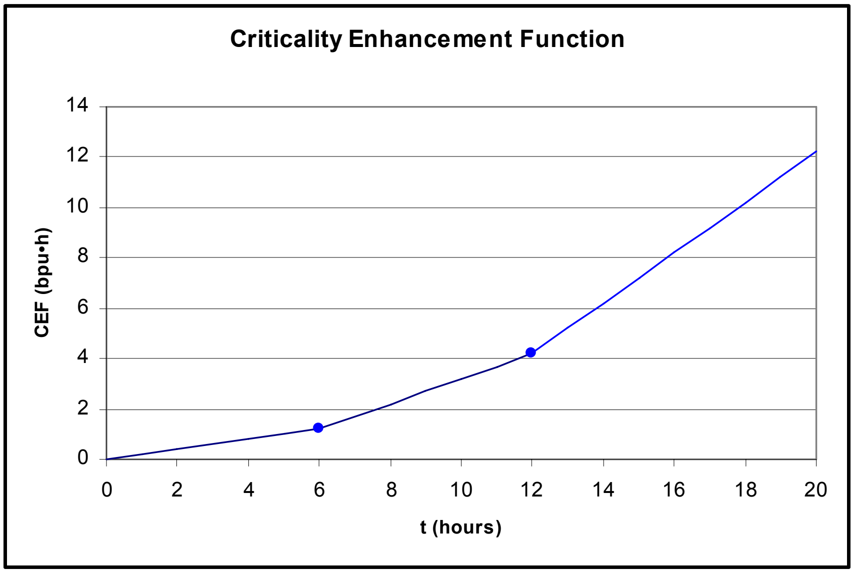


Figure 21: Criticality Enhancement Function Example

Figure 21 illustrates the Criticality Enhancement Function for a refinery unit interruption combination having two stable operating modes prior to a total refinery outage. Assume the following variable definitions. Note the linear regions connected by break points, creating an overall non-linear criticality enhancement function (CEF).

t	interruption duration
a	lost flow rate in the first refinery state after interruption, in bpu
b	lost flow rate in the second refinery state after interruption, in bpu
c	lost flow rate in the third refinery state, in bpu
T_A	amount of time spent in first operating mode in hours
T_B	amount of time spent in second operating mode in hours

$$CEF(t) = \begin{cases} 0, & t < 0 \\ a \cdot t, & 0 \le t < T_A \\ b \cdot t + T_A(a-b), & T_A \le t < T_B \\ c \cdot t + T_A(a-b) + T_B(b-c), & t \ge T_B \end{cases} \tag{6}$$

Table 2: Criticality Enhancement Function Example Parameters

Parameter	Value	Units
a	0.2	bpu
b	0.5	bpu
c	1	bpu
T_A	6	hours
T_B	12	hours

Table 2 notes the values used in equation (6) to arrive at the values for the example criticality enhancement function that is plotted in Figure 21. This example assumes two refinery operating states before a total refinery interruption – in a real refinery process, the refinery may transition through many operating states before a total refinery interruption.

2.2.4 Zone-Branch Reliability Measure 'r'

The conclusion of calculation in the zone-branch algorithm is the computation of load point availability A from the steady state load point interruption frequency λ and the average load point interruption duration.

$$A = \frac{1}{1 + \lambda \cdot r} \tag{7}$$

In the zone-branch algorithm, failure of each of N components in the power system has an average frequency λ_i^0, a probability of affecting the load point during interruption q_i, and average repair duration r_i^0. For a given load point, the expected frequency of interruption and repair may be calculated as follow [5].

$$\lambda = \sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \right) \tag{8}$$

$$r = \frac{\sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \cdot r_i^0 \right)}{\sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \right)} \tag{9}$$

It is proposed that **r** be re-defined as a discrete random variable whose distribution probability mass function contains the information representing load point interruption duration. The calculation of an availability metric would then use the expected value of $E\{\mathbf{r}\}$.

$$A = \frac{1}{1 + \lambda \cdot E\{\mathbf{r}\}} \tag{10}$$

The information required for computing the probability mass function of **r** is contained in the series used to sum its expected value.

$$E\{\mathbf{r}\} = \frac{\sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \cdot r_i^0 \right)}{\sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \right)} = \frac{\sum_{i=0}^{N} \left(q_i \cdot \lambda_i^0 \cdot r_i^0 \right)}{\lambda} = \sum_{i=0}^{N} \left[\left(\frac{q_i \cdot \lambda_i^0}{\lambda} \right) \cdot r_i^0 \right] \tag{11}$$

Define $\lambda_i^n = \frac{q_i \cdot \lambda_i^0}{\lambda}$ to be the 'normalized' frequency of load point interruption by the i'th component. Then λ_i^n represents the fraction of probability associated with the event r_i^0 such that the set $\{\lambda_0^n, \ \lambda_1^n, \cdots, \lambda_{N-1}^n, \ \lambda_N^n\}$ forms a partition.

The random variable **r** may then be described by a countable set of N pairs of points (λ_i^n, r_i^0) which may then be displayed as a probability mass function $p_r(\mathbf{r})$.

$$E\{\mathbf{r}\} = \sum_{i=0}^{N} \left(\lambda_i^n \cdot r_i^0\right) \tag{12}$$

$$\sum_{i=0}^{N} \lambda_i^n = 1 \tag{13}$$

2.2.5 Impact of Interruption Random Variable 'y'

Without the pmf of the random variable **r**, the impact of interruption could only be based upon averaged data as $CEF(E\{r\})$. It is proposed that the random variable '**y**' represent the impact of a single load point interruption; then the pmf of **y** represents the impact of the individual events that make-up **r** and the expected value of **y** would be the expected impact of a single interruption where, due to the non-linearity of $\mathbf{y} = g(\mathbf{r})$, $E\{CEF(\mathbf{r})\} \neq CEF(E\{\mathbf{r}\})$.

Annual expected cost of load point interruption may then be expressed as $\lambda \cdot y$ in units of bpu•h/year. The Criticality Enhancement Function then relates repair time '**r'** to impact '**y'** by mapping discrete points one-to-one.

$$\mathbf{y} = CEF(\mathbf{r}) \tag{14}$$

Take for example the CEF noted in section 2.2.3.

$$\mathbf{y} = \begin{cases} 0, & r < 0 \\ a \cdot \mathbf{r}, & 0 \leq r < T_A \\ b \cdot \mathbf{r} + T_A(a-b), & T_A \leq r < T_B \\ c \cdot \mathbf{r} + T_A(a-b) + T_B(b-c), & r \geq T_B \end{cases} \tag{15}$$

a lost flow rate in the first refinery state after interruption, in bpu
b lost flow rate in the second refinery state after interruption, in bpu
c lost flow rate in the third refinery state, in bpu
T_A amount of time spent in first operating mode in hours
T_B amount of time spent in second operating mode in hours

Then the distribution of **y** may be expressed as the distribution of **r** as follows [13].

$$f_y(\mathbf{y}) = \begin{cases} 0, & \mathbf{y} < 0 \\ \frac{1}{|a|} f_r\left(\frac{\mathbf{y}}{a}\right), & 0 \le \mathbf{y} < a \cdot T_A \\ \frac{1}{|b|} f_r\left(\frac{\mathbf{y} - T_A(a-b)}{b}\right), & a \cdot T_A \le \mathbf{y} < a \cdot T_A + b(T_B - T_A) \\ \frac{1}{|c|} f_r\left(\frac{\mathbf{y} - T_A(a-b) - T_B(b-c)}{c}\right), & \mathbf{y} \ge a \cdot T_A + b(T_B - T_A) \end{cases} \quad (16)$$

Using the Uniform and Gaussian pmfs from section 2.1.3, the resulting discrete pmfs in terms of $p_y(y)$ are shown in Figure 22. Clearly the mass points corresponding to $r < T_A$ are grouped below $y < p_y(T_A)$.

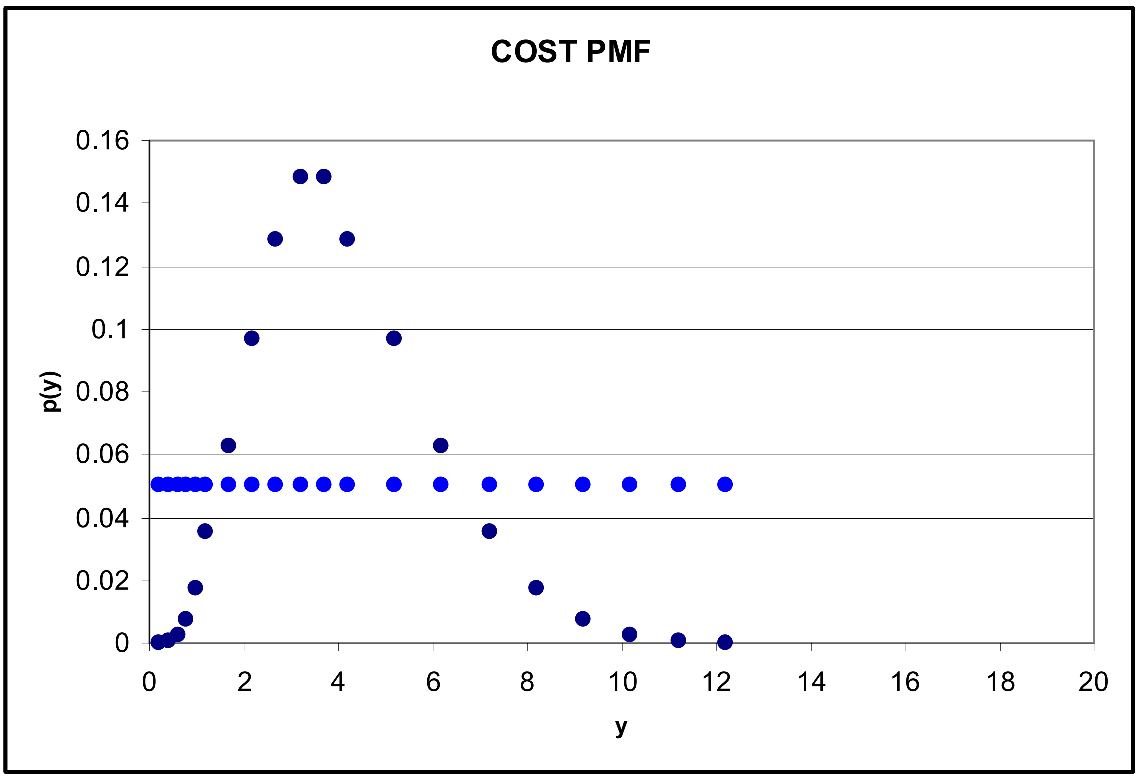


Figure 22: Impact (cost) Probability Mass Function $p_y(y)$

From the probability mass functions in Figure 22, Figure 23 shows their Cumulative Distribution Functions as the probability of the impact from interruption being less-than or equal-to a given value. The Gaussian (normal) distribution approaches unity much more quickly because the bulk of its probability mass is distributed more closely around its mean.

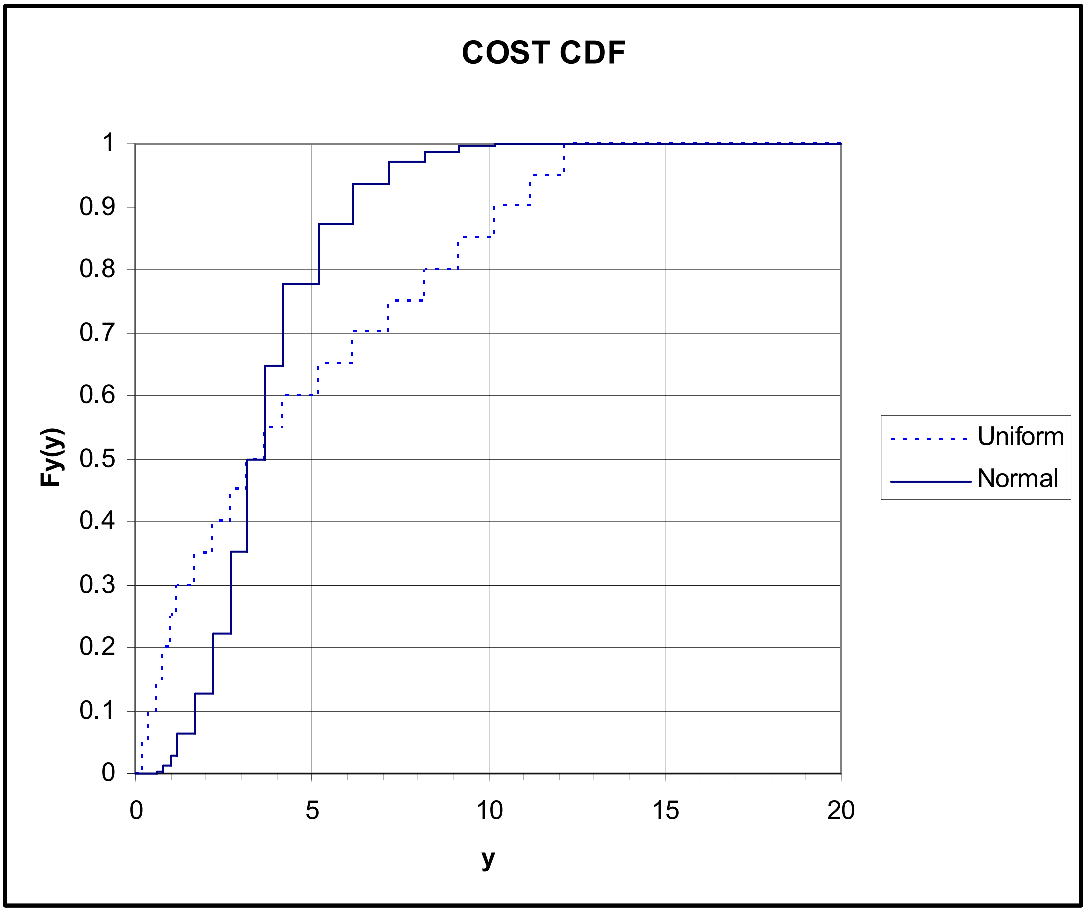


Figure 23: $F_y(y)$

Taking the Gaussian distribution as an example, three methods for calculating the expected annual cost of load point interruptions are shown to illustrate the distinction between methods.

Using Averaged Data Method without process modeling:
r = 10.5 hours
a = 0.3 bpu (nameplate capacity of interrupted unit)
Average Expected Cost Per Interruption = $r \cdot a$ = **3.15** bpu•h
Average Expected Annual Cost of Load Point Interruptions = 3.15•λ (bpu•h/year)

Using Averaged Data Method *with* process modeling:
r = 10.5 hours
Average Expected Cost Per Interruption = $CEF(10.5)$ = **3.2** bpu•h
Average Expected Annual Cost of Load Point Interruptions = 3.2•λ (bpu•h/year)

Using Proposed Random Variable Approach with process modeling:
$E\{r\}$ = 10.5 hours

$y = CEF(r)$

Average Expected Cost Per Interruption $= E\{y\}$ = **3.69** bpu•h

Average Expected Annual Cost of Load Point Interruptions = 3.69•λ (bpu•h/year)

$VAR\{\lambda \cdot y\} = \lambda^2 \cdot VAR\{y\}$ = 2.915•λ^2

σ_y = 1.707• λ bpu•h/year

The resulting average impact per outage, using each of the three methods in this example, is noted in Table 3.

Table 3: Interruption Impact Results by Method

Method	Impact per outage	Units
Average data – no process modeling	3.15	bpu•h
Average data – with process modeling	3.20	bpu•h
Proposed random variable & process modeling	3.69	bpu•h

The importance of quantifying the cascading effect of power system is demonstrated where the three contrasted methods have different results. While the averaged data method is simple in the absence of process modeling, it tends to underestimate impact because total refinery outage is not considered. Even when refinery outage is considered, the use of only averaged data tends to be inaccurate where a non-linearity exists in the Criticality Enhancement Function. When the proposed method is used, the effect of cascading interruption is considered and the use of random variables provides necessary information about cost. Additional information such as standard deviation σ_y enables a better managerial decision regarding risk and where resources should be invested within a power system to lessen the probability of interruption.

Chapter 3 – Petro-Canada Edmonton Refinery Overview

The Petro-Canada Edmonton Refinery is located in Strathcona County and refines synthetic crude oil to supply western Canada with products such as gasoline, diesel, propane, aviation gas, and stove oil. The refinery consists of 17 major production units, which are assisted by utilities such as steam and hydrogen. The refinery power system is fed by two main utility substations on a 138kV ring feed. The Edmonton Refinery currently has a 125,000 barrel-per-day of crude oil equivalent nameplate capacity and has a normal running electrical load of 59 MW.

A refinery has existed on site in various forms since1953. In 1970, production units processed conventional crude oil at a nameplate capacity of 80,000 barrels-per-day. In 1981, an expansion project added an additional 45,000 barrel-per-day capacity of synthetic crude oil, bringing the nameplate capacity of the Edmonton Refinery to 125,000 BPD. In 2004 and 2006, new plants were built to further reduce the sulphur content in gasoline and diesel streams, respectively. The recent Refinery Conversion Project, which was completed in 2008, converted the conventional units to accept sour synthetic crude. The Petro-Canada Edmonton Refinery now boasts the ability to exclusively refine bitumen derived feed stock at 125,000 BPD.

Individual Plant descriptions are included in the following section to enable the building of a basic understanding of the process nature of the case study.

The following Figure 24, which is reproduced in section 4.0, was constructed based on the most recent overall block flow diagram from the Edmonton Refinery [8]. It represents the interconnection of all process units. Note that inter-unit tankage is omitted from Figure 24 for simplicity.

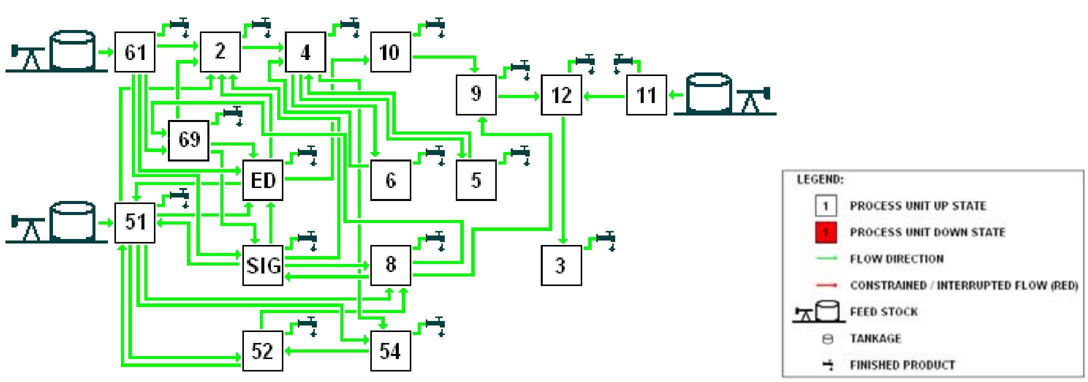


Figure 24: Process Model of the Petro-Canada Edmonton Refinery

3.1 Plant 61 - Crude / Vacuum

The Sour Crude / Vacuum ("crude-vac") Unit was commissioned in 2008 as part of Petro-Canada's Refinery Conversion Project. The crude-vac receives sour synthetic crude oil, which it separates into fractions, based on each fraction's boiling point. The major products of the crude-vac include: wild naphtha, distillate, light and heavy gas oil, and vacuum residue.

3.2 Plant 69 - Coker

The Coker Unit was commissioned in 2008 as part of Petro-Canada's Refinery Conversion Project. A process called 'delayed coking' converts batches of vacuum residue to major products including: gasoline, distillate, gas oil, and coke. Vacuum residue is heated and batched into two coke drums. The coke drums contain a chemical reaction that changes the product into lighter hydrocarbons and coke. The lighter hydrocarbons are sent to other units and the coke from each batch is drilled out and shipped by rail as a finished product.

3.3 Plant 51 - Syncrude Splitter

The Synthetic Crude Fractionation Unit ("syncrude splitter") was commissioned in 1981. It is similar to Plant 61 in that it receives synthetic crude oil as a feedstock. The syncrude splitter uses fractionation to separate synthetic crude oil into products such as naphtha, distillate, and gas oil. Unlike the crude-vac unit, there is no vac residue stream because of the type of synthetic crude oil processed.

3.4 Plant 2 - Naphtha Hydrotreating Unit

Hydrotreating is a process that uses hydrogen to remove sulphur from a process stream. The Naphtha Hydrotreating Unit is designed especially for the hyrdotreating of a naphtha stream. A major revamp of Plant 2 was completed in 2008 and the unit was originally commissioned in 1971.

3.5 Plant 4 - Saturated Gas Plant

The Saturated Gas Plant was commissioned in 1971. It receives a naphtha stream which is separated into propane, butane, pentane, hexane, as well as light and heavy naphtha. The Saturated Gas Plant is closely coupled to the Naphtha Hydrotreater.

3.6 Plant 63 - EDD Distillate Hydrotreating Unit

Plant 63 encompasses two distinct units. The 'EDD' Unit is a Distillate Hydrotreating Unit and was commissioned in 2006. The acronym EDD stands for the Edmonton Diesel Desulphurization project which designed and built the new Unit. In a similar manor to Plant 2, Plant 63 – EDD is a hyrdotreating process that uses hydrogen to remove sulphur from its distillate process stream. Impurities such as nitrogen, oxygen, halides, and trace metals are also extracted.

3.7 Plant 63 - SIG CAT Feed Hydrotreating Unit

The 'SIG' Unit was built and commissioned prior to EDD in 2004. The acronym SIG stands for the Sulphur In Gasoline project that designed and built the new unit. In a similar manor to Plant 2 and EDD, SIG removes sulphur from its gas oil stream. Like EDD, impurities such as nitrogen, oxygen, halides, and trace metals are also extracted.

3.8 Plant 52 - Hydrocracker

The Hydrocracking Unit was commissioned in 1983. It uses high pressure and catalyst to convert gas oil and light cycle oil into naphtha, light and heavy distillate, and gas oil.

3.9 Plant 5 - Platformer

The Platformer Unit was commissioned in 1971. Its process function is to convert desulphurized light naphtha into higher octane gasoline components. By sending its stream through three series reactor sections, a series of chemical reactions produces 95 octane gasoline.

3.10 Plant 10 - Distillate Dewax

The Distillate Dewax Unit was originally commissioned in 1971 as a light cycle oil hydrotreater. After the SIG and EDD projects were completed in 2006, Plant 10 was converted into a Distillate Dewax Unit which uses a hydrotreating process to convert unsaturated hydrocarbons to paraffins, while removing additional impurities.

3.11 Plant 9 - Unsaturated Gas Plant

The Unsaturated Gas Plant was commissioned in 1971. Its main purpose is to separate hydrocarbons from the Plant 8 –FCCU effluent into LPG, gasoline, decant, light cycle oil, and olefin. The Unsaturated Gas Plant is closely coupled to Plant 8.

3.12 Plant 8 - CAT FCCU

Plant 8 is commonly referred to as the 'CAT' or the 'FCCU'. Its full process name is the Fluid Catalytic Cracking Unit. Plant 8 involves a cracking process where heavy unmarketable hydrocarbon chains are cracked into lighter products such as LPG, gasoline, decant, light cycle oil, and olefin. The CAT is considered the heart of the refinery.

3.13 Plant 54 - Isomerization Unit

The Isomerization Unit was commissioned in 1990. Its purpose is to increase the octane number of its stream to produce isomerate by changing its chemical structure.

3.14 Plant 6 - Reformer

The Reformer Unit was originally commissioned in 1953 and is one of the oldest remaining units from the original refinery. The Reformer converts desulphurized light naphtha into higher octane gasoline components. Plant 6 is very similar in process to Plant 5.

3.15 Plant 3 - Aviation Gas Plant

The Aviation Gas Plant is a finishing unit, which produces special blends of fuel for airplanes. The Aviation Gas Plant was originally commissioned in 1956.

3.16 Plant 12 - Alkylation Unit

The Alkylation Unit was commissioned in 1976. Its process function is to combine isobutane and olefin streams into a high octane gasoline blending component named alkylate. A small amount of propane is also recovered as a secondary reaction.

