Mack-Blackwell Transportation Center

MBTC Mack-Blackwell National Rural Transportation Study Center

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Fayetteville, Arkansas 72701

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QUANTIFYING THE IMPACT OF REFRIGERATED UNIT FAILURES

MBTC FR-2005

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Quantifying the Impact of Refrigerated Unit Failures

FINAL REPORT

for

Mack-Blackwell Transportation Center
(MBTC)

Project #2005

Wednesday, March 14, 2001

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ABSTRACT

The shipment of processed meats, like poultry, dictates the necessity of using refrigerated trailer units (commonly call reefers). Reefer failures occur and have serious and costly effects on the performance of rural and urban transportation systems typical of the poultry industry. This project explored the measurable impact of reefer failures through identifying potential reefer failure modes (using FMEA, FTA, and Pareto analysis) and the development of a simulation model based on common poultry industry trucking practices. Reported performance measures include the number of reefer failures and 7-year costs due to both delays in delivery and refrigeration system repairs.

INTRODUCTION

The transportation system of the poultry processing industry embeds multi-layered pick-up and delivery points (like hubs): kill facilities, production facilities and distribution facilities. Live birds are collected from the rural domain of the farmer and delivered to the kill facility. From the kill facility, cleaned birds are transported to the processing facilities, and once the birds are processed, complex shipping rules are implemented to insure that appropriate inventory levels of various product types are maintained at the national distribution centers. The hierarchical design is typical of many transportation systems, but the perishable aspect of the shipped material presents unique challenges.

The shipment of processed meats, like chicken, dictates the necessity of using refrigerated trailer units (commonly call reefers). As the case with any mechanical device, reefer failures (of various modes) are observed and have serious and costly impacts on the operation. At the kill facility, limited warehouse space is available, and the reefer units are used for storage following the killing process and prior to shipment. The time the product is held in the reefer unit is limited, and the trailer time is spent in the facility grounds where local maintenance is available, yet any reefer failure still costs time and money. As the product progresses through the operation, reliable reefer performance becomes even more critical. Important issues include the dispatching rules, fleet size, season of the year, availability of third party reefer repair, time of day, freight/product mixture and geography.

RESEARCH OBJECTIVE AND TASKS

This project explored the measurable impact of reefer failures on the economical and logistical performance of the rural and urban transportation systems typical of the poultry industry. The work presented in this project was appropriate to any organization having refrigerated transportation systems. In this project, we explored and documented the impact of refrigerated unit failures on the logistical infrastructure within the poultry processing industry, namely Tyson Foods, Inc. As a result of these activities, industries having multi-layered pick-up and delivery points will be able to identify opportunities for improved performance and to determine how factors influence total cost.

This project evolved through four successive phases. In phase one, reefer failure types and associated failure distributions were identified by reviewing the pertinent literature and discussion/validation with Tyson's personnel. The second phase of the project incorporated the failure distributions with the known logistical system at Tyson Foods, Inc. to construct a generalized simulation model to measure the potential impact of reefer failures. The third phase of the project utilized the simulation model to construct a useful set of experimental scenarios and to identify how factors influence total cost. The fourth phase of the project consists of documenting and distributing the findings of the research.

PHASE I: REEFER FAILURE DESCRIPTION

Efforts during this phase included many discussions with Tyson Foods personnel (management and maintenance), the inspection of some reefer units under repair, and a thorough review of pertinent Thermo King operation and maintenance literature. This first step identified the potential failure modes associated with the trailer's refrigeration system. There were two methods used to identify or analyze potential system failure modes and their effects on the local and system trucking operations. One method used was Failure Mode and Effects Analysis (FMEA), and the second was Fault Tree Analysis (FTA). Results from both are described below.

Failures Mode and Effects Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a structured, qualitative analysis of a system, subsystem, or function to identify potential system failure modes, their causes, and the effects on operation associated with each failure mode occurrence (Bowles and Bonnell, 1998). The FMEA can be extended to include an assessment of the severity of the failure effect and its probability of occurrence, i.e. a Failure Mode, Effects, and Criticality Analysis (FMECA). A FMEA/FMECA provides a basis for recognizing component failure modes identified in components and system prototype tests and failure modes developed from historical "lessons learned" in design requirements. It aids in identifying unacceptable failure effects that prevent achieving design requirements. It is also used to assess the safety of system components and to identify design modifications and corrective action needed to mitigate the effects of a failure on the system. It is used in planning system maintenance activities, subsystem design, and as a framework for system failure detection and isolation (Bowles and Bonnell, 1998).

In this project, the main purpose of using FMEA was to identify potential system failure modes and their effects on the local and system operations. Before analyzing the system failure modes and their effects, the first step was to learn the system. Currently, Tyson Foods is using the Thermo King refrigerated unit (reefer), and FMEA is based on Thermo King's system. The functional relationships between the different system components were most easily shown as a functional block diagram, such as in Figure 1 (refrigeration cycle) and Figure 2 (defrost/heating cycle). Those functional block diagrams help analysts to understand the relationships between the system components.

The next step of the FMEA was to determine all the ways in which each component can fail and the effect that each failure mode will have on the refrigeration system. Effects were determined at each level of the system hierarchy – the effect on the module containing the failed component (local), the effect on every subsystem of which the component was a part, and the effect on the total system. Results from the FMEA can be seen in Table 1. For example, a broken compressor crankshaft causes the compressor to fail at the local level, and subsequently causes the refrigeration system to fail at the system level. The result of a total system failure can be product delivery delays, product damage, and incurred costs. The process of identifying possible failure modes and determining their effects on the system operation helped develop a better understanding of the relationships between the different system components.

Figure 1. Functional Block Diagram – Refrigeration Cycle (Thermo King).