3.17 Plant 11 - Butamer Unit

The Butamer Unit was commissioned in 1976. The Butamer Unit separates normal butane from isobutane and converts normal butane into isobutane. Product from Plant 11 is fed into the Alkylation Unit and sent to blending.

Chapter 4 – Process Modeling of Edmonton Refinery

The process model for the Petro-Canada Edmonton Refinery is drawn in Figure 25 and was constructed based on the most recent overall block flow diagram from the Edmonton Refinery [8]. Note that inter-unit tankage is omitted from Figure 25 for simplicity.

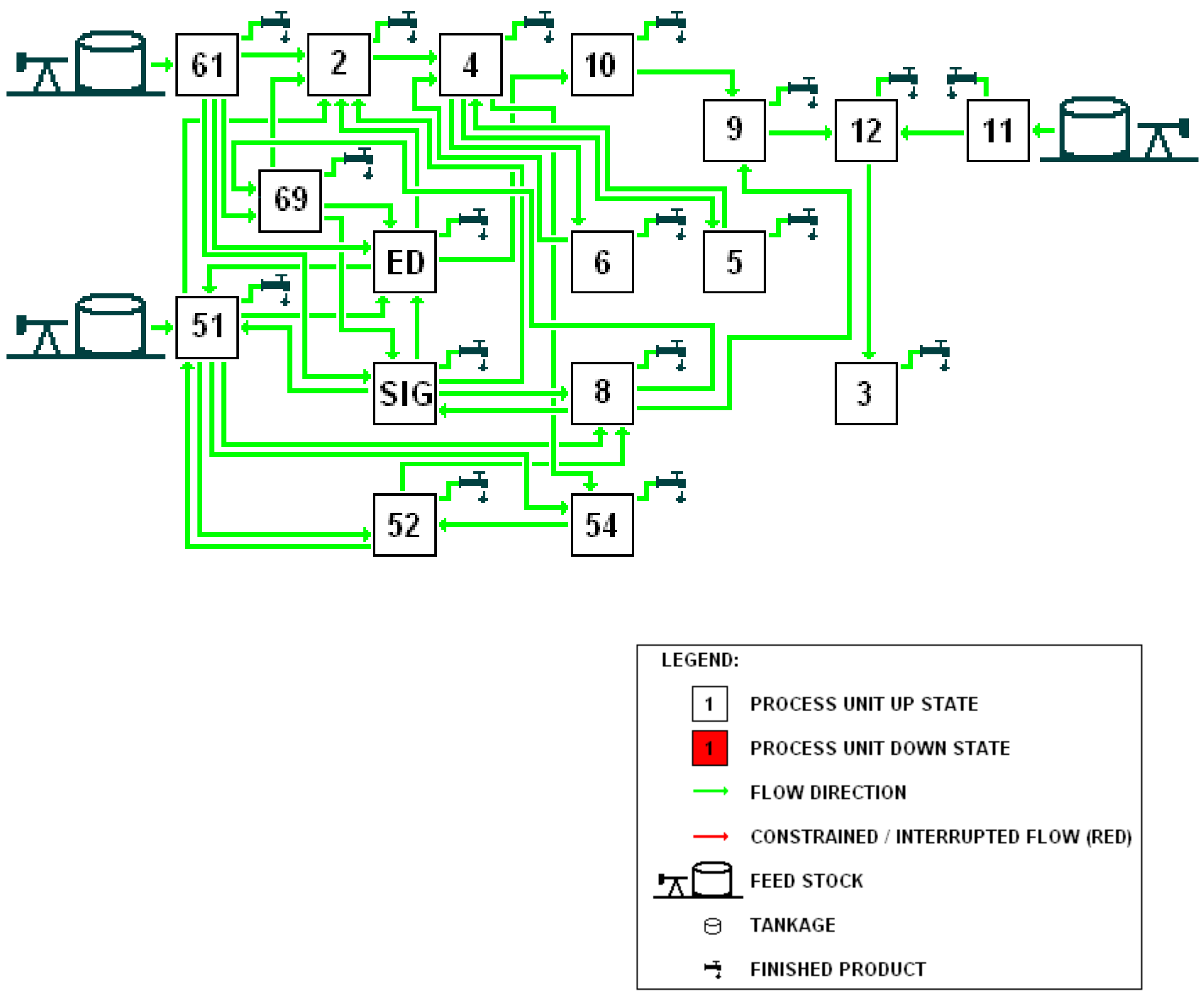


Figure 25: Process Model of the Petro-Canada Edmonton Refinery

Petro-Canada's Edmonton Refinery consists of 17 major hydrocarbon process units, as each was described in Chapter 3. The process model in Figure 25 visually depicts the complex interconnection of refinery process units.

4.1 Unit Dependency

The key to developing a model for a cascading outage simulation is to understand the survival time of a given unit based on the state of all units immediately upstream and downstream of the unit. Once the detailed unit reliability dependencies are determined for each unit, a simulation program can be written. Through analysis of Petro-Canada's process flow diagrams and a series of interviews with Petro-Canada Process Engineers, unit ISTM and OSTM survival times, following an electrical system outage, have been determined for all production units, expressed in hours, for each combination of upstream and downstream unit up/down states (state vectors). The unit ISTM and OSTM survival times were estimated based on unit design, throughput, environmental factors, catalyst restrictions, and average tank inventories (levels).

Many production units have external inputs or outputs which may be pipelines or tankage. Since external pipelines and tankage are not affected by refinery electrical interruption, unit dependence assumes these are always in service and omits them from detailed unit electrical reliability dependence modeling.

Based upon the case study research, the following sub-sections list the complete information required for process reliability modeling including a block diagram, ISTM, IDCV, OSTM, and ODCV for each of the 17 production units within the Petro-Canada Edmonton Refinery. Note that the Cascading Outage Simulation program is discussed in detail in section 4.2.

4.1.1 Plant 61 – Crude / Vacuum

Plant 61 is fed by external pipelines and sends product to four production units, as shown in Figure 26.

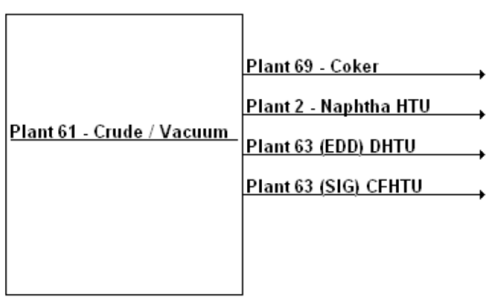


Figure 26: Reliability Block Diagram – Plant 61

The unit dependency matrices for Plant 61 in Figure 27 are constructed with this reliability block diagram in mind. Recall that a unit dependency has four parts: Input State Transition Matrix (ISTM), Output State Transition Matrix (OSTM), Input Don't Care Vector (IDCV), and Output Don't Care Vector (ODCV).

Recall Axiom 2 from section 2.2.2 :

2. A process unit must transition into the down state if either its input or output state transition matrix has a zero survival time corresponding to the current refinery configuration.

Axiom 2 treats a unit's input streams and output streams as independent entities. When considering a unit's survival time in a certain refinery state vector, both the ISTM and OSTM must have non-zero survival times for the unit to remain UP.

The ISTM for Plant 61 is trivial because it does not receive a stream from any other process units within the refinery. It does receive feed stock as an input; however, an interruption of the Edmonton Refinery's power system does not affect the availability of feed stock. It can then be concluded that, regardless of the refinery state vector, and assuming for a moment that all outputs are available, Plant 61 can survive for an indefinitely (∞) long period of time. The trivial ISTM is then constructed showing only 'Don't Care' values 'X' for all units within the refinery and a survival time of ∞.

The IDCV for Plant 61 has a '0' corresponding to an 'X' in the Plant 61 ISTM. If, instead of an X in the ISTM, the ISTM held a 1 or a 0, the IDCV would have a corresponding '1'. The IDCV is used as a bit mask for filtering the current state vector (CSV) to include only information about units upon which the Plant 61 ISTM depends. Because Plant 61 receives only feed stock, the IDCV has all zeros.

The Plant 61 OSTM considers combinations of up/down states of all the plants to which Plant 61 sends flow. Figure 26 shows streams leaving to four units, so the Plant 61 OSTM has $2^4 = 16$ rows. Units to which Plant 61 does not send a stream do not matter to the OSTM and 'Don't Care' X values were inserted. Without the X terms, each OSTM or ISTM would have 2^{17} rows (using a two-state model), which would be unmanageable. The values within the corresponding Plant 61 OSTM unit survival times (ST) were determined based on all the constraints in place for Plant 61. If Plant 69 is down, Plant 61 has nowhere to send or redirect the stream it normally sends to Plant 69 because there is no intermediate tankage between Plant 61 and Plant 69, and no other unit can accept the stream. So the survival time must be 0 hours whenever Plant 69 is down and 0 was entered in the survival time for every combination that includes plant 69 being down. If Plant 2 goes down, there is two hours of tankage available for the stream Plant 61 normally sends to Plant 2. If Plant EDD goes down, there is 48 hours of tankage available for the stream Plant 61 normally sends to EDD. If Plant SIG goes down, there is 48 hours of tankage available for the stream Plant 61 normally sends to SIG. Because all of these constraints are independent of each other, OSTM row survival times are simply the smallest survival time allowed by all constraints in a given refinery state configuration – for example, if SIG and EDD and Plant 2 are DOWN and Plant 69 is UP, the OSTM survival time is 2 hours, as shown in the second from bottom row of the Plant 60 OSTM.

The Plant 61 ODCV includes ones corresponding to the four units to which Plant 61 sends streams and includes an X for each other unit, including itself.

Other Units' ISTM and OSTM are similarly determined by their individual constraints, but may be considerably more complicated than those of Plant 61. A given catalyst, for example, may be able to accept streams from one unit only if another unit is UP, in which case the survival time would not just be the smallest of the downed units. Unit constraints are generally confidential or include information which is proprietary in nature. Only the resulting survival times are published in the following sections.

LEGEND:
- 0 UNIT IS UP
- 1 UNIT IS DOWN
- X DON'T CARE TERM

DEPENDENCY = {ISTM, , IDCV, OSTM, ODCV}
- ISTM Input State Transiton Matrix
- OSTM Output State Transition Matrix
- IDCV Input Don't Care Vector
- ODCV Output Don't Care Vector

Detailed Unit Reliability Dependency Matrices
61 - Crude / Vacuum

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	∞

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	0	X	0	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
X	1	X	0	X	0	0	X	X	X	X	X	X	X	X	X	X	0
X	0	X	1	X	0	0	X	X	X	X	X	X	X	X	X	X	2
X	1	X	1	X	0	0	X	X	X	X	X	X	X	X	X	X	0
X	0	X	0	X	1	0	X	X	X	X	X	X	X	X	X	X	48
X	1	X	0	X	1	0	X	X	X	X	X	X	X	X	X	X	0
X	0	X	1	X	1	0	X	X	X	X	X	X	X	X	X	X	2
X	1	X	1	X	1	0	X	X	X	X	X	X	X	X	X	X	0
X	0	X	0	X	0	1	X	X	X	X	X	X	X	X	X	X	48
X	1	X	0	X	0	1	X	X	X	X	X	X	X	X	X	X	0
X	0	X	1	X	0	1	X	X	X	X	X	X	X	X	X	X	2
X	1	X	1	X	0	1	X	X	X	X	X	X	X	X	X	X	0
X	0	X	0	X	1	1	X	X	X	X	X	X	X	X	X	X	48
X	1	X	0	X	1	1	X	X	X	X	X	X	X	X	X	X	0
X	0	X	1	X	1	1	X	X	X	X	X	X	X	X	X	X	2
X	1	X	1	X	1	1	X	X	X	X	X	X	X	X	X	X	0

0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 27: Detailed Unit Reliability Dependency Matrices – Plant 61

4.1.2 Plant 69 - Coker

Plant 69 receives feed from two production units and sends product to three production units, as shown in Figure 28.

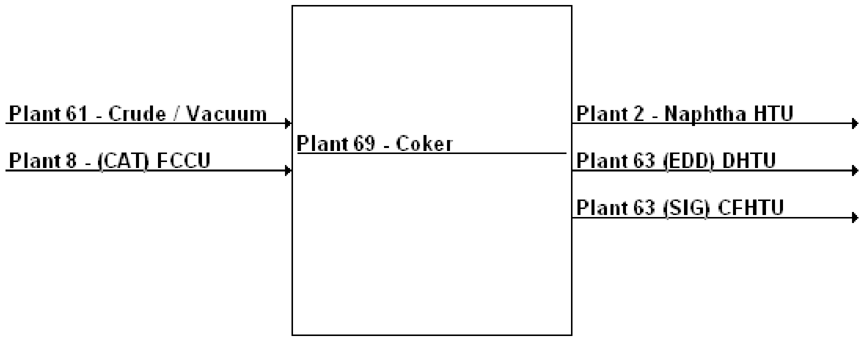


Figure 28: Reliability Block Diagram – Plant 69

Detailed Unit Reliability Dependency Matrices
69 - Coker

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
0	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	∞
1	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	0
0	X	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	∞
1	X	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	0

1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	0	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	1	X	0	0	X	X	X	X	X	X	X	X	X	X	2
X	X	X	0	X	1	0	X	X	X	X	X	X	X	X	X	X	48
X	X	X	1	X	1	0	X	X	X	X	X	X	X	X	X	X	2
X	X	X	0	X	0	1	X	X	X	X	X	X	X	X	X	X	48
X	X	X	1	X	0	1	X	X	X	X	X	X	X	X	X	X	2
X	X	X	0	X	1	1	X	X	X	X	X	X	X	X	X	X	48
X	X	X	1	X	1	1	X	X	X	X	X	X	X	X	X	X	2

0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 29: Detailed Unit Reliability Dependency Matrices – Plant 69

4.1.3 Plant 51 - Syncrude Splitter

Plant 51 receives feed from three production units and sends product to five production units, as shown in Figure 30.

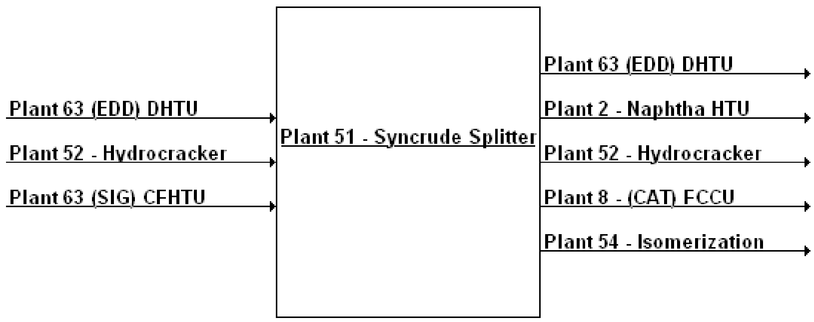


Figure 30: Reliability Block Diagram – Plant 51

Detailed Unit Reliability Dependency Matrices
51 - Syncrude Splitter

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	0	0	0	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	0	1	0	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	0	0	1	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	0	1	1	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	1	0	0	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	1	1	0	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	1	0	1	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	1	1	1	X	X	X	X	X	X	X	X	X	∞

0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	0	X	0	X	0	X	X	X	0	0	X	X	X	X	∞
X	X	X	1	X	0	X	0	X	X	X	0	0	X	X	X	X	∞
X	X	X	0	X	1	X	0	X	X	X	0	0	X	X	X	X	∞
X	X	X	1	X	1	X	0	X	X	X	0	0	X	X	X	X	∞
X	X	X	0	X	0	X	1	X	X	X	0	0	X	X	X	X	∞
X	X	X	1	X	0	X	1	X	X	X	0	0	X	X	X	X	∞
X	X	X	0	X	1	X	1	X	X	X	0	0	X	X	X	X	∞
X	X	X	1	X	1	X	1	X	X	X	0	0	X	X	X	X	∞
X	X	X	0	X	0	X	0	X	X	X	1	0	X	X	X	X	∞
X	X	X	1	X	0	X	0	X	X	X	1	0	X	X	X	X	∞
X	X	X	0	X	1	X	0	X	X	X	1	0	X	X	X	X	∞
X	X	X	1	X	1	X	0	X	X	X	1	0	X	X	X	X	∞
X	X	X	0	X	0	X	1	X	X	X	1	0	X	X	X	X	0
X	X	X	1	X	0	X	1	X	X	X	1	0	X	X	X	X	0
X	X	X	0	X	1	X	1	X	X	X	1	0	X	X	X	X	0
X	X	X	1	X	1	X	1	X	X	X	1	0	X	X	X	X	0
X	X	X	0	X	0	X	0	X	X	X	0	1	X	X	X	X	∞
X	X	X	1	X	0	X	0	X	X	X	0	1	X	X	X	X	∞
X	X	X	0	X	1	X	0	X	X	X	0	1	X	X	X	X	∞
X	X	X	1	X	1	X	0	X	X	X	0	1	X	X	X	X	∞
X	X	X	0	X	0	X	1	X	X	X	0	1	X	X	X	X	∞
X	X	X	1	X	0	X	1	X	X	X	0	1	X	X	X	X	∞
X	X	X	0	X	1	X	1	X	X	X	0	1	X	X	X	X	∞
X	X	X	1	X	1	X	1	X	X	X	0	1	X	X	X	X	∞
X	X	X	0	X	0	X	0	X	X	X	1	1	X	X	X	X	∞
X	X	X	1	X	0	X	0	X	X	X	1	1	X	X	X	X	∞
X	X	X	0	X	1	X	0	X	X	X	1	1	X	X	X	X	∞
X	X	X	1	X	1	X	0	X	X	X	1	1	X	X	X	X	∞
X	X	X	0	X	0	X	1	X	X	X	1	1	X	X	X	X	0
X	X	X	1	X	0	X	1	X	X	X	1	1	X	X	X	X	0
X	X	X	0	X	1	X	1	X	X	X	1	1	X	X	X	X	0
X	X	X	1	X	1	X	1	X	X	X	1	1	X	X	X	X	0

0	0	0	1	0	1	0	1	0	0	0	1	1	0	0	0	0	ODCV

Figure 31: Detailed Unit Reliability Dependency Matrices – Plant 51

4.1.4 Plant 2 - Naphtha HTU

Plant 2 receives feed from five production units and sends product to one production unit, as shown in Figure 32.

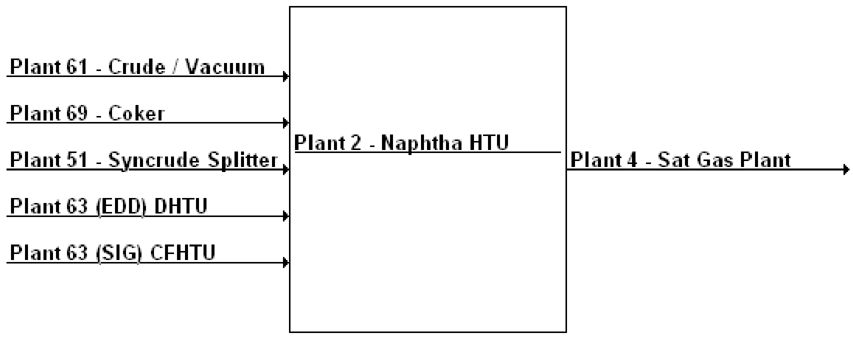


Figure 32: Reliability Block Diagram – Plant 2

Detailed Unit Reliability Dependency Matrices
2 - Naphtha HTU

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP

61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
0	0	0	X	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	0	0	X	X	X	X	X	X	X	X	X	X	0
0	1	0	X	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	0	0	X	X	X	X	X	X	X	X	X	X	0
0	0	1	X	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	0	0	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	0	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	0	0	X	X	X	X	X	X	X	X	X	X	0
0	0	0	X	X	1	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	1	0	X	X	X	X	X	X	X	X	X	X	0
0	1	0	X	X	1	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	1	0	X	X	X	X	X	X	X	X	X	X	0
0	0	1	X	X	1	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	1	0	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	1	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	1	0	X	X	X	X	X	X	X	X	X	X	0
0	0	0	X	X	0	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	0	1	X	X	X	X	X	X	X	X	X	X	0
0	1	0	X	X	0	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	0	1	X	X	X	X	X	X	X	X	X	X	0
0	0	1	X	X	0	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	0	1	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	0	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	0	1	X	X	X	X	X	X	X	X	X	X	0
0	0	0	X	X	1	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	1	1	X	X	X	X	X	X	X	X	X	X	0
0	1	0	X	X	1	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	1	1	X	X	X	X	X	X	X	X	X	X	0
0	0	1	X	X	1	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	1	1	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	1	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	1	1	X	X	X	X	X	X	X	X	X	X	0

1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP

61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	X	0

0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 33: Detailed Unit Reliability Dependency Matrices – Plant 2

4.1.5 Plant 4 - Sat Gas Plant

Plant 4 receives feed from three production units and sends product to three production units, as shown in Figure 34.

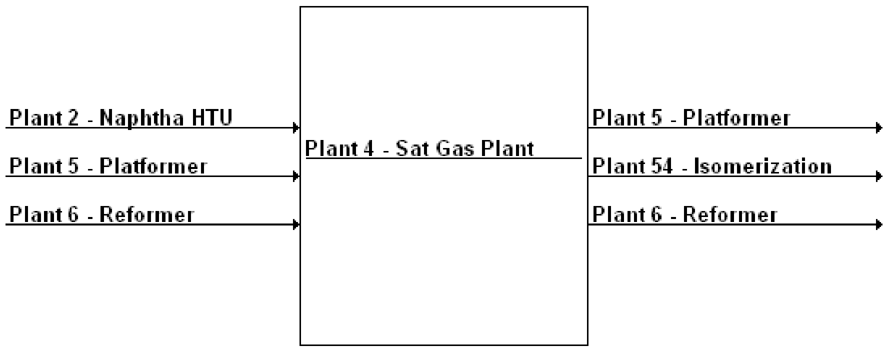


Figure 34: Reliability Block Diagram – Plant 4

Detailed Unit Reliability Dependency Matrices
4 - Sat Gas PLant

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	0	X	X	X	X	0	X	X	X	X	0	X	X	X	∞
X	X	X	1	X	X	X	X	0	X	X	X	X	0	X	X	X	0
X	X	X	0	X	X	X	X	1	X	X	X	X	0	X	X	X	∞
X	X	X	1	X	X	X	X	1	X	X	X	X	0	X	X	X	0
X	X	X	0	X	X	X	X	0	X	X	X	X	1	X	X	X	∞
X	X	X	1	X	X	X	X	0	X	X	X	X	1	X	X	X	0
X	X	X	0	X	X	X	X	1	X	X	X	X	1	X	X	X	∞
X	X	X	1	X	X	X	X	1	X	X	X	X	1	X	X	X	0
0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	0	X	X	X	0	0	X	X	X	∞
X	X	X	X	X	X	X	X	1	X	X	X	0	0	X	X	X	∞
X	X	X	X	X	X	X	X	0	X	X	X	1	0	X	X	X	∞
X	X	X	X	X	X	X	X	1	X	X	X	1	0	X	X	X	∞
X	X	X	X	X	X	X	X	0	X	X	X	0	1	X	X	X	∞
X	X	X	X	X	X	X	X	1	X	X	X	0	1	X	X	X	∞
X	X	X	X	X	X	X	X	0	X	X	X	1	1	X	X	X	∞
X	X	X	X	X	X	X	X	1	X	X	X	1	1	X	X	X	∞
0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	ODCV

Figure 35: Detailed Unit Reliability Dependency Matrices – Plant 4

4.1.6 Plant 63 (EDD) DHTU

Plant 63 (EDD) receives feed from four production units and sends product to three production units, as shown in Figure 36.

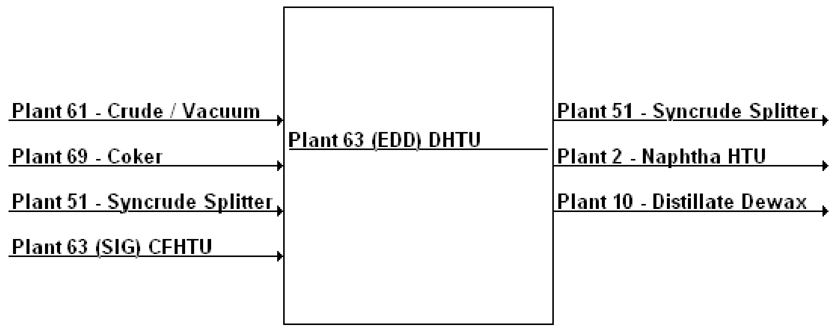


Figure 36: Reliability Block Diagram – Plant 63 (EDD)

Detailed Unit Reliability Dependency Matrices
(EDD) 63 DHTU - Distillate HTU

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
0	0	0	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
0	1	0	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
0	0	1	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	X	0	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	X	0	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	X	0	X	X	X	X	X	X	X	X	X	X	0
0	0	0	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	0	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
0	1	0	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	0	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
0	0	1	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
1	0	1	X	X	X	1	X	X	X	X	X	X	X	X	X	X	0
0	1	1	X	X	X	1	X	X	X	X	X	X	X	X	X	X	∞
1	1	1	X	X	X	1	X	X	X	X	X	X	X	X	X	X	0

1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	0	0	X	X	X	X	X	0	X	X	X	X	X	X	X	∞
X	X	0	1	X	X	X	X	X	0	X	X	X	X	X	X	X	∞
X	X	0	0	X	X	X	X	X	1	X	X	X	X	X	X	X	∞
X	X	0	1	X	X	X	X	X	1	X	X	X	X	X	X	X	∞
X	X	1	0	X	X	X	X	X	0	X	X	X	X	X	X	X	∞
X	X	1	1	X	X	X	X	X	0	X	X	X	X	X	X	X	2
X	X	1	0	X	X	X	X	X	1	X	X	X	X	X	X	X	∞
X	X	1	1	X	X	X	X	X	1	X	X	X	X	X	X	X	2

0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	ODCV

Figure 37: Detailed Unit Reliability Dependency Matrices – Plant 63 (EDD)

4.1.7 Plant 63 (SIG) CFHTU

Plant 63 (SIG) receives feed from three production units and sends product to four production units, as shown in Figure 38.

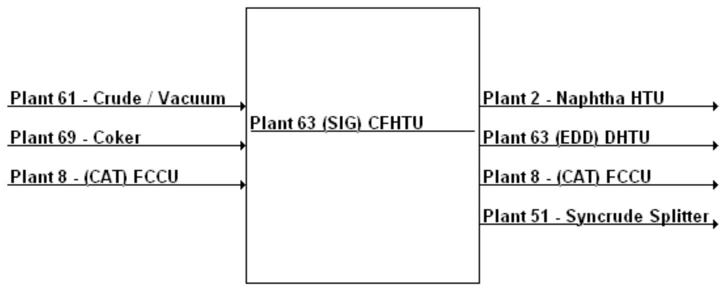


Figure 38: Reliability Block Diagram – Plant 63 (SIG)

Detailed Unit Reliability Dependency Matrices
(SIG) 63 CFHTU - Cat Feed HTU

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
0	0	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	∞
1	0	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	48
0	1	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	∞
1	1	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	48
0	0	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	∞
1	0	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	48
0	1	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	∞
1	1	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	0

1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	0	0	X	0	X	X	X	X	X	0	X	X	X	X	X	∞
X	X	0	1	X	0	X	X	X	X	X	0	X	X	X	X	X	∞
X	X	0	0	X	1	X	X	X	X	X	0	X	X	X	X	X	48
X	X	0	1	X	1	X	X	X	X	X	0	X	X	X	X	X	48
X	X	0	0	X	0	X	X	X	X	X	1	X	X	X	X	X	96
X	X	0	1	X	0	X	X	X	X	X	1	X	X	X	X	X	96
X	X	0	0	X	1	X	X	X	X	X	1	X	X	X	X	X	48
X	X	0	1	X	1	X	X	X	X	X	1	X	X	X	X	X	48
X	X	1	0	X	0	X	X	X	X	X	0	X	X	X	X	X	∞
X	X	1	1	X	0	X	X	X	X	X	0	X	X	X	X	X	2
X	X	1	0	X	1	X	X	X	X	X	0	X	X	X	X	X	48
X	X	1	1	X	1	X	X	X	X	X	0	X	X	X	X	X	2
X	X	1	0	X	0	X	X	X	X	X	1	X	X	X	X	X	96
X	X	1	1	X	0	X	X	X	X	X	1	X	X	X	X	X	2
X	X	1	0	X	1	X	X	X	X	X	1	X	X	X	X	X	48
X	X	1	1	X	1	X	X	X	X	X	1	X	X	X	X	X	2

0	0	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	ODCV

Figure 39: Detailed Unit Reliability Dependency Matrices – Plant 63 (SIG)

4.1.8 Plant 52 – Hydrocracker

Plant 52 receives feed from two production units and sends product to two production units, as shown in Figure 40.

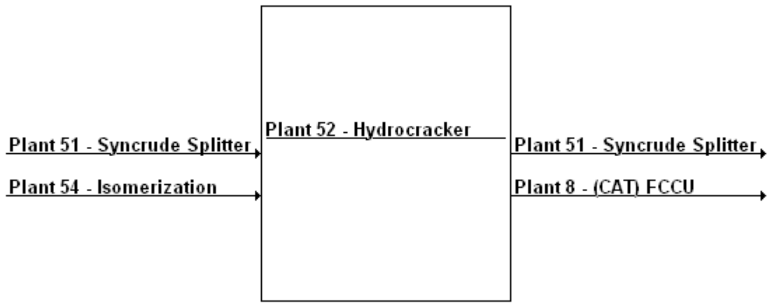


Figure 40: Reliability Block Diagram – Plant 52

Detailed Unit Reliability Dependency Matrices
52 - Hydrocracker

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	0	X	X	X	X	X	X	X	X	X	0	X	X	X	X	∞
X	X	1	X	X	X	X	X	X	X	X	X	0	X	X	X	X	0
X	X	0	X	X	X	X	X	X	X	X	X	1	X	X	X	X	∞
X	X	1	X	X	X	X	X	X	X	X	X	1	X	X	X	X	0
0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	0	X	X	X	X	X	X	X	X	0	X	X	X	X	X	∞
X	X	1	X	X	X	X	X	X	X	X	0	X	X	X	X	X	0
X	X	0	X	X	X	X	X	X	X	X	1	X	X	X	X	X	96
X	X	1	X	X	X	X	X	X	X	X	1	X	X	X	X	X	0
0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	ODCV

Figure 41: Detailed Unit Reliability Dependency Matrices – Plant 52

4.1.9 Plant 5 - Platformer

Plant 5 receives feed from one production unit and sends product to one production unit, as shown in Figure 42.

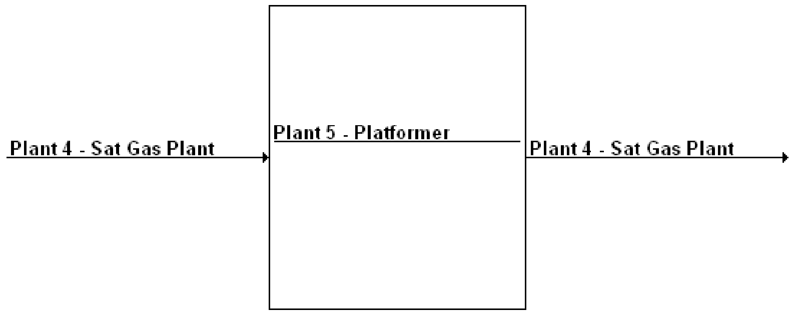


Figure 42: Reliability Block Diagram – Plant 5

Detailed Unit Reliability Dependency Matrices
5 - Platformer

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	X	0

0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	X	∞

0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 43: Detailed Unit Reliability Dependency Matrices – Plant 5

4.1.10 Plant 10 - Distillate Dewax

Plant 10 receives feed from one production unit and sends product to one production unit, as shown in Figure 44.

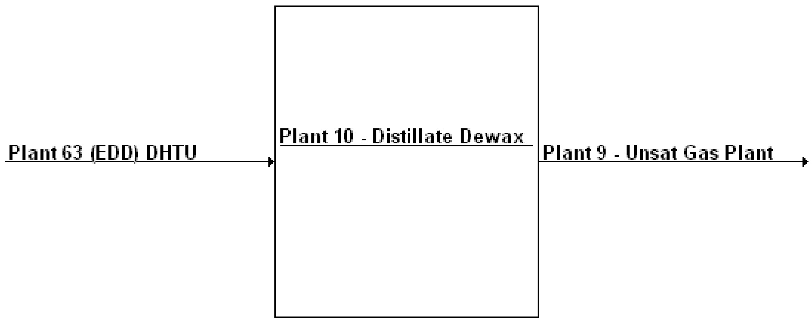


Figure 44: Reliability Block Diagram – Plant 10

Detailed Unit Reliability Dependency Matrices
10 - Distillate Dewax

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	X	∞
X	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	X	∞
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	ODCV

Figure 45: Detailed Unit Reliability Dependency Matrices – Plant 10

4.1.11 Plant 9 - Unsat Gas Plant

Plant 9 receives feed from two production units and sends product to one production unit, as shown in Figure 46.

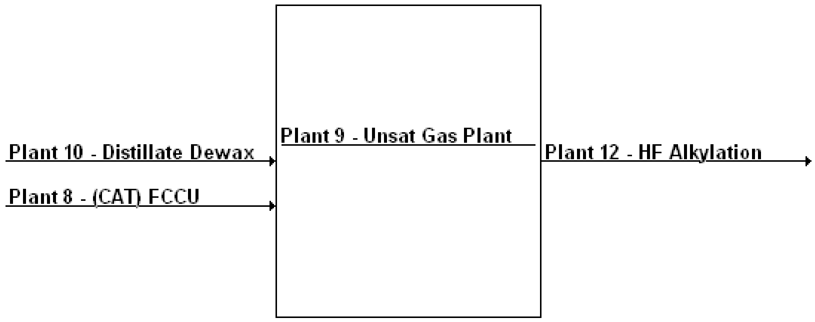


Figure 46: Reliability Block Diagram – Plant 9

Detailed Unit Reliability Dependency Matrices
9 - Unsat Gas Plant

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	0	X	0	X	X	X	X	X	∞
X	X	X	X	X	X	X	X	X	1	X	0	X	X	X	X	X	∞
X	X	X	X	X	X	X	X	X	0	X	1	X	X	X	X	X	0
X	X	X	X	X	X	X	X	X	1	X	1	X	X	X	X	X	0

0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	0	X	∞
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	1	X	0

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	ODCV

Figure 47: Detailed Unit Reliability Dependency Matrices – Plant 9

4.1.12 Plant 8 - (CAT) FCCU

Plant 8 receives feed from three production units and sends product to three production units, as shown in Figure 48.

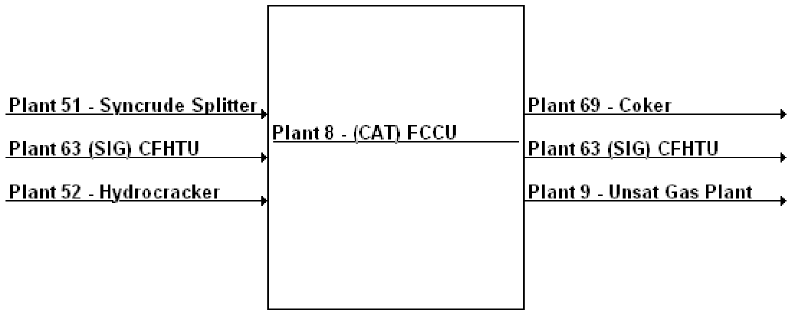


Figure 48: Reliability Block Diagram – Plant 8

Detailed Unit Reliability Dependency Matrices
8 - CAT (FCCU)

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	X	0	X	X	X	0	0	X	X	X	X	X	X	X	X	X	∞
X	X	1	X	X	X	0	0	X	X	X	X	X	X	X	X	X	∞
X	X	0	X	X	X	1	0	X	X	X	X	X	X	X	X	X	∞
X	X	1	X	X	X	1	0	X	X	X	X	X	X	X	X	X	0
X	X	0	X	X	X	0	1	X	X	X	X	X	X	X	X	X	∞
X	X	1	X	X	X	0	1	X	X	X	X	X	X	X	X	X	960
X	X	0	X	X	X	1	1	X	X	X	X	X	X	X	X	X	72
X	X	1	X	X	X	1	1	X	X	X	X	X	X	X	X	X	0

0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	0	X	X	X	X	0	X	X	X	0	X	X	X	X	X	X	∞
X	1	X	X	X	X	0	X	X	X	0	X	X	X	X	X	X	∞
X	0	X	X	X	X	1	X	X	X	0	X	X	X	X	X	X	∞
X	1	X	X	X	X	1	X	X	X	0	X	X	X	X	X	X	240
X	0	X	X	X	X	0	X	X	X	1	X	X	X	X	X	X	48
X	1	X	X	X	X	0	X	X	X	1	X	X	X	X	X	X	48
X	0	X	X	X	X	1	X	X	X	1	X	X	X	X	X	X	48
X	1	X	X	X	X	1	X	X	X	1	X	X	X	X	X	X	48

0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	ODCV

Figure 49: Detailed Unit Reliability Dependency Matrices – Plant 8 ISTM & IDCV

4.1.13 Plant 54 - Isomerization

Plant 54 receives feed from two production units and sends product to one production unit, as shown in Figure 50.

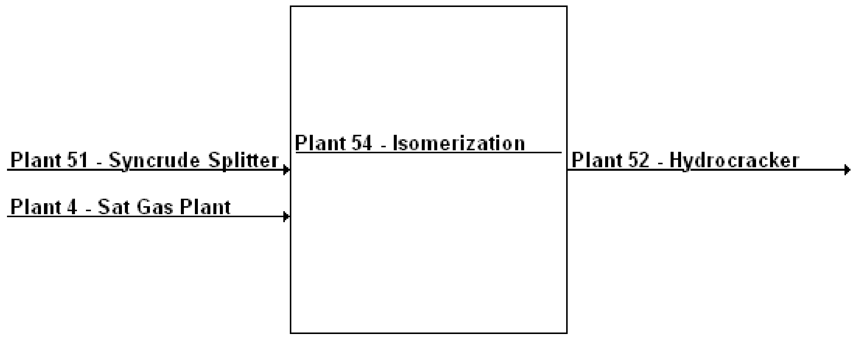


Figure 50: Reliability Block Diagram – Plant 54

Detailed Unit Reliability Dependency Matrices
54 - Isomerization (ISOM)

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	0	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	1	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	0	X	1	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	1	X	1	X	X	X	X	X	X	X	X	X	X	X	X	144

0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	0	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	X	X	X	1	X	X	X	X	X	X	X	X	X	∞

0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	ODCV

Figure 51: Detailed Unit Reliability Dependency Matrices – Plant 54

4.1.14 Plant 6 - Reformer

Plant 6 receives feed from one production unit and sends product to one production unit, as shown in Figure 52.

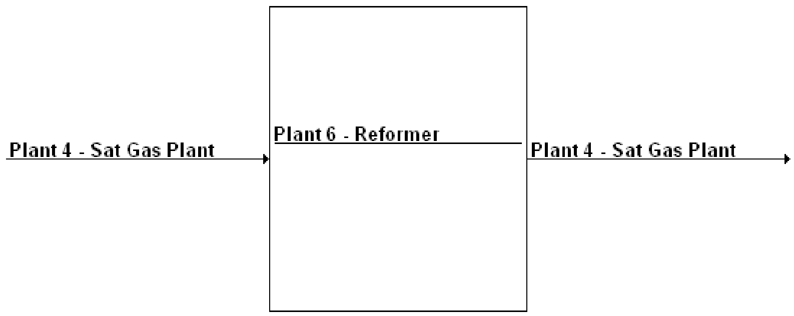


Figure 52: Reliability Block Diagram – Plant 6

Detailed Unit Reliability Dependency Matrices
6 - Reformer

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	X	144

0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	0	X	X	X	X	X	X	X	X	X	X	X	X	∞
X	X	X	X	1	X	X	X	X	X	X	X	X	X	X	X	X	∞

0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 53: Detailed Unit Reliability Dependency Matrices – Plant 6

4.1.15 Plant 3 - Avgas

Plant 3 receives feed from one production unit and sends product only to tankage of external pipelines, as shown in Figure 54.

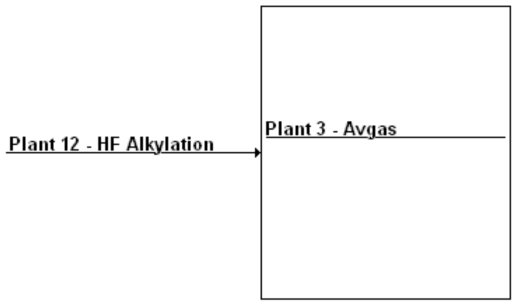


Figure 54: Reliability Block Diagram – Plant 3

Detailed Unit Reliability Dependency Matrices
3 - Avgas

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	0	X	∞
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	1	X	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	∞
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	ODCV

Figure 55: Detailed Unit Reliability Dependency Matrices – Plant 3

4.1.16 Plant 12 - HF Alkylation

Plant 12 receives feed from two production units and sends product to one production unit, as shown in Figure 56.

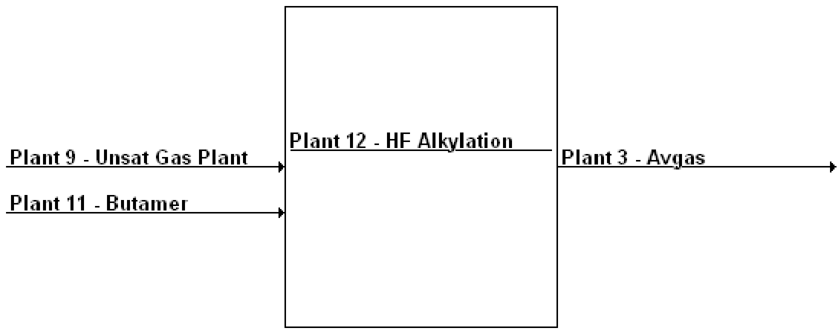


Figure 56: Reliability Block Diagram – Plant 12

Detailed Unit Reliability Dependency Matrices
12 - HF Alkylation (ALKY)

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP

61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	0	∞
X	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	0	0
X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	1	24
X	X	X	X	X	X	X	X	X	X	1	X	X	X	X	X	1	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP

61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST
X	X	X	X	X	X	X	X	X	X	X	X	X	X	0	X	X	∞
X	X	X	X	X	X	X	X	X	X	X	X	X	X	1	X	X	∞
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	ODCV

Figure 57: Detailed Unit Reliability Dependency Matrices – Plant 12

4.1.17 Plant 11 – Butamer

Plant 11 receives feed from external pipelines or tankage and sends product to one production unit, as shown in Figure 58.

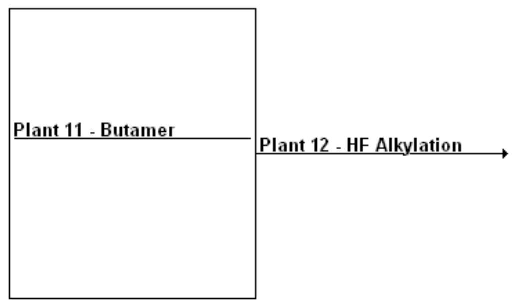


Figure 58: Reliability Block Diagram – Plant 11

Detailed Unit Reliability Dependency Matrices
11 - Butamer

INPUT COMBINATION (ISTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	∞
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	IDCV

OUTPUT COMBINATION (OSTM): 1=DOWN, 0=UP																	ST
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	0	X	∞
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	1	X	24
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	ODCV

Figure 59: Detailed Unit Reliability Dependency Matrices – Plant 11

4.2 Cascading Interruption Algorithm

4.2.1 Simulation Programming

When a refinery has 17 process units, there are $2^{17} = 131{,}072$ possible refinery state vectors (in a two-state model), through which the refinery may or may not transition during a cascading interruption. A simulation must be able to determine how long each state will survive, based on time spent in previous states, as well as determine into which state will be the next transition. This must continue until a stable operating state is reached. The input to the program should be an initial state vector and the output of the simulation should be a table of operating states and their associated survival times which will form the basis of the CEF() function.

The Current State Vector ("CSV") is a 1x17 matrix whose entries represent the state of each unit in its position. Negative logic is employed where 0 represents an UP state and 1 represents a DOWN state. Negative logic is convenient because logical vector operations such as AND and OR are more easily understood than NOR and NAND, respectively.

The Next State Vector ("NSV") is a 1x17 matrix like the CSV whose values contain the state into which the refinery will transition at the end of the current survival time. In the case where the NSV equals the CSV, no units will change state and the survival time must be infinite, creating the condition for exiting iteration.

The EDMR_CASCADE.m program is written in Matlab® software. The source code itself is approximately 2,000 lines in length. A simplified program structure is shown in Figure 60. Once an input CSV enters the main 'while' iteration loop, the program remains within the while loop and must continue to loop until it has found a stable state where ST = ∞ or NSV = CSV.

Within each iteration of the master while loop, there are two main sections, as well as some additional house-keeping variable updates and result printing.

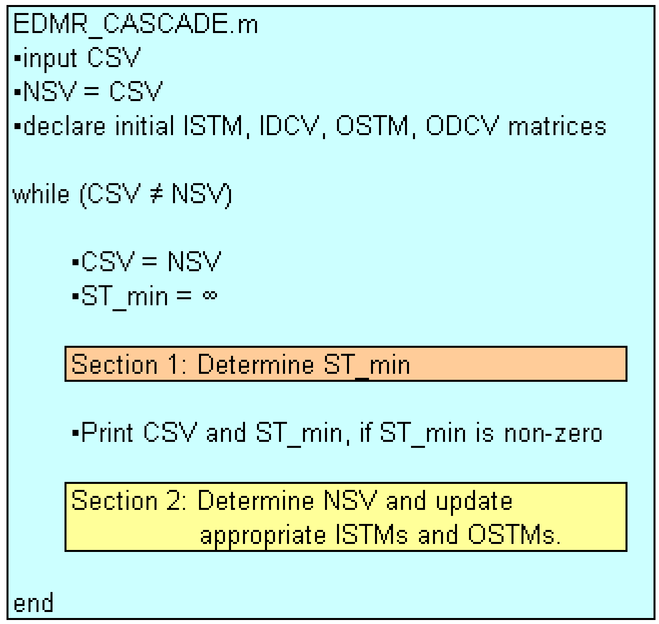


Figure 60: EDMR_CASCADE Simplified Program Structure

4.2.1.1 Section 1 Code Description

The first main section called 'Determine ST_min' sorts through all plant ISTMs and OSTMs to find the smallest survival time amongst all plants, given the CSV. It is possible that more than one plant will share the smallest survival time and that survival time may have a value of zero hours. At the conclusion of the first section, the ST_min will have a value between zero and infinity.

Consider the section 1 code for Plant 61 shown in Figure 61.

Lines 344 and 372 contain the section inside an if statement. CSV(1) represents the current state of the plant 61 because Plant 61 is in position 1 within the CSV, by Table 5. Only plants which are in the up state (0) can contribute to finding the ST_min, so if CSV(1) equals 1, Plant 61 should be skipped.

Line 346 notes that Plant 61 has no inputs from other process units, so there are no ISTM_61 rows to consider.

Line 350 creates a new local CSV by which to search OSTM_61 using a logical vector AND function of the CSV and the ODCV_61. This method eliminates the need to store 2^{17} permutations worth of data by masking out don't care terms. Because don't care terms are loaded into the ISTM or OSTM as zeros, masking don't care terms away in the CSV means the CSV_local variable has the potential to exactly match the first 17 columns of a row in the OSTM_61.

Lines 353 through 366 constitute a loop which searches one row of OSTM_61 with each pass.

Lines 355 through 357 create a 1x17 vector called Target_Row_Check out of the first 17 columns of a given row in OSTM_61.

Line 361 then checks to see if the CSV is affecting the given plant by checking if Target_Row_Check equals CSV_local. If so, the ST_min can be updated where applicable by executing lines 362-364. If ST_min is larger than the ST associated with the OSTM_61 row where Target_Row_Check was copied, lower ST_min to the ST value.

```
% Plant 61 - Crude / Vacuum
if not(CSV(1))

  %INPUTS: (none)

  %OUTPUTS:

  CSV_local = and(CSV,ODCV_61); %mask out local don't cares
  b = size(OSTM_61); %find number of local rows and columns

  for i=1:1:b(1) %i represents the row we are currently searching
    %copy STM row into a new possibly target vector, but don't copy the ST
    for j=1:1:b(2)-1
      Target_Row_Check(j)=OSTM_61(i,j);
    end
    clear j;

    %Check if a target row is present
    if Target_Row_Check == CSV_local
      if ST_min > OSTM_61(i,b(2))
        ST_min = OSTM_61(i,b(2));
      end
    end
  end
  clear i;
  clear b;
  clear CSV_local;
  clear Target_Row_Check;
```

Figure 61: Section 1 Code Sample

4.2.1.2 Section 2 Code Description

The second main section called ‘Determine NSV and update appropriate ISTMs and OSTMs’ uses the CSV and ST_min to search through each plants ISTM and OSTM. If a given plant’s ISTM or OSTM row matches the CSV, a variable called ST_local_max is computed from ST of the given row minus ST_min. If ST_local_max is zero in either the ISTM or OSTM, the unit state is set to down (1) in the NSV. In that manor, multiple units can move into the down state during one iteration. In the case of a non-zero ST_local_max, to include the effect time spent in the current CSV state on survival time, all remaining rows of a unit’s ISTM or OSTM must have an ST which is equal to or lesser than a non-zero ST_local_max, so each row is updated. It is important to note that, by Axiom 1, rows that are not a superset of the CSV will never be equal to the CSV in future iterations. Therefore, it is most efficient to update all rows of an ISTM or OSTM with ST ≤ ST_local_max.

Consider the section 2 code for ISTM_52, shown in Figure 62.

In a similar manor to section 1, the CSV_local variable is created from the CSV and the IDCV_52 in line 1632.

The Target_Row_Check vector is also created in each iteration of a for loop, similar to the section 1 code.

In the for loop between lines 1635 and 1660, when a Target_Row_Check equals CSV_local condition is present, ST_min is used as an input, not an output. Line 1646 determines the ST_local_max by subtracting the ST_min from the ST of the ISTM_52 row from which Target_Row_Check was copied. In lines 1648-1650, if the ST_local_min equals zero, the NSV(8) position, corresponding to Plant 52, is updated with 1 to represent Plant 52 transitioning into a down state at the next master while loop iteration.

If the Target_Row_Check equals SCV_local condition is satisfied, but the ST_local_min is non-zero (positive), ST_local_min represents the maximum time remaining for the given plant to survive in any superset of the CSV and all ISTM_52 rows must have their ST updated. Lines 1653-1655 accomplish this by checking if an ISTM_52 row's ST is greater than ST_local_max. If so, ST is set equal to ST_local_max.

```
1628    % Plant 52 - Hydrocracker
1629
1630        %INPUTS:
1631
1632    CSV_local = and(CSV,IDCV_52); %mask out local don't cares
1633    b = size(ISTM_52); %find number of local rows and columns
1634
1635        for i=1:1:b(1) %i represents the row we are currently searching
1636          %copy STM row into a new possibly target vector, but don't copy the ST
1637          for j=1:1:b(2)-1
1638            Target_Row_Check(j)=ISTM_52(i,j);
1639          end
1640          clear j;
1641
1642          %Check if a target row is present
1643          if Target_Row_Check == CSV_local
1644
1645            %determine local max
1646            ST_local_max = ISTM_52(i,b(2))-ST_min;
1647
1648            if ST_local_max == 0
1649              %Set Unit Out of Service for in Next State Vector;
1650              NSV(8)=1;
1651            else % go through all of unit's rows to check/alter ST
1652              for k = 1:1:b(1) %k represents the row we are searching
1653                if ISTM_52(k,b(2)) > ST_local_max
1654                  ISTM_52(k,b(2))=ST_local_max;
1655                end
1656              end
1657              clear k;
1658            end
1659          end
1660        end
1661        clear i;
```

```
clear b;
clear CSV_local;
clear ST_local_max;
clear Target_Row_Check;
```

Figure 62: Section 2 Code Sample

4.3 Determination of CEF() Data

To construct a criticality enhancement function, the slope of each segment is required in units of bpu.

To determine the impact of process interruption in a given configuration, an additional calculation is required within the EDMR_CASCADE.m program to determine the flow rate of hydrocarbon streams between operating units and how much of each unit's throughput is turned into finished product.

Based upon data contained in the Petro-Canada Edmonton Refinery 2008 Business Plan Volumetrics document [8], the stream fractions passed between operating units were determined. Table 4 shows the sender-receiver fractions of production unit streams. Since the business plan represents the expected case, interruption should reference a deviation from the expected case. Units listed in the left-most column send product to units listed in the columns to the right. Finished product streams coming from each unit are expressed in a percentage of unit flow rate in the Finished Product column. The sum of each row's stream fractions must equal 100% and that sum is checked in the right-most column.

Table 4: Case Study Production Unit Product Streams Matrix

FROM \ TO	61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	FINISHED PRODUCT	CHECK SUM
61		18.4%		25.6%		22.6%	33.4%												100%
69				20.6%		21.0%	36.8%											21.7%	100%
51				8.7%		37.0%		39.7%				3.3%	4.8%					6.5%	100%
2					100.0%														100%
4									34.3%				10.8%	0.0%				55.0%	100%
EDD				7.3%						44.7%								48.0%	100%
SIG				7.7%		23.7%						68.6%							100%
52			19.1%									37.8%						43.1%	100%
5					0.0%													100.0%	100%
10											12.6%							87.4%	100%
9																31.8%		68.2%	100%
8		0.0%					11.6%				88.4%							0.0%	100%
54								3.1%										96.9%	100%
6					0.0%													100.0%	100%
3																		100.0%	100%
12															0.3%			99.7%	100%
11																56.6%		43.4%	100%

The cost in bpu of interruption may then be calculated iteratively for each stable Current State Vector (CSV). The expected fraction of the refinery's total 1.0 BPU that each unit sends as finished product is calculated, and then total production in bpu is subtracted from 1.0. When a unit is down, its flow is set to zero during this calculation and units relying on tankage are subjected to the minimum flow criteria upon which their survival times were based.

4.4 Substation – Unit Dependence

The relationship between electrical substation interruption and process cut-sets is the initial CSV caused by an outage of a given substation. Based upon the single line diagrams and process & instrumentation diagrams of the Petro-Canada Edmonton Refinery, Table 5 identifies eleven substation outage cases that require study. The matrix created by the eleven CSV vectors is the input to the EDMR_CASCADE.m program.

Table 5: Case Study Substation – Unit Dependence Matrix

CASE #	CSV / SUB	61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11
1	SUB # 08	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	SUB # 44	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	SUB # 29	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
4	SUB # 06	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
5	SUB # 26	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
6	SUB # 25	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	SUB # 20	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8	SUB # 47	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
9	SUB # 11	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0
10	SUB # 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
11	SUB # 12/22	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0

4.5 Results

After running the EDMR_CASCADE.m program for the eleven substation interruption cases specified in Table 5, the following results displayed in Tables 6 through 16 were computed.

Case 1: Sub # 08 Outage

Plant 61 is a critical unit because it receives crude feed and there is no intermediate tankage between Plant 61 and 69. The initial survival time is 0, and the unit configuration immediately proceeds to an additional outage of Plants 69, 2, 4, and 5. The bpu in this configuration is relatively stable for 48, 96, then 144 hour segments. When Plant 8 runs out of tankage and is interrupted, bpu jumps from 0.41 to 0.6. The final state includes an entire refinery outage if power to Sub # 8 is not restored and reaches 0.96 bpu at 384 hours or about 55 days. Because Plant 61 is one of two units that receive crude feed, running with Plant 61 down is relatively stable with low initial bpu.

Table 6: Case 1 Results – Sub# 08 Outage

SUB # 08 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	0	0.17853	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	48	0.30419	1.70388
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	96	0.41742	2.3381
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	UP	144	0.41742	2.3381
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.60303	3.37776
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.60303	3.37776
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	5.39952
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	5.60128

Case 2: Sub # 44 Outage

Due to the dependence of Plant 61 on Plant 69, the first configuration that includes a non-zero survival time is common to Cases 1 and 2. As such, the survival times and bpu values beyond the first row in these cases are identical. Where in case 1, Plant 61 interrupts Plant 69, in case 2, plant 69 interrupts plant 61. Hence, interruption of Sub#44 or Sub#08 have similar consequences.

Table 7: Case 2 Results – Sub# 44 Outage

SUB # 44 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	0	0.1114	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	48	0.30419	2.73077
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	96	0.41742	3.74721
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	UP	144	0.41742	3.74721
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.60303	5.41344
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.60303	5.41344
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	8.65367
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	8.97702

Case 3: Sub # 29 Outage

SIG and EDD share some common equipment and a common substation. When power to Sub#29 is interrupted, SIG and EDD go down as a pair. The first non-zero survival time includes an additional outage of plant 10. The cascade sequence includes plant 61 and associated plants, then plant 8 and associated plants, then plant 51. This cascade also reaches 0.96 bpu in 384 hours, but with different survival times and bpu values.

Table 8: Case 3 Results – Sub# 29 Outage

SUB # 29 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	0	0.44975	1
UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.49403	1.09844
DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	144	0.68798	1.52969
DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	96	0.68798	1.52969
DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.87359	1.94238
DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.87359	1.94238
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.14335
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.22344

Case 4: Sub # 06 Outage

Clearly, the interruption of Substation#06 does not affect the production of other units. It has a very small bpu because little aviation gas is planned for production in 2009.

Table 9: Case 4 Results – Sub# 06 Outage

SUB # 06 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	INF	0.00045	1

Case 5: Sub # 26 Outage

Interruption of Sub#26 also has little impact on process. Since all other plants can run in the absence of plant 54, there is negligible impact.

Table 10: Case 5 Results – Sub# 26 Outage

SUB # 26 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	UP	UP	UP	UP	INF	0.04381	1

Case 6: Sub # 25 Outage

Plant 51 receives crude oil. When 51 is initially interrupted, the survival time is zero and plant 52 is immediately interrupted. With plants 51 and 52 out of service, the refinery can run on gas oil for a lengthy 960 hours, so running on crude from plant 61 and gas oil tankage allows little impact for a long period of time and running without plant 51 is a stable configuration.

Table 11: Case 6 Results – Sub# 25 Outage

SUB # 25 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	0	0.17932	1
UP	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	960	0.25791	1.43828
UP	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	UP	24	0.49551	2.76336
UP	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	72	0.49551	2.76336
UP	UP	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	48	0.51031	2.84588
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	144	0.96398	5.37589
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	5.57677

Case 7: Sub # 20 Outage

Interruption of Sub#20 interrupts plant 52. Plant 52 interruption has little impact on the production of other units and a very small bpu.

Table 12: Case 7 Results – Sub# 20 Outage

SUB # 20 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	INF	0.16813	1

Case 8: Sub # 47 Outage

Interruption of Sub#47 interrupts plant 2, which is a critical plant to the refinery. Plants 4 and 5 immediately follows plant 2, but are only stable for 2 hours, after which plant 61 is interrupted, initiating a cascade similar to the interruption of Sub#08. A bpu of 0.96 is reached at 386 hours.

Table 13: Case 8 Results – Sub# 47 Outage

SUB # 47 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	0	0.18919	1
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	2	0.21622	1.14286
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	48	0.30419	1.60784
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	UP	UP	UP	UP	94	0.41742	2.20631
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	UP	UP	UP	DOWN	UP	UP	UP	146	0.41742	2.20631
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.60303	3.18737
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.60303	3.18737
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	5.09517
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	5.28556

Case 9: Sub # 11 Outage

Because an interruption of Sub#11 also interrupts critical plant 2, the cascade initiated by the interruption of plant 2 as well as other less critical units is identical to that of the interruption of Sub#47.

Table 14: Case 9 Results – Sub# 11 Outage

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Case 10: Sub # 13 Outage

Interruption of Sub#13 interrupts plants 12 and 11. The first non-zero survival time includes the additional immediate interruption of plants 3 and 9. After 48 hours, plant 8 is interrupted and cascade quickly interrupts both crude receiving plants 61 and 51. After 192 hours, bpu has reached 0.96 and relatively large bpu values have occurred in each configuration. Interruption of Sub#13 has relatively high consequences.

Table 15: Case 10 Results – Sub# 13 Outage

SUB # 13 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	0	0.18197	1
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	UP	UP	UP	DOWN	DOWN	DOWN	48	0.33848	1.86008
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	96	0.34673	1.90544
UP	UP	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	48	0.51031	2.80436
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	144	0.96398	5.29745
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	5.4954

Case 11: Sub # 12/22 Outage

Plant 8 is the heart of the Edmonton Refinery and an interruption of associated substation #12/22 interrupts Plants 8 and 9. After 24 hours, plants 3 and 12 follow. Plant 11 is interrupted 72 hours later, then plant 51, then 61, until 0.96 bpu is reached in 144 hours.

Table 16: Case 11 Results – Sub# 12/22 Outage

SUB # 12/22 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	0	0.28565	1
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	UP	24	0.34673	1.21385
UP	UP	UP	UP	UP	UP	UP	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	72	0.34673	1.21385
UP	UP	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	48	0.51031	1.7865
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	UP	DOWN	DOWN	DOWN	144	0.96398	3.37471
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	3.50081

4.5.1 Discussion of Case #9 results.

As an illustration of a cascading interruption, consider case#9 which involves the interruption of substation #11. Units initially interrupted include {Plant 2, Plant 4, Plant 5, Plant 10}. The process model in this refinery state is shown in Figure 63.

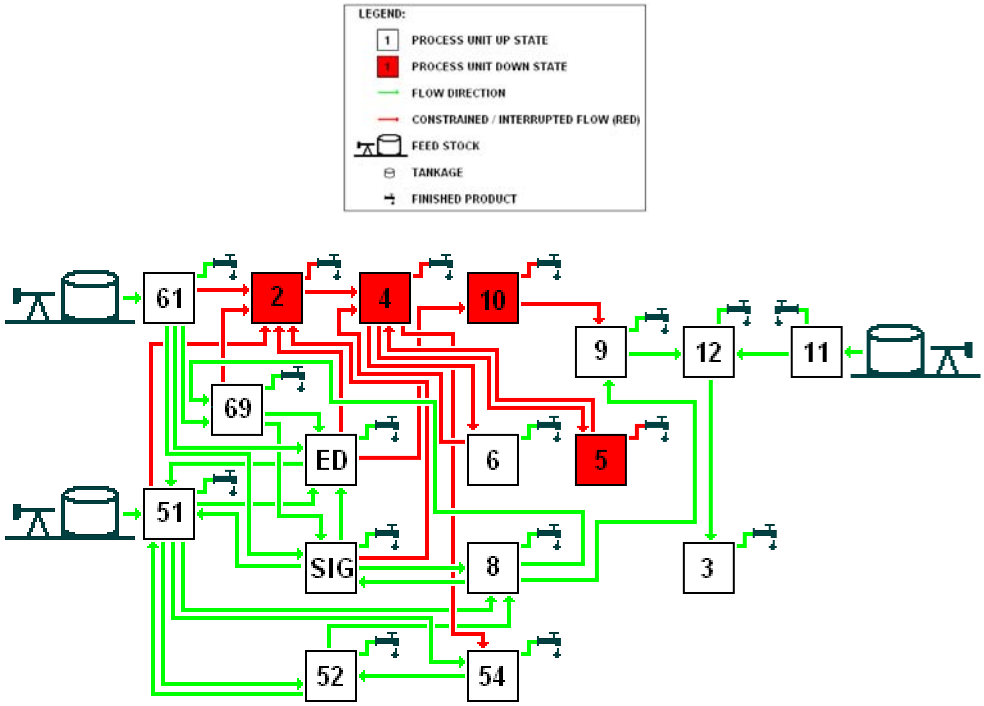


Figure 63: Process Model – Initial Interrupted State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 64.

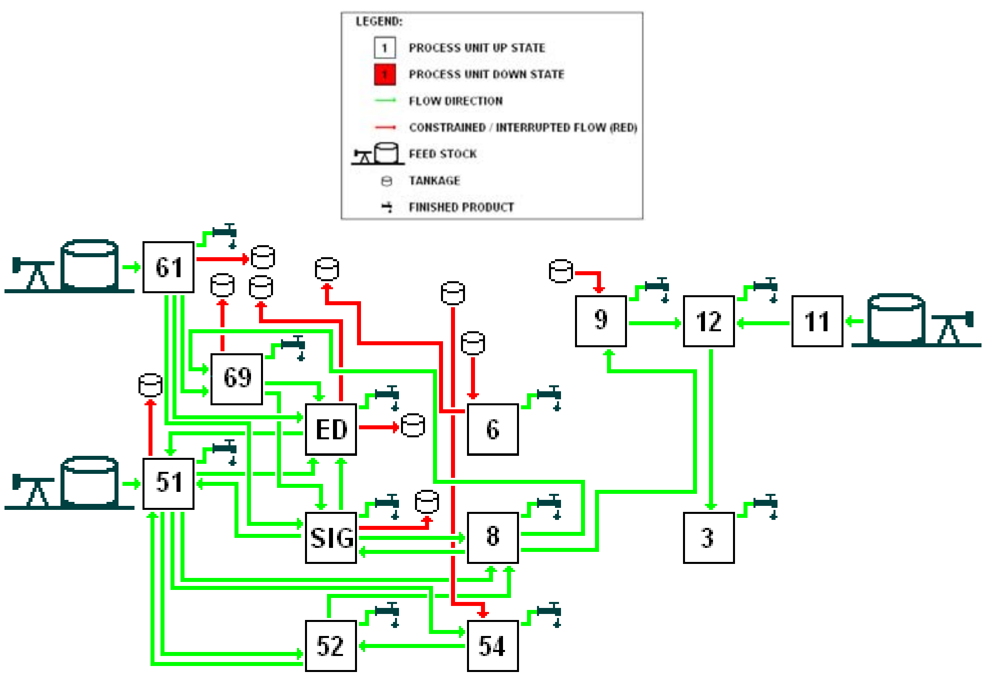


Figure 64: Process Model – Initial Interrupted State – Some Tankage Included

The process can remain in this state for two hours. Two hours is the smallest ‘tank’⊖ in use during this refinery. Figure 65 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 65: Highlighted Result for Current Refinery State

After two hours, plant 61 and 69 go down and the process model is shown in Figure 66.

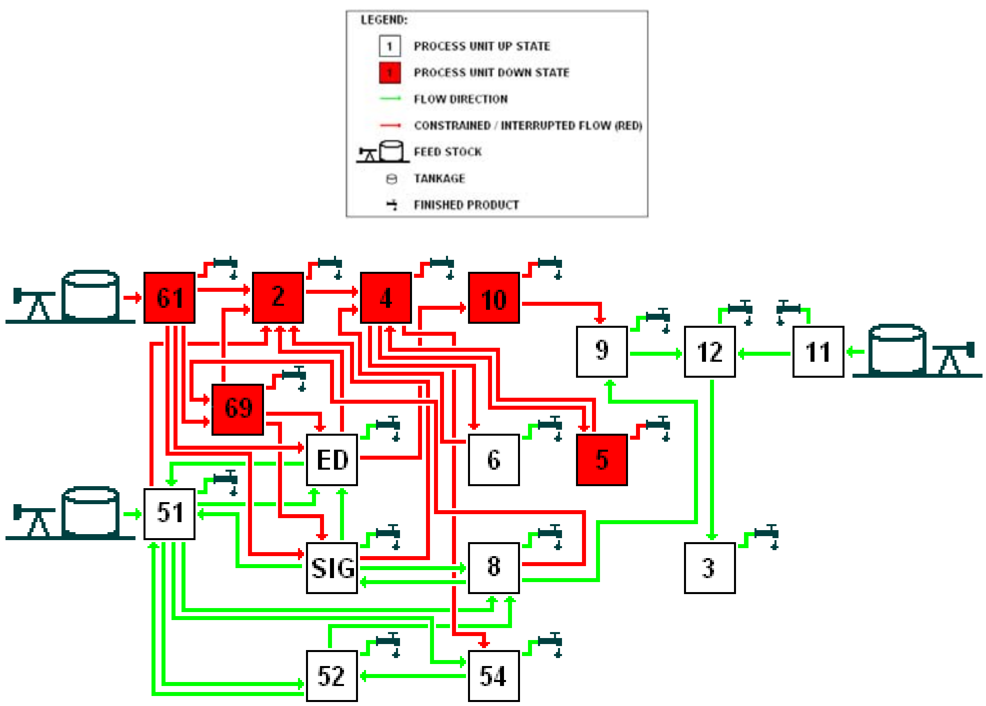


Figure 66: Process Model – First Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 67.

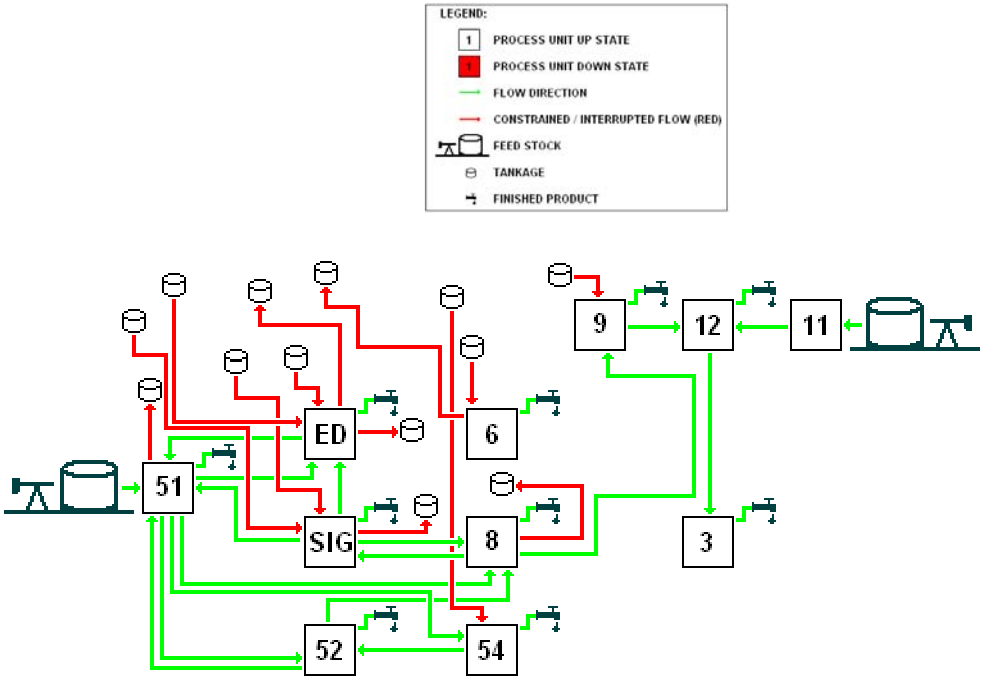


Figure 67: Process Model – First Cascaded State – Some Tankage Included

The process can remain in this state for 48 more hours before any of the imaginary tanks are used up or full. Figure 68 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 68: Highlighted Result for Current Refinery State

Next, plant SIG goes down and the process model is shown in Figure 69.

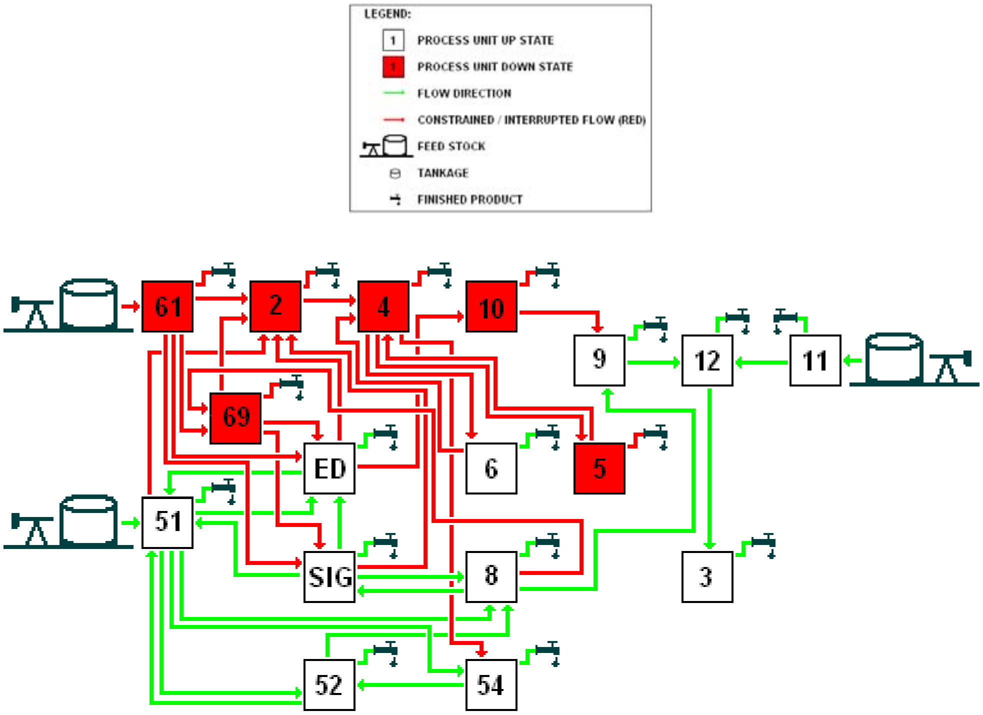


Figure 69: Process Model – Second Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 70.

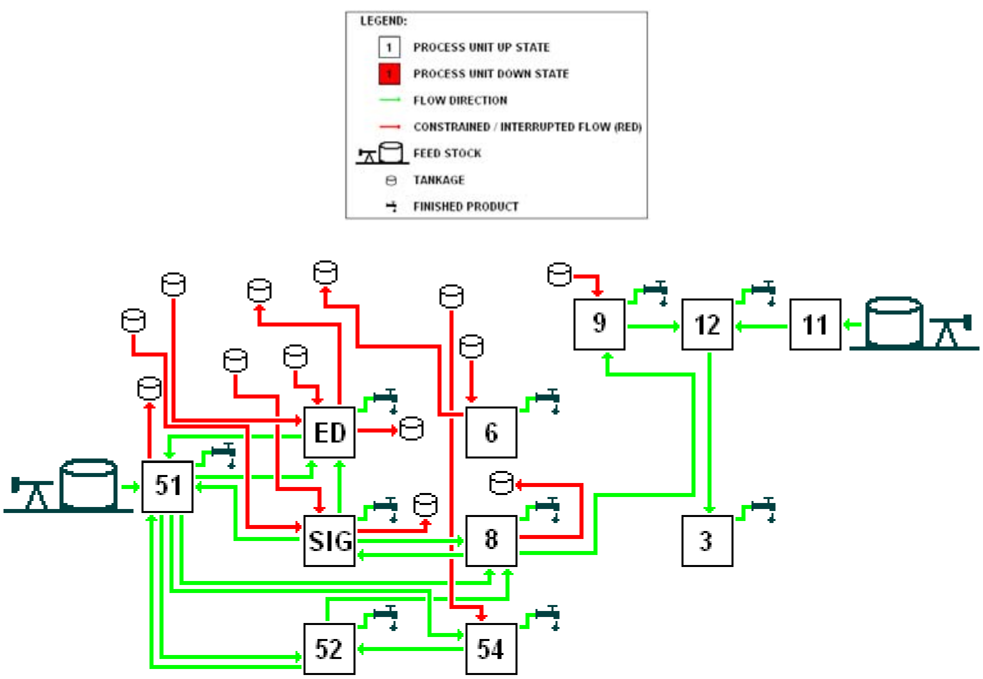


Figure 70: Process Model – Second Cascaded State – Some Tankage Included

The refinery can remain in this state for an additional 94 hours. Figure 71 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 71: Highlighted Result for Current Refinery State

Next, plant 6 goes down and the process model is shown in Figure 72.

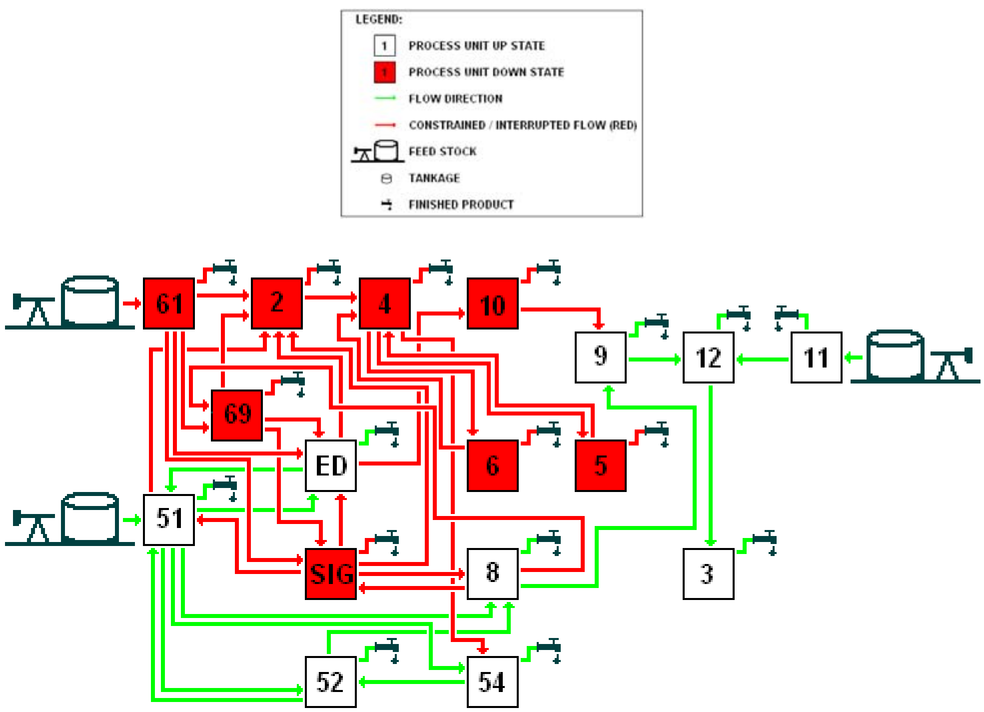


Figure 72: Process Model – Third Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 73.

.

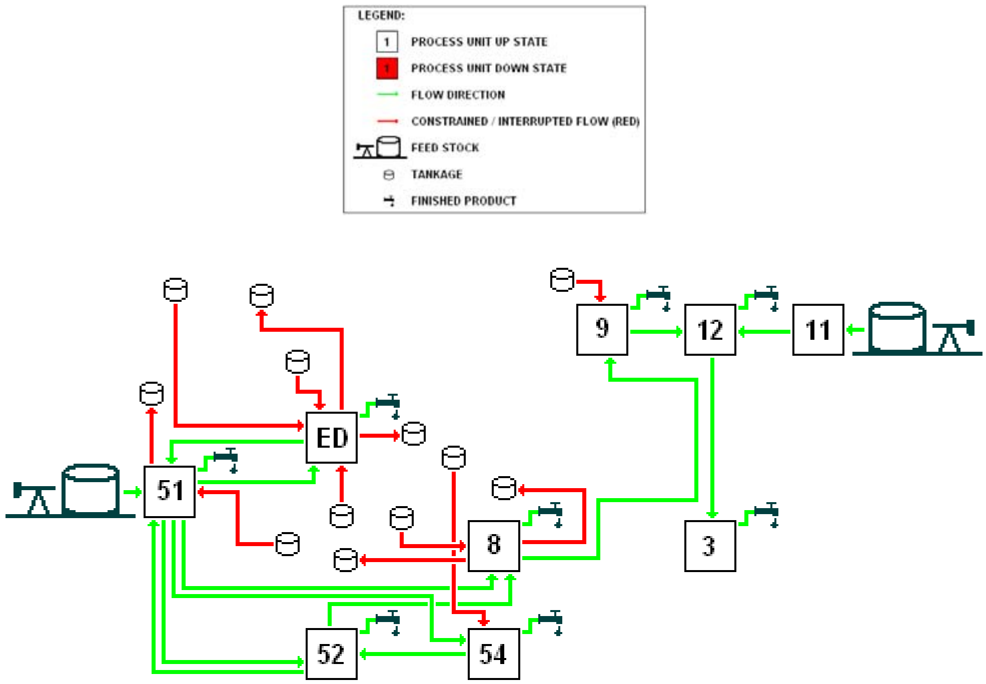


Figure 73: Process Model – Third Cascaded State – Some Tankage Included

The refinery can remain in this state for 146 hours. Figure 74 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 74: Highlighted Result for Current Refinery State

Next, plants 8, 9, 3, and 12 go down and the process model is shown in Figure 75.

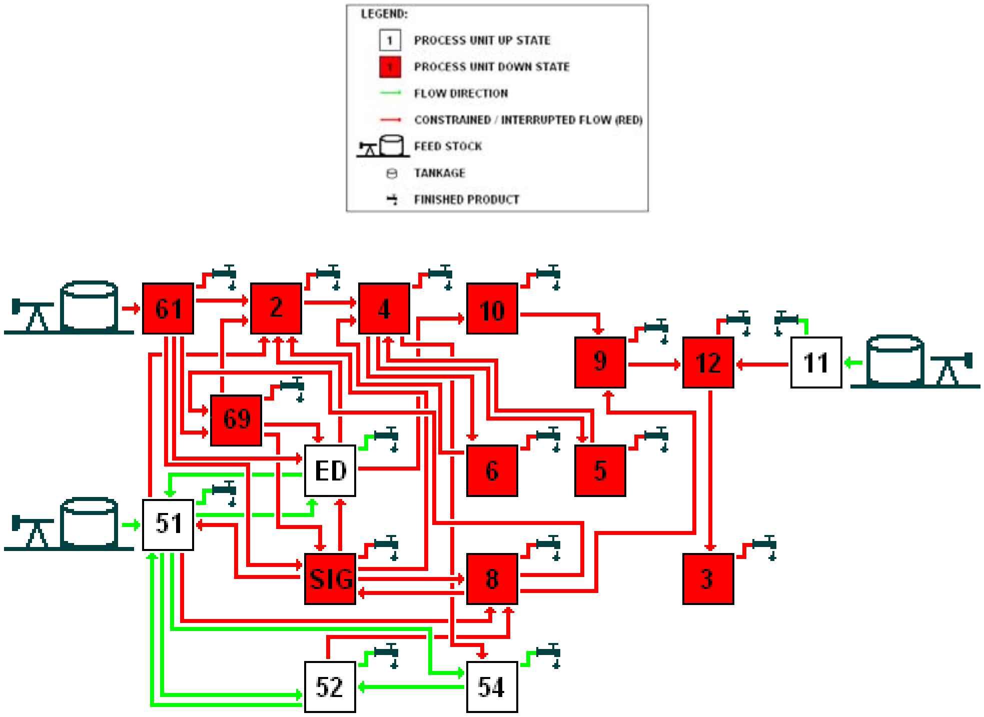


Figure 75: Process Model – Fourth Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 76.

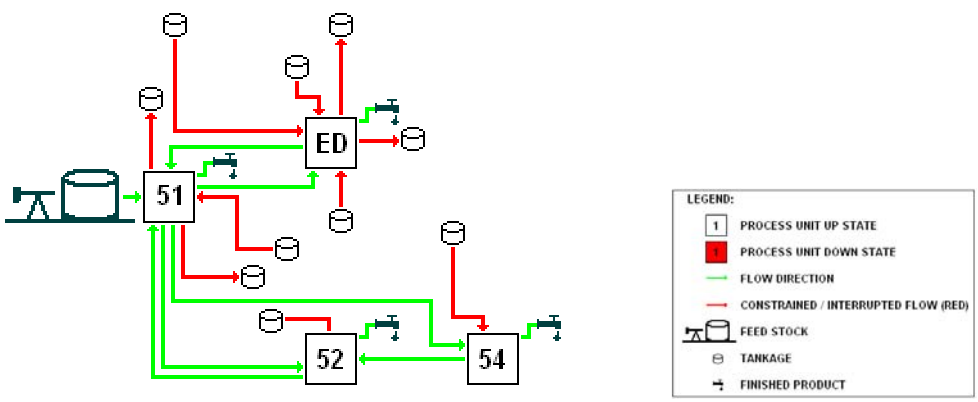


Figure 76: Process Model – Fourth Cascaded State – Some Tankage Included

The refinery can remain in this state for 24 hours. Figure 77 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 77: Highlighted Result for Current Refinery State

Next, plant 11 goes down and the process model is shown in Figure 78.

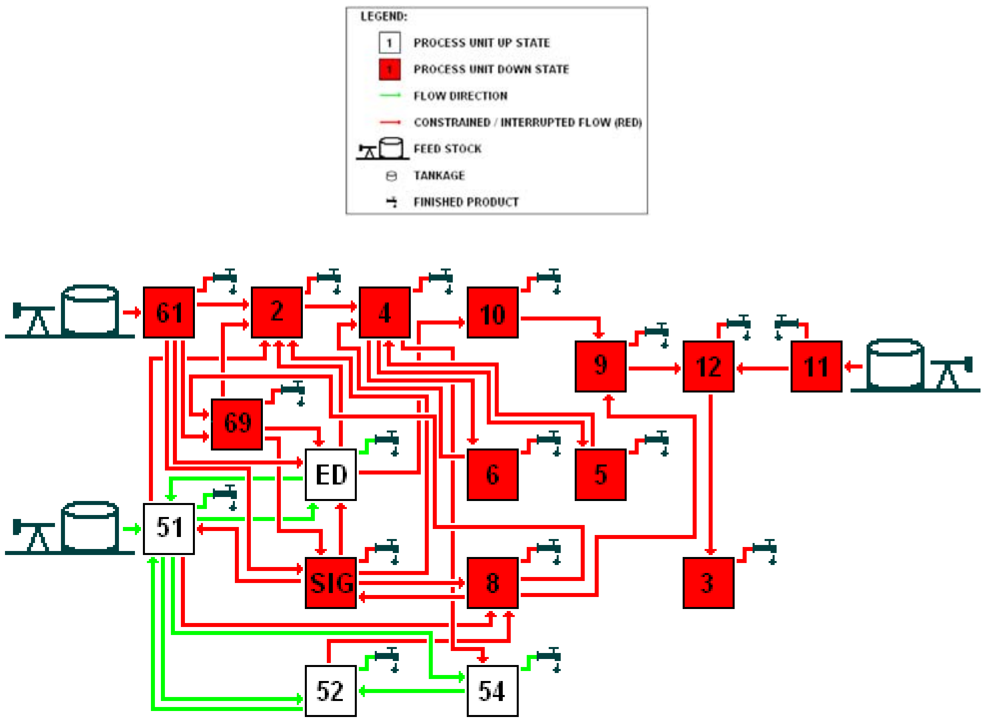


Figure 78: Process Model – Fifth Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 79.

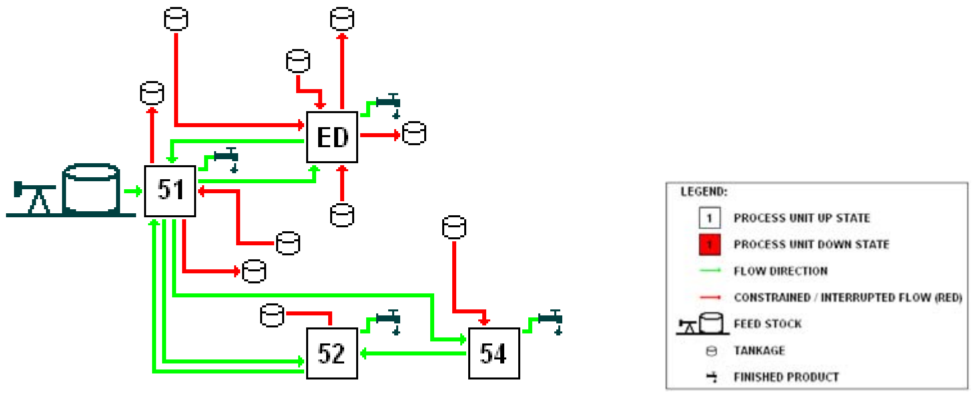


Figure 79: Process Model – Fifth Cascaded State – Some Tankage Included

The refinery can remain in this state for 72 hours. Figure 80 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 80: Highlighted Result for Current Refinery State

Next, plants 51, EDD, and 52 go down and the process model is shown in Figure 81.

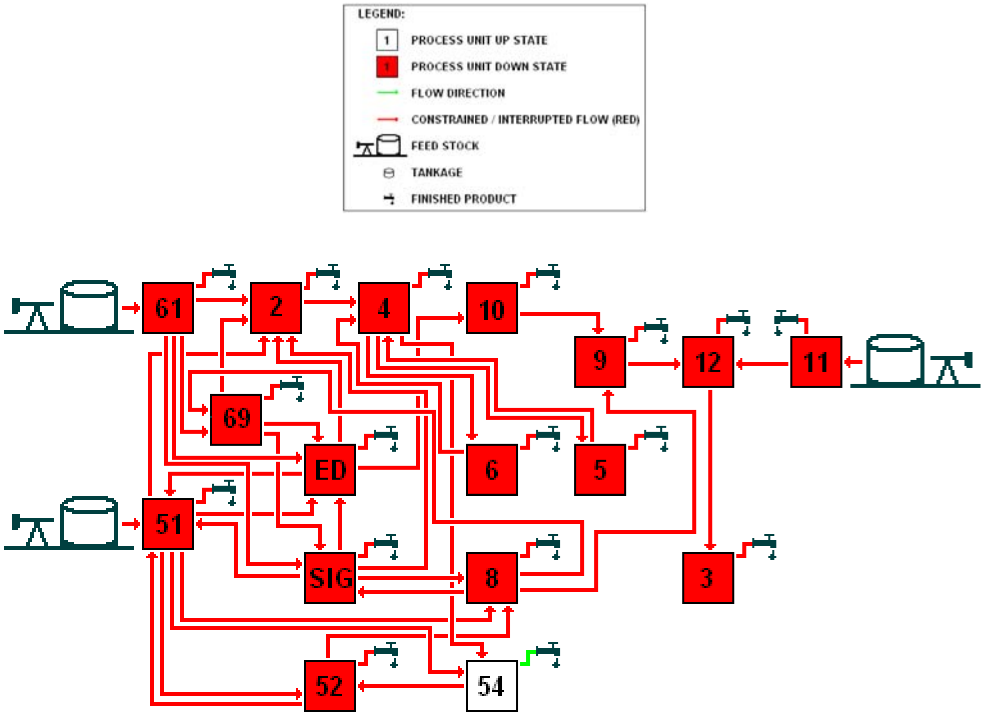


Figure 81: Process Model – Sixth Cascaded State – Inter-Unit Tankage Omitted

This model is updated to reflect the reduced production capability in Figure 82.

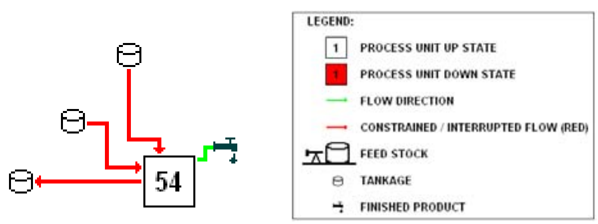


Figure 82: Process Model – Sixth Cascaded State – Some Tankage Included

The refinery can remain in this state for 144 hours. Figure 83 highlights the result of this state.

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 83: Highlighted Result for Current Refinery State

Then the remaining producing unit goes down and there is no production, so BPU =1 and the process remains in this state indefinitely.

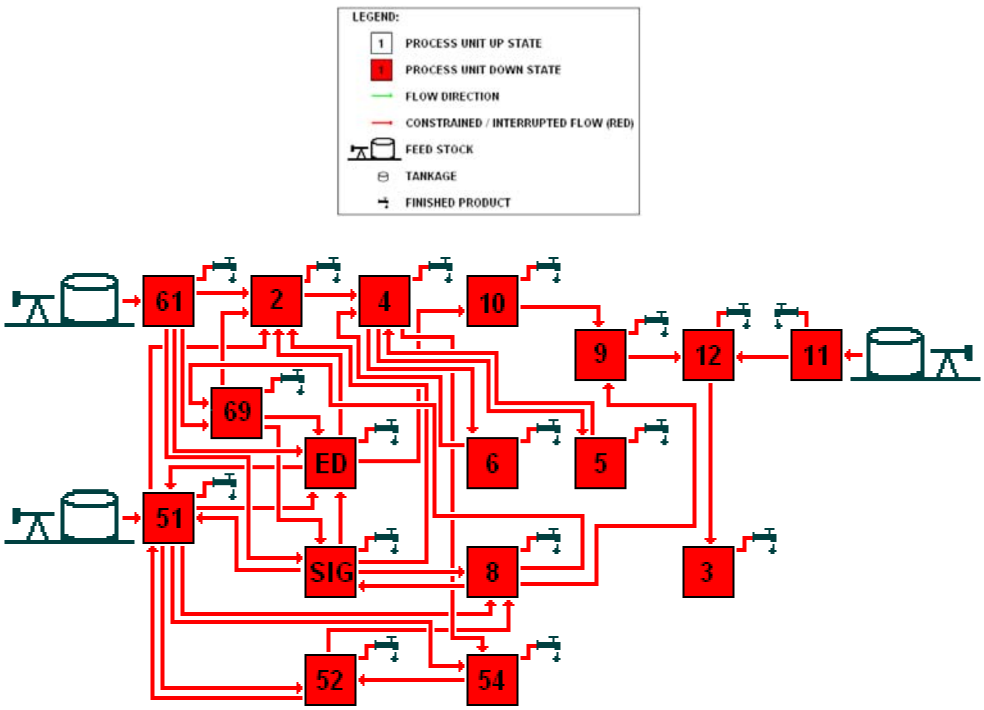


Figure 84: Process Model – Final Cascaded State – Inter-Unit Tankage Omitted

SUB # 11 OUTAGE																			
61	69	51	2	4	EDD	SIG	52	5	10	9	8	54	6	3	12	11	ST	BPU	BPUn
UP	UP	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	2	0.3781	1
DOWN	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	48	0.4514	1.19385
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	UP	UP	UP	UP	94	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	UP	UP	UP	DOWN	UP	UP	UP	146	0.53875	1.42487
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	UP	24	0.72436	1.91577
DOWN	DOWN	UP	DOWN	DOWN	UP	DOWN	UP	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	72	0.72436	1.91577
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	UP	DOWN	DOWN	DOWN	DOWN	144	0.96398	2.54951
DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	DOWN	INF	1	2.64477

Figure 85: Highlighted Result for Current Refinery State

Validation of Results

Each of the eleven cases considered has a unique combination of initially interrupted units. Each cascading sequence and survival time output has been verified by a Sr. Process Engineer within the Petro-Canada Edmonton Refinery. With few exceptions, intermediate process configurations (where survival time is not zero and not infinite) are commonly used during planned maintenance partial shutdowns. However, in planned shutdown configurations, the survival times of intermediate states are higher because intermediate tankage levels are intentionally filled beyond their normal inventories to accommodate planned activity.

Chapter 5 - Electrical Reliability Analysis

To demonstrate the method of reliability analysis, as discussed in the second chapter, an actual case study scenario is analyzed using the ‘Spreadsheet Method’, and then the proposed technique. Results of both techniques are then compared and discussed.

5.1 Spreadsheet Electrical Reliability Model

The ‘Spreadsheet Electrical Reliability Model’ was created by John Propst in 1993. Recently, Propst’s model was verified by calculating the reliability of the IEEE Gold Book Standard Network [12].

The Spreadsheet Electrical Reliability Model is a breakthrough in reliability engineering for four major reasons:

1. It’s **correct**, as validated with the calculation of the IEEE Standard Network reliability.
2. It’s **free**, subject to minor restrictions, available from the IEEE PCIC website.
3. It’s applicable to electrical reliability analysis and the **cost of interruption** within a refinery.
4. It’s **user friendly** with clear instructions and the formulas and methods used for calculation are available by looking through the formulas contained within various cells.

There are subtle distinctions between the reliability calculation method used by the Propst model and the method demonstrated in this thesis. The Propst model uses a form of zone-branch and cut-set method. By first calculating the failure rate and availability of each zone within the system, the MTTR is then solved. Based upon the configuration of series or parallel zones within the system, series and parallel formulae are then employed to calculate point reliability metrics from the individual zones at all points in the system. The assumptions apparently inherent in the Propst model are: (1) power system is assumed to be coordinated and (2) interrupting devices are assumed to operate correctly when called upon to interrupt. The method proposed in this thesis is similar to classical zone branch, when assuming both (1) and (2) above. Annual downtime (λr) and failure rate (λ) of each zone is calculated. Instead of using parallel formulas, a form of Bayes rule is employed where, for example, when one parallel bus is out of service, the availability of the redundant zone is used to evaluate the probability that the second zone is also out of service. Furthermore, the proposed method assumes independence of parallel zones, which implies a zero common cause factor. The Propst Spreadsheet Model is well described by a series of documents, noted in the reference section of this thesis, including its Operating Manual [9], a paper titled ‘Calculating Electrical Risk and Reliability’ [10], a paper titled ‘Improvements in Modeling and Evaluation of Electrical Power System Reliability’ [11], and a paper titled ‘Reliability of Various Industrial Substations’ [4], and ‘Modeling and Evaluating Electrical Power System: Risk and Reliability’ [7].

5.2 Selection of Target Substation and Scenario

Selection of the target substation and scenario attempt to draw the largest possible contrast, within the constraints of the case study, between the proposed CEF() method of expected impact estimation and the classical method assuming the independence of process plants.

Substation 11 is chosen as the target for reliability study for two reasons. Firstly, as a demonstration of the proposed method, a less reliable substation will tend to have longer repair/restore times to provide data points beyond two hours. Secondly, Sub 11 feeds Plant 2, amongst others, which is a particularly critical plant to process stability. The outage of Substation 11 is studied in chapter four as case 9. The combination of a relatively unreliable substation with a sensitive CEF() function will yield the optimal demonstration of the proposed method.

The scenario chosen is an evaluation of the reliability of the Substation 11 primary selective 13.8kV switchgear point during the replacement of its alternate feeder. In this scenario, the alternate feeder is unavailable for switching. This scenario is chosen because the replacement of the Substation 11 alternate feeder is being considered by Petro-Canada and such a reliability analysis could form the basis for the decision whether to wait for a planned maintenance shutdown or to replace the feeder with a running plant relying upon the normal feeder alone.

Figure 86, on the following page, is a single line diagram which represents the selected scenario, from the perspective of the target substation, with the assumptions noted in section 5.1. The red 'X' marks the feeder that is out of service in the target scenario.

Two transmission lines feed a 138kV substation. This 138kV substation parallels the two transmission lines and steps down voltage to 13.8kV to feed Main Substation #1. The configuration is secondary selective and the transmission lines are run with the tie breaker normally closed.

Main Substation #1 also consists of a secondary selective configuration. The two 13.8kV busses run with a tie breaker normally closed. Downstream unit substations are fed from both the Normal and Alternate 13.8kV busses. The Normal bus supplies power to downstream substations while the Alternate bus acts as a spare for the Normal bus and its feeders carry no load. Because the tie breaker between Normal bus and Alternate bus is normally closed the step-down transformers load share, although each transformer is sized to accommodate the electrical load on the Normal bus.

The incoming transmission lines are drawn as Utilities #1 and #2. The transmission lines are routed from the north and south with a great deal of physical separation. As such they may be thought to exhibit a low instance of common cause failure.

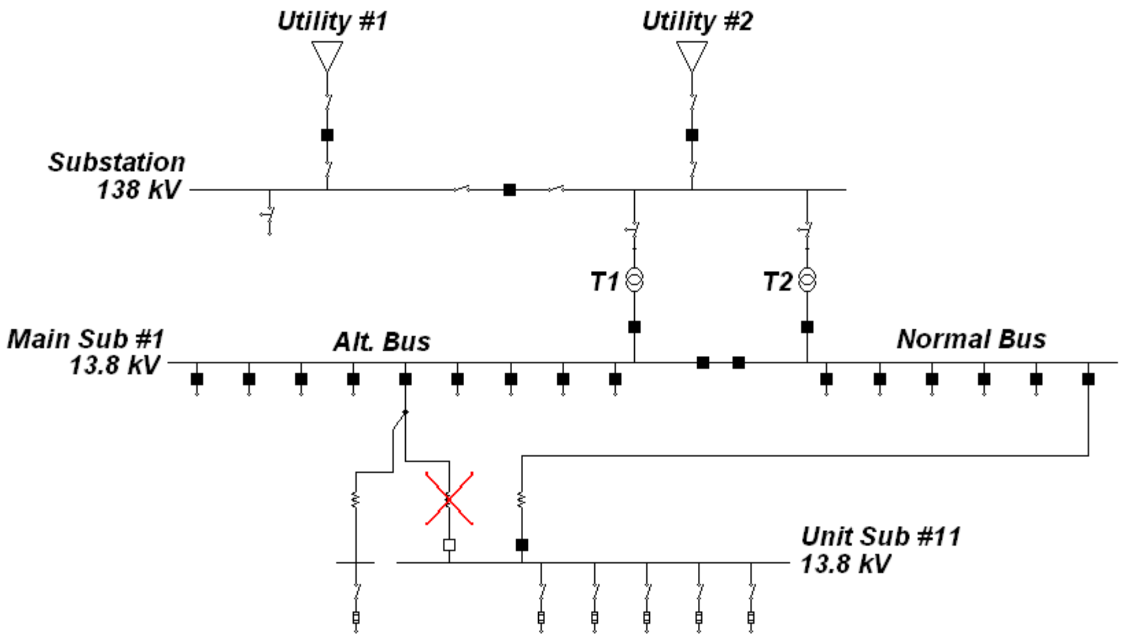


Figure 86: Case Study Target Substation & Scenario Single Line Diagram

5.3 Substation # 11 Reliability Modeling

Reliability modeling in the following sections 5.3.1 and 5.3.2 use single line diagrams that are based upon Figure 86.

5.3.1 Spreadsheet Method

The zoning technique used for the Spreadsheet Method is shown in Figure 87. In this technique, secondary selective bus configurations are modeled to include phantom breakers, as suggested by the operating manual [9].

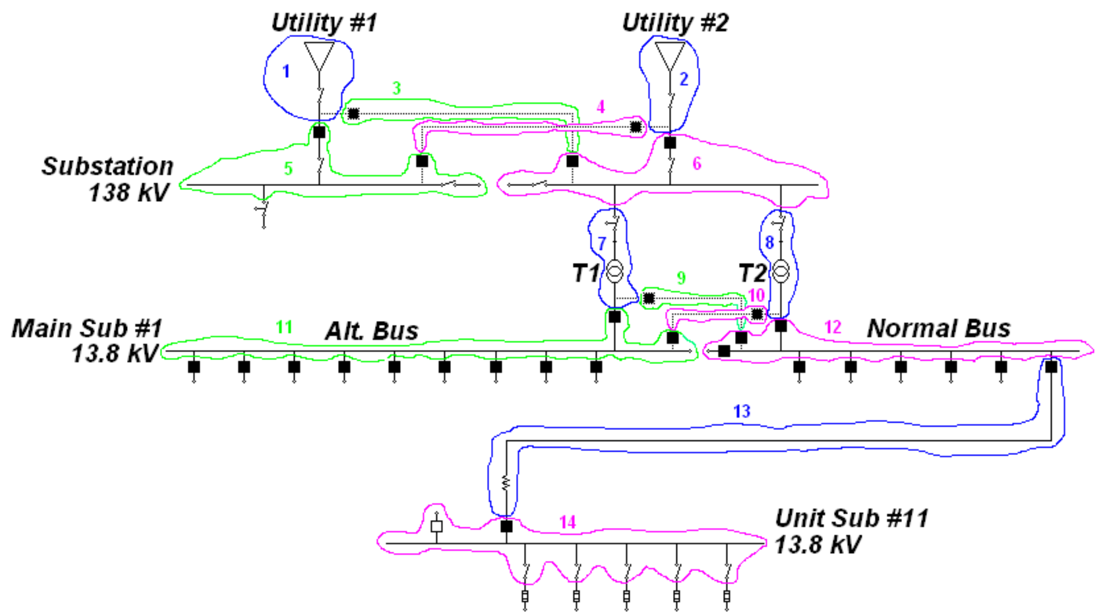


Figure 87: Spreadsheet Method Zoning

The Ram Table is a listing of failure and repair data for 142 common electrical compontents and is contained within the '2007 modelJAN2307.xls' spreadsheet. This data source is used herein for reliability data. The 142 components were numbered as per their row in the Ram Table from (8)-(149). References to individual component data will use this numbering reference. For example, $\lambda_{(149)}$ is the failure rate of component (149), which represents the Utility.

Zones 1 and 2:
These zones include Utilities #1 and #2. Each utility is modeled as a 'Single Circuit' utility using data from the IEEE Gold Book 2007, Table 3-1 [3]. The failure rate $\lambda_{(149)}$ and MTTR $r_{(149)}$ are then 1.956 failures/year and 1.32 hours/failure, respectively. Each of zone 1 and 2 are comprised of one utility (149) and one 138 kV disconnect switch (108).

Zone 3:
This zone is the Propst model method for representing a secondary selective configuration with a closed tie breaker. It includes one phantom breaker (145).

Zone 4:
This zone is the Propst model method for representing a secondary selective configuration with a closed tie breaker. It includes one phantom breaker (145).

Zone 5:
This zone includes two disconnect switches (108), two breakers (48), and one outdoor 138kV bus (21).

Zone 6:
This zone includes two disconnect switches (108), two breakers (48), and one outdoor 138kV bus (21).

Zone 7:
This zone includes one 138kV breaker (48), one transformer (132), and 0.060 thousand feet of cable (35).

Zone 8:
This zone includes one 138kV breaker (48), one transformer (132), and 0.060 thousand feet of cable (35).

Zone 9:
This zone is the Propst model method for representing a secondary selective configuration with a closed tie breaker. It includes one phantom breaker (145).

Zone 10:
This zone is the Propst model method for representing a secondary selective configuration with a closed tie breaker. It includes one phantom breaker (145).

Zone 11:
This zone contains eleven sections of switchgear (117), one protective relay (87), and two breakers (54).

Zone 12:
This zone contains nine sections of switchgear (117), one protective relay (87), and three breakers (54).

Zone 13:
This zone contains one complex relay (88), and 1.250 thousand feet of underground cable (40).

Zone 14 (Include Target Point):
This zone contains two kirk-keyed load break switches (110), seven sections of switchgear (117), and five fused disconnect switches (70).

The zone table denoting the series or parallel zone configuration is listed in Table 17.

	HJ	HK	HL	HM	HN
582	**Zone Table**				
583	Series		Parallel		
584	Zone	Point	CZone	Point "1"	Point "2"
585	1	0	0	0	0
586	2	0	0	0	0
587	3	1	0	0	0
588	4	2	0	0	0
589	5	1	0	0	0
590	0	0	6	2	3
591	7	6	0	0	0
592	8	6	0	0	0
593	9	7	0	0	0
594	10	8	0	0	0
595	11	7	0	0	0
596	0	0	12	8	9
597	13	12	0	0	0
598	14	13	0	0	0

Table 17: Spreadsheet Method Zone Table from Propst Model

5.3.2 Proposed Method

The zoning technique used for the Proposed Method is shown in Figure 88. The numbering of zones is intentionally not contiguous because it means to be correspondent to the zone numbers in the Spreadsheet Method Zoning in Figure 87.

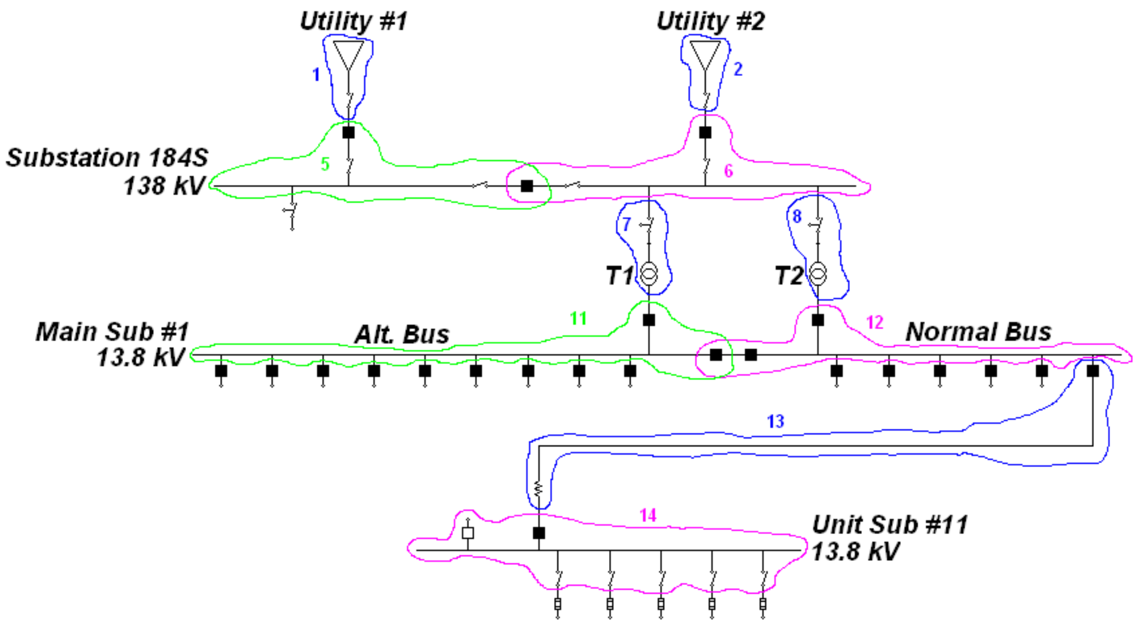


Figure 88: Proposed Method Zoning

This method uses the same reliability data contained within the Ram Table as the Spreadsheet Method.

<u>Zone 1:</u>
This zone contains Utility #1 and one 138 kV disconnect switch (108).

Annual expected downtime λr and Availability A are calculated as follow:

$$\lambda r_{ZONE\ 1} = \lambda_{(149)} \cdot r_{(149)} + \lambda_{(108)} \cdot r_{(108)}$$

$$A_{ZONE\ 1} = \frac{1}{1 + \frac{\lambda r_{ZONE\ 1}}{8760}}$$

<u>Zone 2:</u>
This zone contains Utility #2 and one 138 kV disconnect switch (108).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 2} = \lambda_{(149)} \cdot r_{(149)} + \lambda_{(108)} \cdot r_{(108)}$$

$$\lambda_{ZONE\ 2} = \lambda_{(149)} + \lambda_{(108)}$$

Zone 5:
This zone contains two disconnect switches (108), two breakers (48), and one outdoor 138kV bus (21).

Annual expected downtime λr and Availability A are calculated as follow:

$$\lambda r_{ZONE\ 5} = 2 \cdot \lambda_{(108)} \cdot r_{(108)} + 2 \cdot \lambda_{(48)} \cdot r_{(48)} + \lambda_{(21)} \cdot r_{(21)}$$

$$A_{ZONE\ 5} = \frac{1}{1 + \frac{\lambda r_{ZONE\ 5}}{8760}}$$

Zone 6:
This zone contains two disconnect switches (108), two breakers (48), and one outdoor 138kV bus (21).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 6} = 2 \cdot \lambda_{(108)} \cdot r_{(108)} + 2 \cdot \lambda_{(48)} \cdot r_{(48)} + \lambda_{(21)} \cdot r_{(21)}$$

$$\lambda_{ZONE\ 6} = 2 \cdot \lambda_{(108)} + 2 \cdot \lambda_{(48)} + \lambda_{(21)}$$

Zone 7:
This zone contains one 138kV breaker (48), one transformer (132), and 0.060 thousand feet of cable (35).

Annual expected downtime λr and Availability A are calculated as follow:

$$\lambda r_{ZONE\ 7} = \lambda_{(48)} \cdot r_{(48)} + \lambda_{(132)} \cdot r_{(132)} + 0.06 \cdot \lambda_{(35)} \cdot r_{(35)}$$

$$A_{ZONE\ 7} = \frac{1}{1 + \frac{\lambda r_{ZONE\ 7}}{8760}}$$

Zone 8:
This zone contains one 138kV breaker (48), one transformer (132), and 0.060 thousand feet of cable (35).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 8} = \lambda_{(48)} \cdot r_{(48)} + \lambda_{(132)} \cdot r_{(132)} + 0.06 \cdot \lambda_{(35)} \cdot r_{(35)}$$

$$\lambda_{ZONE\ 8} = \lambda_{(48)} + \lambda_{(132)} + 0.06 \cdot \lambda_{(35)}$$

Zone 11:
This zone contains eleven sections of switchgear (117), one protective relay (87), and two breakers (54).

Annual expected downtime λr and Availability A are calculated as follow:

$$\lambda r_{ZONE\ 11} = 11 \cdot \lambda_{(117)} \cdot r_{(117)} + \lambda_{(87)} \cdot r_{(87)} + 2 \cdot \lambda_{(54)} \cdot r_{(54)}$$

$$A_{ZONE\ 11} = \frac{1}{1 + \frac{\lambda r_{ZONE\ 11}}{8760}}$$

Zone 12:
This zone contains nine sections of switchgear (117), one protective relay (87), and three breakers (54).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 12} = 9 \cdot \lambda_{(117)} \cdot r_{(117)} + \lambda_{(87)} \cdot r_{(87)} + 3 \cdot \lambda_{(54)} \cdot r_{(54)}$$

$$\lambda_{ZONE\ 12} = 9 \cdot \lambda_{(117)} + \lambda_{(87)} + 3 \cdot \lambda_{(54)}$$

Zone 13:
This zone contains one complex relay (88), and 1.250 thousand feet of underground cable (40).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 13} = \lambda_{(88)} \cdot r_{(88)} + 1.25 \cdot \lambda_{(40)} \cdot r_{(40)}$$

$$\lambda_{ZONE\ 13} = \lambda_{(88)} + 1.25 \cdot \lambda_{(40)}$$

Zone 14 (Include Target Point):
This zone contains two kirk-keyed load break switches (110), seven sections of switchgear (117), and five fused disconnect switches (70).

Annual expected downtime λr and failure rate λ are calculated as follow:

$$\lambda r_{ZONE\ 14} = 2 \cdot \lambda_{(110)} \cdot r_{(110)} + 7 \cdot \lambda_{(117)} \cdot r_{(117)} + 5 \cdot \lambda_{(70)} \cdot r_{(70)}$$

$$\lambda_{ZONE\ 14} = 2 \cdot \lambda_{(110)} + 7 \cdot \lambda_{(110)} + 5 \cdot \lambda_{(70)}$$

Calculations of reliability metrics for our target point are conducted as follow:

$$\lambda r_{POINT\ 14} = \lambda r_{ZONE\ 14} + \lambda r_{ZONE\ 13} + \lambda r_{ZONE\ 12} + (1 - A_{11})(1 - A_7) \cdot \lambda r_{ZONE\ 8} + \lambda r_{ZONE\ 6} + (1 - A_5)(1 - A_1) \cdot \lambda r_{ZONE\ 2}$$

$$\lambda_{POINT\ 14} = \lambda_{ZONE\ 14} + \lambda_{ZONE\ 13} + \lambda_{ZONE\ 12} + (1 - A_{11})(1 - A_7) \cdot \lambda_{ZONE\ 8} + \lambda_{ZONE\ 6} + (1 - A_5)(1 - A_1) \cdot \lambda_{ZONE\ 2}$$

$$A_{ZONE\ 14} = \frac{1}{1 + \frac{\lambda r_{ZONE\ 14}}{8760}}$$

$$\lambda r_{POINT\ 14} = \lambda r_{ZONE\ 14} + \lambda r_{ZONE\ 13} + \lambda r_{ZONE\ 12} + (1 - A_{11})(1 - A_7) \cdot \lambda r_{ZONE\ 8} + \lambda r_{ZONE\ 6}$$
$$+ (1 - A_5)(1 - A_1) \cdot \lambda r_{ZONE\ 2}$$

The detailed calculation, including intermediate and final data is included as Appendix A.

5.4 Results

Both the Spreadsheet Method and Proposed Method calculate load point λ, average r, and Availability. Values are presented below in Table 18.

Table 18: Spreadsheet Method and Proposed Method Reliability Results

Substation #11 Reliability Data	Failure Rate λ (failures/year)	MTTR r (hours/failure)	Availability A (pure units)
Spreadsheet Method	0.113308633	16.753393115	0.999783346
Proposed Method	0.122347216	15.668539774	0.999781212
Difference:	-0.009038583	1.084853341	0.000002134

Difference between the two methods is considerably small. As a validation of the proposed method, consider the difference between the spreadsheet method and the minimal cut-set method when applied to the IEEE Gold Book [12]. The spreadsheet method vs. cut-set method yielded a difference in availability on a similar Lighting bus in the sixth decimal. In this thesis, a similar difference in the sixth decimal place (10^{-6}) is apparent between the proposed method and the spreadsheet method. Similar comparisons of data differences in the failure rates and MTTRs yield 10^{-4} vs. 10^{-3} and 10^{0} vs. 10^{0}, respectively. From this, the author concludes that the proposed method, when applied to this particular system, yields reliability data that is as close to the spreadsheet method's data as the cut-set method.

The additional benefit from the proposed method is the calculation of the $p_r(r)$ function. The normalized frequency interruption $p_r(r)$ and interruption durations are listed in Table 19 below.

Table 19: Substation #11 p(r) Data

Index i	$p_r(r_i)$	r_i (hours)
1	0.000000103025	1.32
2	0.081734593885	4.00
3	0.051492794148	8.00
4	0.664583982879	12.00
5	0.051084121178	16.00
6	0.023703032303	24.00
7	0.100124877509	36.00
8	0.000000000428	48.00
9	0.027276468780	72.00
10	0.000000025865	1200.00

As a check of the data within Table 19, we can see that:

$$\sum_{i=1}^{10} p_r(r_i) = 1$$

$$E\{r\} = \sum_{i=1}^{10} r_i \cdot p_r(r_i) = 15.668539774$$

The data within Table 19 is graphed in Figure 89 below. Due to the range of very large and very small values, a log-log plot is employed.

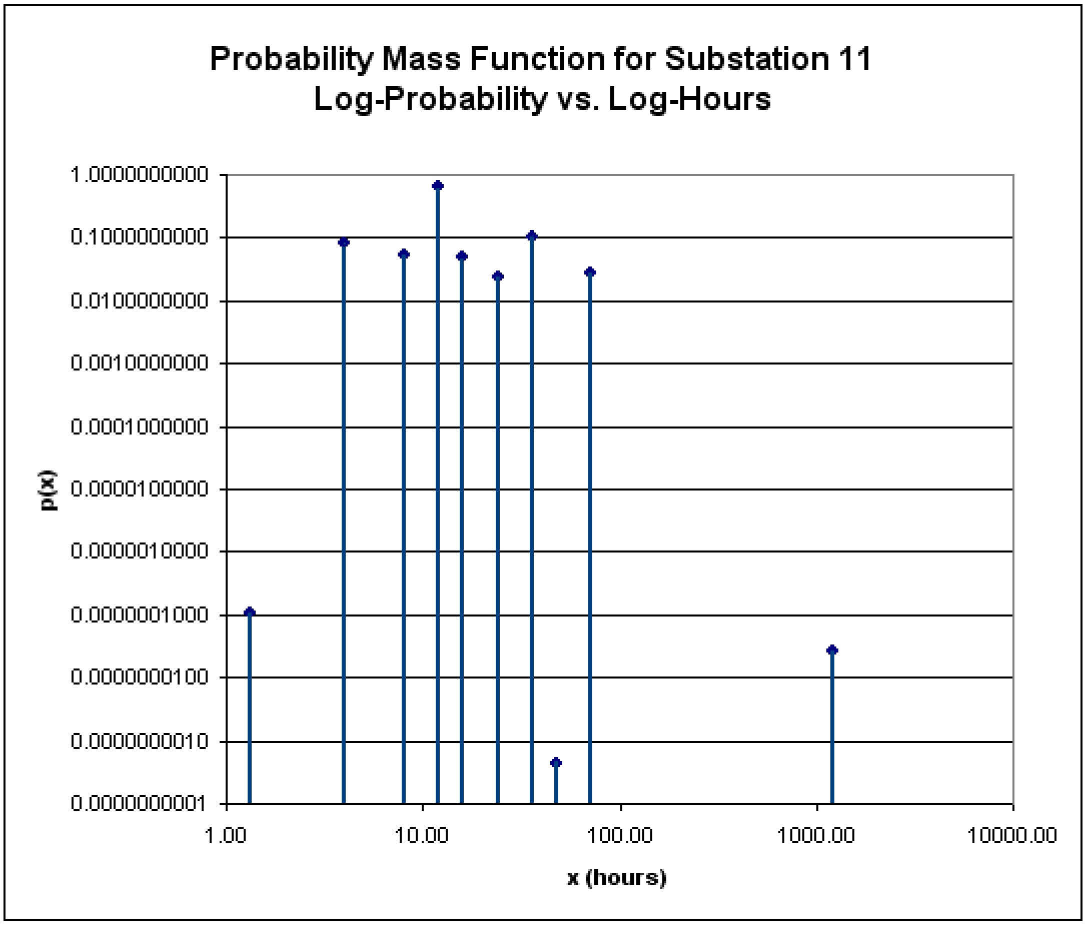


Figure 89: Probability Mass Function for Substation #11

The probability mass function for the interruption duration of Substation #11 will be used as a basis for further calculation in the following chapter.

Chapter 6 - Criticality Results

6.1 Interruption BPU Plots

From the process simulations in Chapter 4, the tables of durations and interrupted flows form the basis for construction of BPU interruption plots. The BPU interruption plot shows the cascading effect of the initially interrupted unit (or units) when power is lost to a given unit substation. BPU interruption plots for all eleven cases are shown together in Figure 90. The legend on the right hand side of Figure 90 notes the name of the substation, whose interruption creates the initially interrupted set of units. While there are 47 substations within the Petro-Canada Edmonton Refinery, our investigation is restricted to only electrical substations that serve process units.

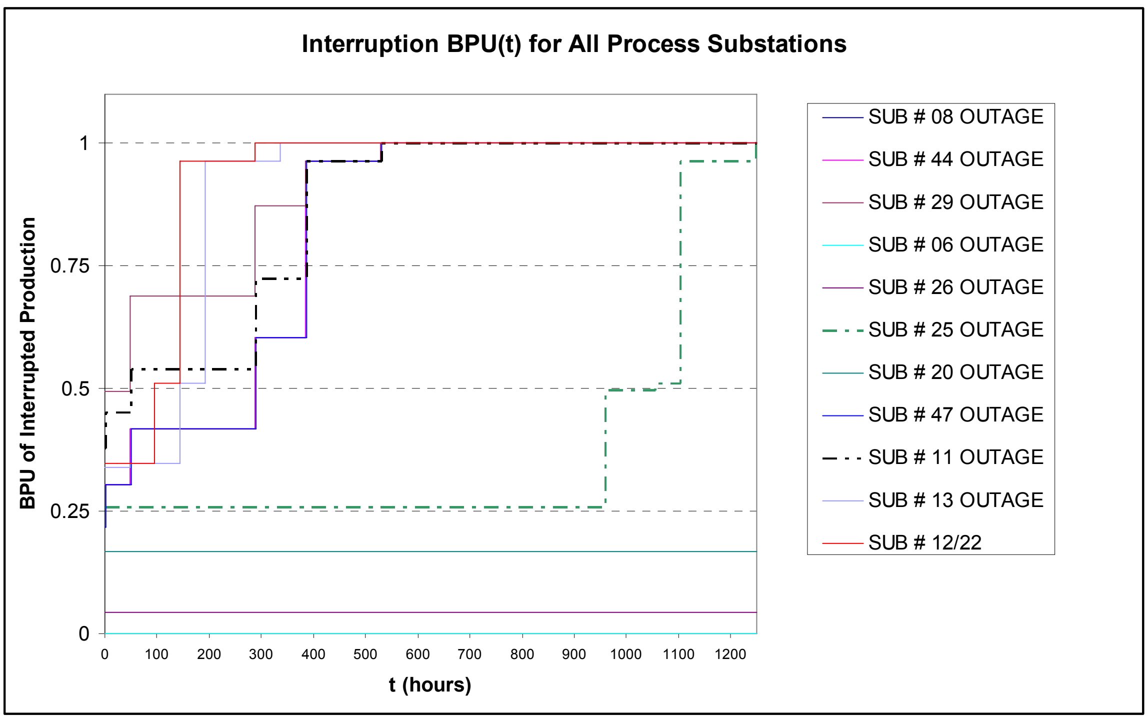


Figure 90: Interruption $BPU(t)$ ***for All Case Study Process Substations***

It is obvious that, while most interruption functions tend toward 1.0 bpu, interruption of Substations #20, #26, or #6 (which is indistinguishable from the x-axis), do not cause a cascading interruption.

It is also evident that, while the majority of functions that do tend to 1.0 are clustered about the left side of the graph, the interruption of substation #25 has a much delayed impact due an abundance of gasoil tankage present in the case study.

6.2 Calculation of standard interruption BPU curve

Instead of undertaking the construction of a time consuming process model, another company may wish to use a standard interruption curve based on the average of unit curves within this case study.

If we assume that a standard interruption curve is to be used for a unit that is critical to the refining process (its interruption BPU function will tend to 1.0) and that associated tankage is not unusually large, we can omit data from the outage of substations #25, #20, #26, and #06, leaving the curves present in Figure 91.

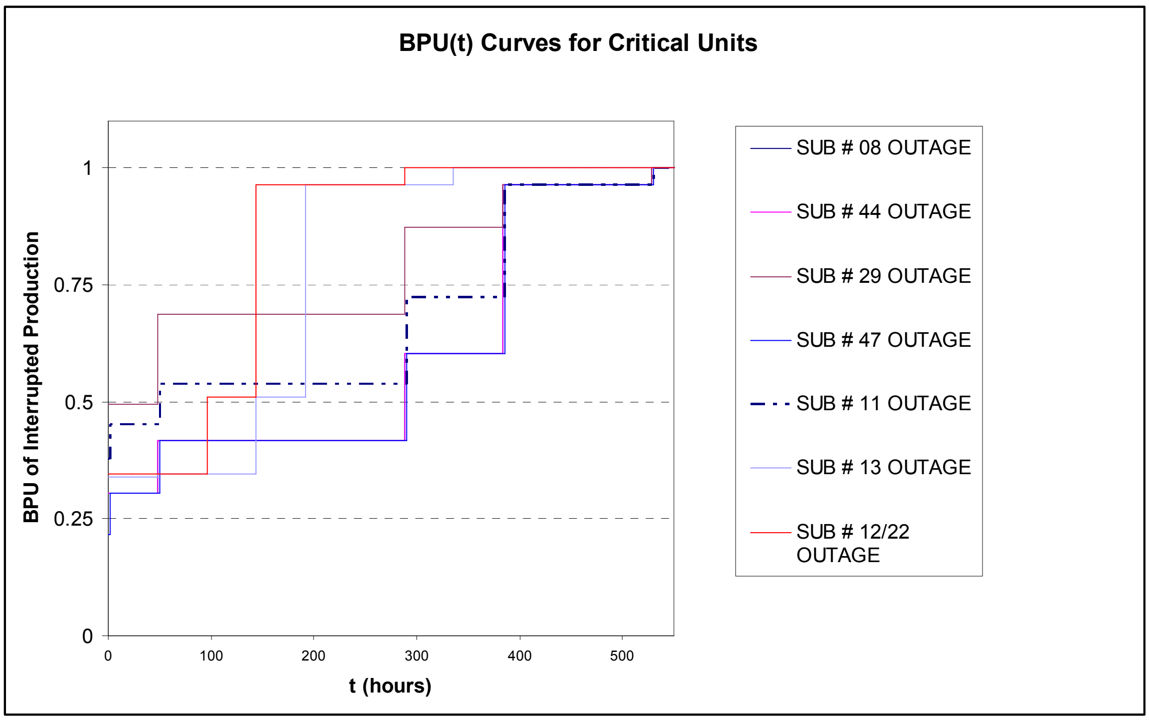


Figure 91: $BPU(t)$ ***Curves for Critical Case Study Units***

Taking the mean value of remaining curves at each point, a Standard Interruption $BPU_{Std.}(t)$ curve may be calculated with values presented in Table 20 and graphed in Figure 92.

Table 20: Standard $BPU_{Std.}(t)$ Interruption Curve Data

STANDARD BPU(t) CURVE DATA		
Start Time (hours)	End Time (hours)	Interruption (BPU)
0	2	0.340277143
2	24	0.363315714
24	48	0.363315714
48	50	0.424552857
50	96	0.453207143
96	144	0.476575714
144	192	0.564754286
192	288	0.629564286
288	290	0.714257143
290	312	0.767288571
312	314	0.767288571
314	336	0.767288571
336	384	0.772434286
384	386	0.888475714
386	528	0.974271429
528	530	0.989708571
530	∞	1

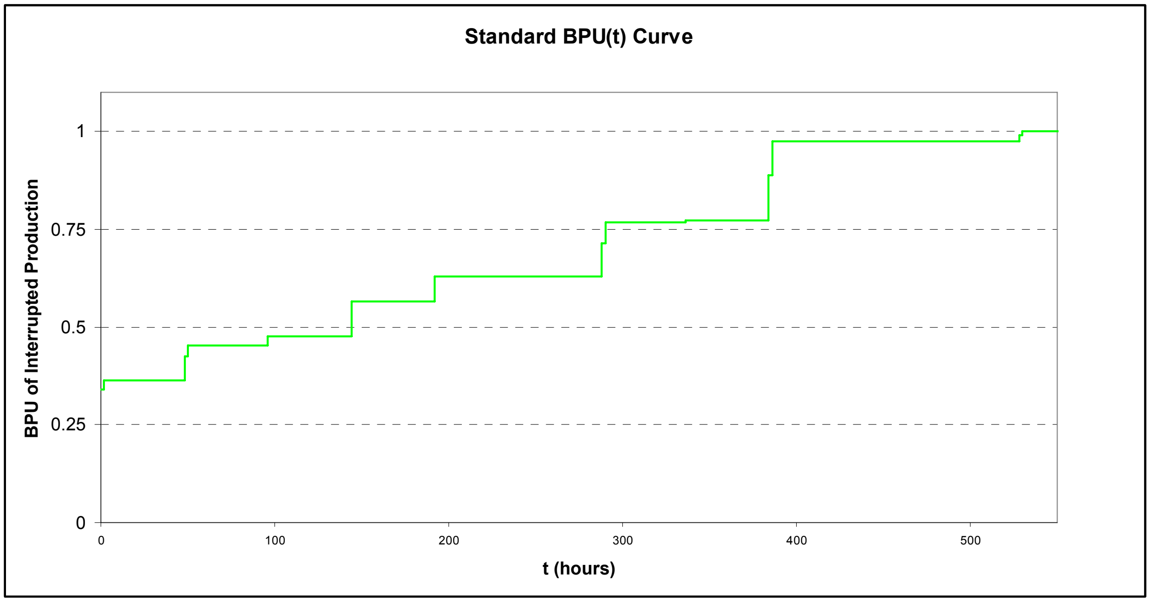


Figure 92: Standard $BPU_{Std.}(t)$ *Curve for Critical Units*

6.3 $CEF_{11}()$ for Substation #11

From the interruption BPU data in Table 14, the $CEF(t)$ function of interruption duration time 't' may be calculated and displayed in Figure 93. Note that $CEF(t)$ is measured in units of bpu•h and time is in units of hours.

$$CEF_{11}(t) = \begin{cases} 0, & t < 0 \\ 0.3781 \cdot t, & 0 \le t < 2 \\ 0.4514 \cdot t - 0.1466, & 2 \le t < 50 \\ 0.5388 \cdot t - 4.5141, & 50 \le t < 290 \\ 0.7244 \cdot t - 58.3410, & 290 \le t < 386 \\ 0.9640 \cdot t - 150.8343, & 386 \le t < 530 \\ 1.0000 \cdot t - 169.9249, & t \ge 530 \end{cases}$$

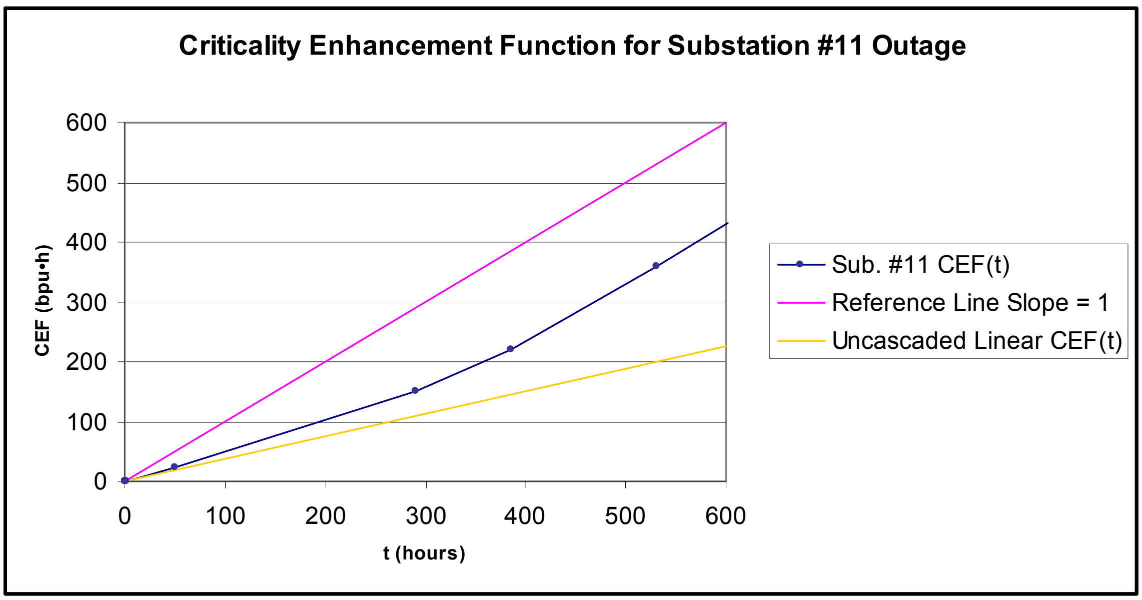


Figure 93: $CEF_{11}(t)$ Criticality Enhancement Function for Substation #11

Figure 93 displays three lines. The middle line is the criticality enhancement function for the interruption of Substation #11. The top line is a reference line with a slope of 1. In the refinery state where all units are down, the Sub. #11 criticality enhancement function segment becomes parallel to this line for $t \ge 530$ hours. The bottom line, called 'Uncascaded Linear $CEF(t)$' shows the implied linear criticality enhancement when the effect of cascading impact is ignored. From $0 \le t < 2$ hours, $CEF_{11}(t)$ is parallel to the uncascaded linear line, whose slope takes on only the initially interrupted bpu value.

6.4 $CEF_{Std.}$() for Standard Refinery Unit Interruption

From the interruption BPU data in Table 20, the $CEF_{Std.}(t)$ function may be calculated and displayed in Figure 94. Note again that CEF is measured in units of bpu•h and time is in units of hours.

$$CEF_{Std.}(t) = \begin{cases} 0, & t < 0 \\ 0.3633 \cdot t & 0 \le t < 24 \\ 0.4246 \cdot t - 1.4697 & 24 \le t < 48 \\ 0.4532 \cdot t - 2.8451 & 48 \le t < 50 \\ 0.4766 \cdot t - 4.0135 & 50 \le t < 96 \\ 0.5648 \cdot t - 12.4787 & 96 \le t < 144 \\ 0.6296 \cdot t - 21.8113 & 144 \le t < 192 \\ 0.7143 \cdot t - 38.0723 & 192 \le t < 288 \\ 0.7673 \cdot t - 53.3454 & 288 \le t < 314 \\ 0.7724 \cdot t - 54.9611 & 314 \le t < 336 \\ 0.8885 \cdot t - 93.9511 & 336 \le t < 384 \\ 0.9743 \cdot t - 126.8966 & 384 \le t < 386 \\ 0.9897 \cdot t - 132.8554 & 386 \le t < 528 \\ 1.0000 \cdot t - 138.2892 & t \ge 530 \end{cases}$$

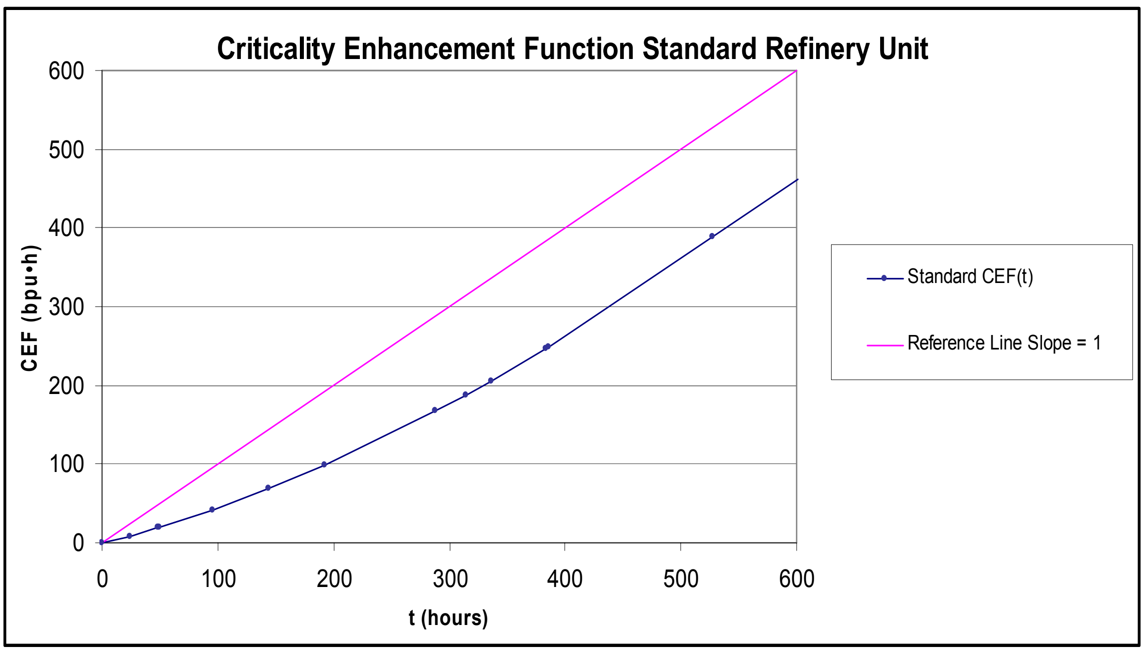


Figure 94: $CEF_{Std.}(t)$ Criticality Enhancement Function for Standard Refinery Unit

6.5 Target Scenario Expected Interruption Impact E{y}

To demonstrate the value of using the proposed method, calculation of annual expected impact from interruption $\lambda \cdot E\{y\}$ may be done using the three methods noted in Chapter 2, plus one additional calculation using the standard $CEF_{Std.}(t)$ function in place of $CEF_{11}(t)$.

6.5.1 Averaged Data Method: $\lambda \cdot r_{AVG} \cdot BPU_0$

The Averaged Data Method is the method currently employed to calculate the annual expected cost of load point interruption.

r_{AVG} = 15.66 (hours/interruption)
BPU_0 = 0.3781(bpu)
λ = 0.1223 (annual interruptions)

$y = r_{AVG} \cdot BPU_0 = 5.9243$ bpu•h/interruption

<u>Annual Expected Cost of Load Point Interruption:</u>
$\lambda \cdot E\{y\} = \lambda \cdot r_{AVG} \cdot BPU_0 = 0.7248$ bpu•h

6.5.2 Averaged Data Method with Process Modeling: $\lambda \cdot CEF_{11}(r_{AVG})$

The Averaged Data Method with Process Modeling employs the process model $CEF_{11}(t)$, but still uses the averaged data point r_{AVG}.

r_{AVG} = 15.66 (hours/interruption)
$CEF(t) = CEF_{11}(t)$ from Figure 93 (bpu•h/interruption)
λ = 0.1223 (annual interruptions)

$y = CEF_{11}(r_{AVG}) = 6.9262$ bpu•h/interruption

<u>Annual Expected Cost of Load Point Interruption:</u>
$\lambda \cdot E\{y\} = \lambda \cdot CEF_{11}(r_{AVG}) = 0.8474$ bpu•h

6.5.3 Random Variable with Process Modeling: $\lambda \cdot \sum_{i=1}^{\infty} \left[CEF_{11}(r_i) \cdot p_r(r_i) \right]$

The Random Variable with Process Modeling method uses the process model $CEF_{11}(t)$ and does not average the data until the end of the calculation.

Using $y = CEF_{11}(r)$, as displayed in Figure 93, the transformed random variable y, denoting impact from interruption, may then be displayed as $p_y(y)$ in Figure 95, from values Tabled in Table 21.

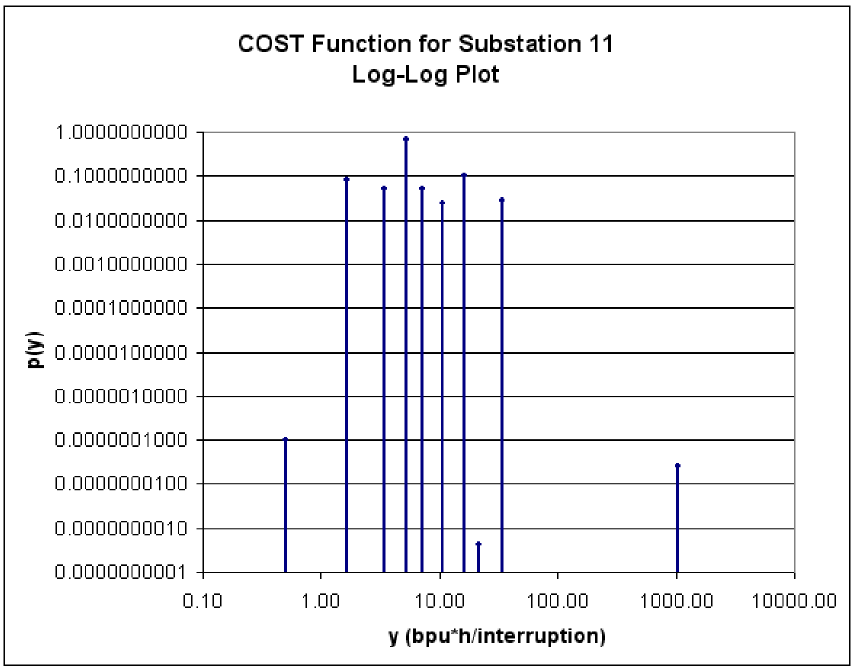


Figure 95: $p_y(y)$ ***for Substation #11***

Table 21: $p_y(y)$ data points for Substation #11

p(y)	y
0.000000103025	0.50
0.081734593885	1.66
0.051492794148	3.46
0.664583982879	5.27
0.051084121178	7.08
0.023703032303	10.69
0.100124877509	16.10
0.000000000428	21.52
0.027276468780	34.28
0.000000025865	1030.08

The expected value of y may then be calculated.

$$E\{y\} = \sum y \cdot p_y(y) = \sum_{i=1}^{\infty}\left[CEF_{11}(r_i)\cdot p_r(r_i)\right] = 6.9786 \text{ bpu•h/interruption}$$

<u>Annual Expected Cost of Load Point Interruption:</u>

$$\lambda \cdot E\{y\} = \lambda \cdot \sum_{i=1}^{\infty}\left[CEF_{11}(r_i)\cdot p_r(r_i)\right] = 0.8538 \text{ bpu•h}$$

<u>Variance and Standard Deviation of Load Point Interruption:</u>

$$VAR(y) = \sum p_y(y)\cdot(y - E\{y\})^2 = 33.91 \text{ bpu•h}$$

$$\sigma = \sqrt{VAR(y)} = 5.82 \text{ bpu•h}$$

6.5.4 Using Standard Interruption Curve: $\lambda \cdot \sum_{i=1}^{\infty}\left[CEF_{Std.}(r_i)\cdot p_r(r_i)\right]$

When performing the Random Variable with Process Modeling method as per section 6.5.3, using the standard interruption curve $CEF_{Std.}(t)$ in place of $CEF_{11}(t)$ yields the results listed below in Table 22.

Table 22: Table of Impact Values Using Standard Interruption Curve

p(y)	y (bpu•h)
0.000000103025	0.48
0.081734593885	1.45
0.051492794148	2.91
0.664583982879	4.36
0.051084121178	5.81
0.023703032303	8.72
0.100124877509	13.81
0.000000000428	18.91
0.027276468780	30.30
0.000000025865	1061.71

<u>Annual Expected Cost of Load Point Interruption:</u>

$$\lambda \cdot E\{y\} = \lambda \cdot \sum_{i=1}^{\infty}\left[CEF_{Std.}(r_i)\cdot p_r(r_i)\right] = 0.7193 \text{ bpu•h}$$

6.5.5 Comparison of Results

Four different methods were used to calculate the annual expected cost of load point interruption for our target scenario. The results of each method are tabled in Table 23. The symbol r_{AVG} is used for clarity in place of the expected value $E\{r\}$.

Table 23: Annual Expected Cost Results for All Methods

Method #	Method Name	Method Equation $\lambda \cdot E\{y\} =$	Annual Expected Cost (bpu•h)	% Difference v.s. Method #1
#1	Averaged Data Method	$\lambda \cdot r_{AVG} \cdot BPU_0$	0.72482	0.00%
#2	Averaged Data with Process Modeling	$\lambda \cdot CEF_{11}(r_{AVG})$	0.84740	+16.91%
#3	Random Variable with Process Modeling	$\lambda \cdot \sum_{i=1}^{\infty} [CEF_{11}(r_i) \cdot p_r(r_i)]$	0.85381	+17.80%
#4	Method #3 using Standard Curve	$\lambda \cdot \sum_{i=1}^{\infty} [CEF_{Std.}(r_i) \cdot p_r(r_i)]$	0.71930	-0.76%

Method #1 is the simplest calculation and produces an expected annual cost of 0.725 bpu•h. For Method #1, a reliability analysis needs only averaged data for λ and r and requires only the knowledge of how much production is constricted immediately when the interrupted unit is isolated as BPU_0.

Method #2 includes a more complex calculation and produces an expected annual cost of 0.8474 bpu•h. For Method #2, reliability analysis needs only averaged data for λ and r, but requires the process modeling of cascading interruption to produce the $CEF(t)$ function for the given load point. This annual expected cost accounts for cascading interruption and this is evident in a 16.91% higher annual expected cost versus Method #1.

Method #3 includes the most complex calculation and produces an expected annual cost of 0.8574 bpu•h. For Method #3, reliability analysis requires the use of the proposed zone-branch variation to calculate the spectrum $p_r(r)$. Impact analysis requires the process modeling of cascading interruption to produce a $CEF(t)$ function for the given load point. This annual expected cost accounts for cascading interruption and this is evident in a 17.8% higher annual expected cost versus Method #1.

Method #4 includes a somewhat less complex calculation and produces an annual cost of 0.7193 bpu•h. For Method #4, reliability analysis requires the use of the proposed zone-branch variation to calculate the spectrum $p_r(r)$. Impact analysis, however, is avoided by using the standard curve, which provides the $CEF_{Std.}(t)$ function. This annual expected cost is meant to account for cascading interruption, but its calculated value is 0.76% *lower* than calculated by Method #1. This surprising result raises the question of why Method #4 gives a lower result than Method #1?

The distinction between methods is most easily understood when comparing the $CEF(t)$ function they employ. Figure 96 plots $CEF_{11}(t)$ used by Methods #2 and #3, $CEF_{Std.}(t)$ used by Method #4, and a linear $CEF(t)$ called 'uncascaded linear' used by Method #1 whose value is simply BPU_0•t. A reference line with a slope of 1 is also provided as a visual aid.

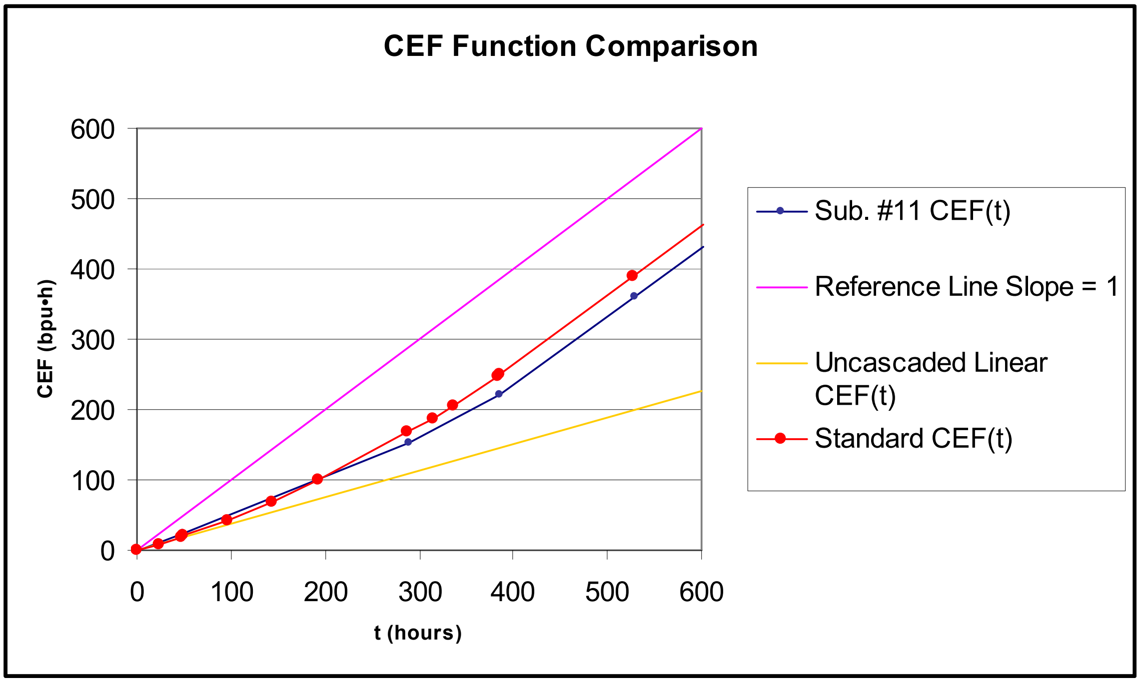


Figure 96: Multiple CEF Function Plots

At a glance, both non-linear CEF's appear to be obviously higher than the uncascaded linear CEF at all points. It is important to note that the criticality enhancement function (CEF) is only the transform of interruption duration ('r' in units of time) to lost production impact (y) whereas the probability mass function $p_y(y)$ or $p_r(r)$ give the relative 'importance' of each point y or r, respectively.

Recall Table 19, listing the Substation #11 probability mass points, now reproduced as Table 24.

Table 24: Probability Mass Function Value Consideration

Index i	$p_r(r_i)$	r_i (hours)
1	0.000000103025	1.32
2	0.081734593885	4.00
3	0.051492794148	8.00
4	0.664583982879	12.00
5	0.051084121178	16.00
6	0.023703032303	24.00
7	0.100124877509	36.00
8	0.000000000428	48.00
9	0.027276468780	72.00
10	0.000000025865	1200.00

On closer inspection, the probability mass function is dominated by two 'most probable' points, shown in Table 24 and indexed 4, and 7. When an event occurs, it is expected be point 4, 66% of the time, and point 7, 10% of the time. For large values of interruption time (r), we expect the largest separation between curves. Considering the points within Table 24, the first nine points have $r \leq 100$ while the tenth point has almost zero probability of occurring.

The region of interest for the accuracy of this calculation appears to be $t \leq 40$, which is shown in Figure 97.

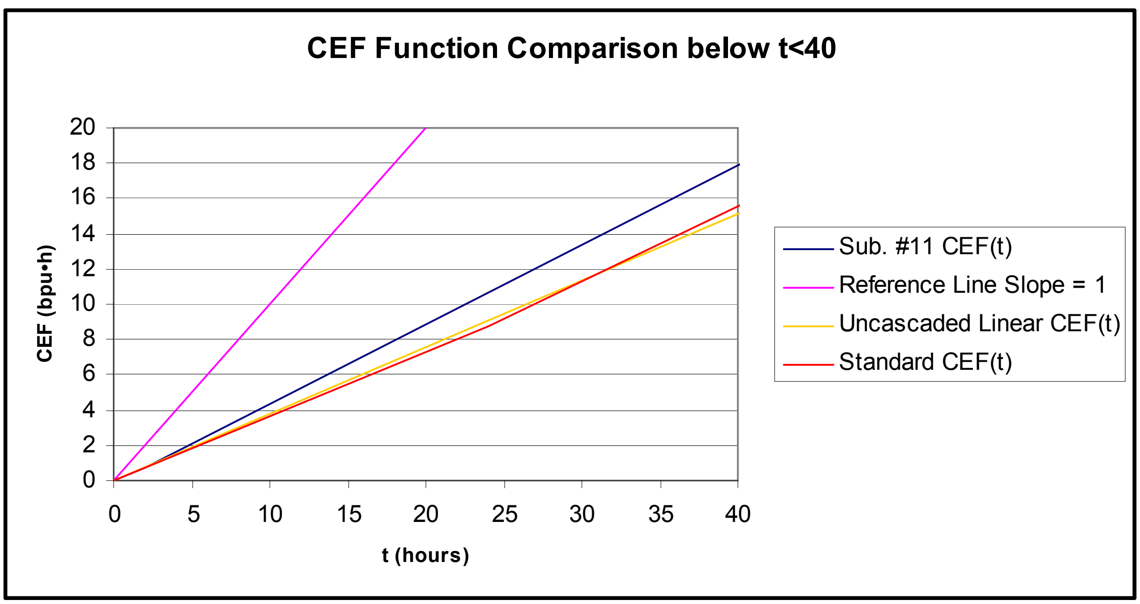


Figure 97: CEF Function Comparison t<40 hours

When comparing CEF curves within the 'meaningful' region below 40 hours, it is evident that the standard CEF curve is below the uncascaded linear CEF in the most probable region. Because production interruption ($y = CEF(r)$) values for the dominant points are calculated within this region, Method #4 yields a result that is below that of Method #1.

Chapter 7 - Conclusions

7.1 Summary

In a refining era that places enhanced importance on reliable unit operation, a more accurate estimation of the expected cost of load point interruption enables a better managerial decision as to the dispersion of limited resources to improve power system reliability. This thesis has included the cascading interruption of process units in the calculation of load point interruption cost. Through the marriage of electrical reliability modeling and process reliability modeling, this thesis has quantified the cascading impact of load point interruptions within a refinery in per-unit (bpu) terms of refinery production and introduced the concept of the Criticality Enhancement Function ("$CEF(t)$"). The $CEF(t)$ operates on random variable r, mapping into the cost domain y.

Four methods of computation were employed on the target scenario of the case study to calculate the annual expected cost of load point interruption ("$\lambda \cdot E\{y\}$").

Method #1 – Averaged Data Method: $\lambda \cdot E\{y\} = \lambda \cdot r_{AVG} \cdot BPU_0$

Method #2 – Averaged Data + Process Modeling: $\lambda \cdot E\{y\} = \lambda \cdot CEF(r_{AVG})$

Method #3 – Random Variable + Process Modeling: $\lambda \cdot E\{y\} = \lambda \cdot \sum_{i=1}^{\infty} CEF_{11}(r_i) \cdot p_r(r_i)$

Method #4 – Random Variable with Standard $CEF_{Std.}(t)$ curve

The conclusions drawn within this thesis are here summarized:

1. When the cascading impact of unit interruption is considered in a $\lambda \cdot E\{y\}$ calculation, by including the target unit's $CEF(t)$ in Method #2 or Method #3, the resulting $\lambda \cdot E\{y\}$ is more accurate than without, in Method #1, and yields a bpu•h value that is larger by about 17%. The magnitude of this increase is sizeable and it is concluded that the effort put into process modeling is worthwhile. Method #3 and Method #2 are recommended over Method #1.
2. When the probability mass function $p_r(r)$ is computed and used in calculation in Method #3, the $\lambda \cdot E\{y\}$ calculation is 0.89% higher than that of Method #2, which uses averaged reliabilty data (when both are related to the result in Method #1). Method #3 limits reliability modeling to a variation of zone-branch, where Method #2 does not, but the increase in accuracy is preferrable and the proposed method could easily be adopted by existing reliability software. It is concluded that, because of its superior accuracy, Method #3 is recommended over Method #2.
3. In an attempt to relieve the burden of process modeling from the Reliability Engineer, use of the $CEF_{Std.}(t)$ transform in Method #4 highlights the sensitivity of $\lambda \cdot E\{y\}$ to accuracy around especially probable interruption

points. Because Method #4 calculated a lower value than Method #1, Method #4 is not recommended, and again speaks to the conclusion that process modeling is worthwhile to a $\lambda \cdot E\{y\}$ calculation.

4. By analyzing the spectrum of interruption probability duration $p_r(r)$ and calculating its expected value in the case study, it is concluded that averaged reliability measures *are* good measures of system performance. Because the expected value is dominated by a very few most probable points, an analogous conclusion would be that a chain may be well characterized by its weakest few links. This is a surprising conclusion to the author and was not the original hypothesis of this thesis. On further consideration, engineered power systems are designed to minimize long interruptions through redundancy and the use of robust components, so the most probable interruptions could be expectedly short in duration. During the course of investigation, the substation configuration believed to be least reliable was chosen to clearly show a distinction in the calculation methods. While method #3 yields superior results, when compared with the results using method #2, the difference in the results between the two methods is small and allows us to draw two further conclusions. Firstly, the case study has a very reliable power system. Secondly, a sub-optimal calculation can perform as well as an optimal calculation on a very reliable power system.
5. Since a full cascade of unit interruptions is on the order of 2-3 months, where the most probable interruptions from electrical reliability are on the order of 2-3 days, it is concluded that the most sensitive and important region for process modeling is $0 \le t \le 40$ hours. It is for this reason that a standard $CEF_{Std.}(t)$ transform curve creates an inaccurate result.

This thesis has proposed a novel modeling technique that marries electrical and process reliability models for the calculation of annual expected cost of load point interruptions within a refinery. This technique was explored within the context of various calculation methods which demonstrated the value of including the cascading effect of process interruption and the value in the marriage of reliability modeling.

7.2 Contributions

The main contributions of this thesis are here listed:

1. Treatment of repair time as a random variable 'r' with MTTR as its expected value $E\{r\}$ and spectrum $p_r(r)$.
2. The concept of Criticality Enhancement Function $CEF(t)$, and its time derivative $BPU(t)$, to map points in the time domain into the impact domain.
3. Treatment of 'cost' information in units of interrupted refinery production on a per-unit of rated capacity basis. Units representing barrels-per-unit of rated refinery production ("bpu") and bpu•h, where 'h' denotes hours, represent interrupted flow and impact, respectively. By avoiding the discussion of cost in financial terms, information is not sensitive, enabling the publication of interruption case study data.

4. A novel technique of process modeling and its marriage with reliability analysis in the calculation of annual expected impact from load point interruption.
5. The publication of actual data in $BPU(t)$ and $CEF(t)$ curves regarding the cascading impact of unit interruption on a case study.

7.3 Future Work

To further extend the study of the impact of load point interruption within a refinery, the author suggests an improvement in the method by which we calculate the cut-sets created by outages.

When we calculate reliability data for load point interruptions, we consider all the scenarios in which the load point in question is interrupted, but we fail to consider other load points that may be coincidently affected. This thesis argues that the cascading interruption of units must be considered, but assumes that load point interruptions are mutually exclusive.

For example, if we consider load points A and B with the following states:

Table 25: Mutually Exclusive Load Point States

State	A	B
1	UP	UP
2	DOWN	UP
3	DOWN	DOWN
4	UP	DOWN

Reliability metrics for A would be calculated based on time spent in states 2 and 3. Reliability metrics for B would be calculated based on time spent in states 3 and 4. The problem arises when criticality enhancement function is applied for units interrupted by only A or only B to a calculation that involves state 3. By treating the interruption of A and B as mutually exclusive, we are adding the values from state 3 to both A and B. This double-counts the impact of one interruption, while failing to consider a possibly faster cascade involving the units interrupted by both A and B. It leaves room for an even more accurate approach within the context of the cascading unit interruption within a refinery. A new reliability analysis algorithm could be developed by which the outage of each combination of component up/down states could be considered to produce its own cut-set of load point outages. The union of sets of units interrupted from each component could then be run individually in the process model simulation to produce the appropriate $CEF(t)$.

Bibiliography

[1] C. Krohn, Reliability Analysis Techniques, Proceedings of the IRE Volume 48, Issue 2, 1960.

[2] D. Koval, Evaluation of Distribution System Reliability, The University of Saskatchewan, 1974.

[3] IEEE Std. 493-2007 GOLD BOOK, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, 2007.

[4] Z. Dong, D. Koval, J, Propst, Reliability of various industrial substations, Industry Applications, IEEE Transactions on Volume 40, Issue 4, July-Aug. 2004 Page(s):989 – 994, 2004

[5] D. Koval, Zone-branch reliability methodology for analyzing industrial power systems, Industry Applications, IEEE Transactions on, Volume 36, Issue 5, Page(s):1212 – 1218, Sept.- Oct. 2000.

[6] R. Subramaniam, R. Billinton, G. Wacker, Factors Affecting The Development Of An Industrial Customer Damage Function, IEEE Transactions on Power Apparatus and Systems, Volume PAS-104, Issue 11, Page(s):3209 – 3215, Nov. 1985.

[7] Z. Dong, Modeling and evaluating electrical power system: Risk and reliability, University of Alberta, 2004.

[8] Petro-Canada Internal Documents

- Edmonton Refinery 2008 Business Plan Refinery Volumentrics;
- Edmonton Refinery Productions Employee Orientation Package, Revision, 2005;
- Edmonton Refinery Block Flow Diagram, Revision 2008;
- Single Line Diagram 30E-P-1-1, Rev. 42B2;
- Single Line Diagram 30B-P-176-1, Rev. 4;

[9] J. Propst, Operating Manual for Calculating Electrical Risk and Reliability, June 9, 1994, Revised January 23, 2007.

[10] J. Propst, Calculating electrical risk and reliability, Industry Applications, IEEE Transactions on, Volume 31, Issue 5, Page(s):1197 – 1205, Sept.-Oct. 1995.

[11] J. Propst, D. Doan, Improvements in modeling and evaluation of electrical power system reliability, Industry Applications, IEEE Transactions on, Volume 37, Issue 5, Page(s):1413 – 1422, Sept.-Oct. 2001.

[12] D. Koval, X. Zhang, J. Propst, T. Coyle, R. Hale Jr., Reliability Methodologies Applied to the IEEE Gold Book Standard Network, IEEE IAS Applications Magazine, JAN/FEB 2003.

[13] A. Papoulis, S. Pillai, Probability, Random Variables and Stochastic Processes, Fourth Edition, McGraw-Hill, Page(s): 123-168, 2002.

Appendix A – Reliability Evaluation by Proposed Method

Zone	Equipment	λo	ro	Ao	q	q*λo	q*ro*λo	λn
1	(149) Utility (linked from utility)	1.95600000	1.32	0.999705347	0.000000000	0.000000000	0.000000000000	0.000000000000
1	(108) Switch 138 KV Disconnect	0.00145000	24.00	0.999996027	0.000000000	0.000000000	0.000000000000	0.000000000000
2	(149) Utility (linked from utility)	1.95600000	1.32	0.999705347	0.000000006	0.000000013	0.000000016638	0.000000103025
2	(108) Switch 138 KV Disconnect	0.00145000	24.00	0.999996027	0.000000006	0.000000000	0.000000000224	0.000000000076
5	(108) Switch 138 KV Disconnect	0.00290000	24.00	0.999992055	0.000000000	0.000000000	0.000000000000	0.000000000000
5	(48) Circuit Breaker, 138 KV Outdoor Oil	0.00027000	72.00	0.999997781	0.000000000	0.000000000	0.000000000000	0.000000000000
5	(21) Bus, Open Substation outdoor	0.00625000	16.00	0.999988585	0.000000000	0.000000000	0.000000000000	0.000000000000
6	(108) Switch 138 KV Disconnect	0.00290000	24.00	0.999992055	1.000000000	0.002900000	0.069600000000	0.023703032227
6	(48) Circuit Breaker, 138 KV Outdoor Oil	0.00027000	72.00	0.999997781	1.000000000	0.000270000	0.019440000000	0.002206834035
6	(21) Bus, Open Substation outdoor	0.00625000	16.00	0.999988585	1.000000000	0.006250000	0.100000000000	0.051084121178
7	(48) Circuit Breaker, 138 KV Outdoor Oil	0.00013500	72.00	0.999998890	0.000000000	0.000000000	0.000000000000	0.000000000000
7	(132) Transformer > 10000 KVA > 40 yr	0.03200000	1200.00	0.995635570	0.000000000	0.000000000	0.000000000000	0.000000000000
7	(35) Cable in Conduit/OH 15 KV > 15 yrs	0.00052920	48.00	0.999997100	0.000000000	0.000000000	0.000000000000	0.000000000000
8	(48) Circuit Breaker, 138 KV Outdoor Oil	0.00013500	72.00	0.999998890	0.000000099	0.000000000	0.000000000961	0.000000000109
8	(132) Transformer > 10000 KVA > 40 yr	0.03200000	1200.00	0.995635570	0.000000099	0.000000003	0.000003797348	0.000000025865
8	(35) Cable in Conduit/OH 15 KV > 15 yrs	0.00052920	48.00	0.999997100	0.000000099	0.000000000	0.000000002512	0.000000000428
11	(117) Switchgear, Cubicle InDoor > 600v >15 yr	0.00210870	72.00	0.999982669	0.000000000	0.000000000	0.000000000000	0.000000000000
11	(87) Protective Relays - Basic - Misoperation	0.01000000	4.00	0.999995434	0.000000000	0.000000000	0.000000000000	0.000000000000
11	(54) Circuit Breaker, 15 KV Indoor > 15 yr	0.00054000	12.00	0.999999260	0.000000000	0.000000000	0.000000000000	0.000000000000
12	(117) Switchgear, Cubicle InDoor > 600v >15 yr	0.00172530	72.00	0.999985820	1.000000000	0.001725300	0.124221600000	0.014101669483
12	(87) Protective Relays - Basic - Misoperation	0.01000000	4.00	0.999995434	1.000000000	0.010000000	0.040000000000	0.081734593885
12	(54) Circuit Breaker, 15 KV Indoor > 15 yr	0.00081000	12.00	0.999998890	1.000000000	0.000810000	0.009720000000	0.006620502105
13	(88) Protective Relays - Complex - Misoperation	0.05000000	12.00	0.999931512	1.000000000	0.050000000	0.600000000000	0.408672969425
13	(40) Cable,UG, duct bank, 601-15kv non-plc > 15 yrs	0.01225000	36.00	0.999949660	1.000000000	0.012250000	0.441000000000	0.100124877509
14	(110) Switch 15 KV Indoor Enc Disc	0.00630000	8.00	0.999994247	1.000000000	0.006300000	0.050400000000	0.051492794148
14	(117) Switchgear, Cubicle InDoor > 600v >15 yr	0.00134190	72.00	0.999988971	1.000000000	0.001341900	0.096616800000	0.010967965153
14	(70) Fused switch, 15 KV Enclosed, outdoor	0.03050000	12.00	0.999958221	1.000000000	0.030500000	0.366000000000	0.249290511349

Substation #11 Reliability Metrics:	-	15.67	0.999781212	-	0.122347216	1.917002217684	1.000000000000
		r	A		λ	λr	sum check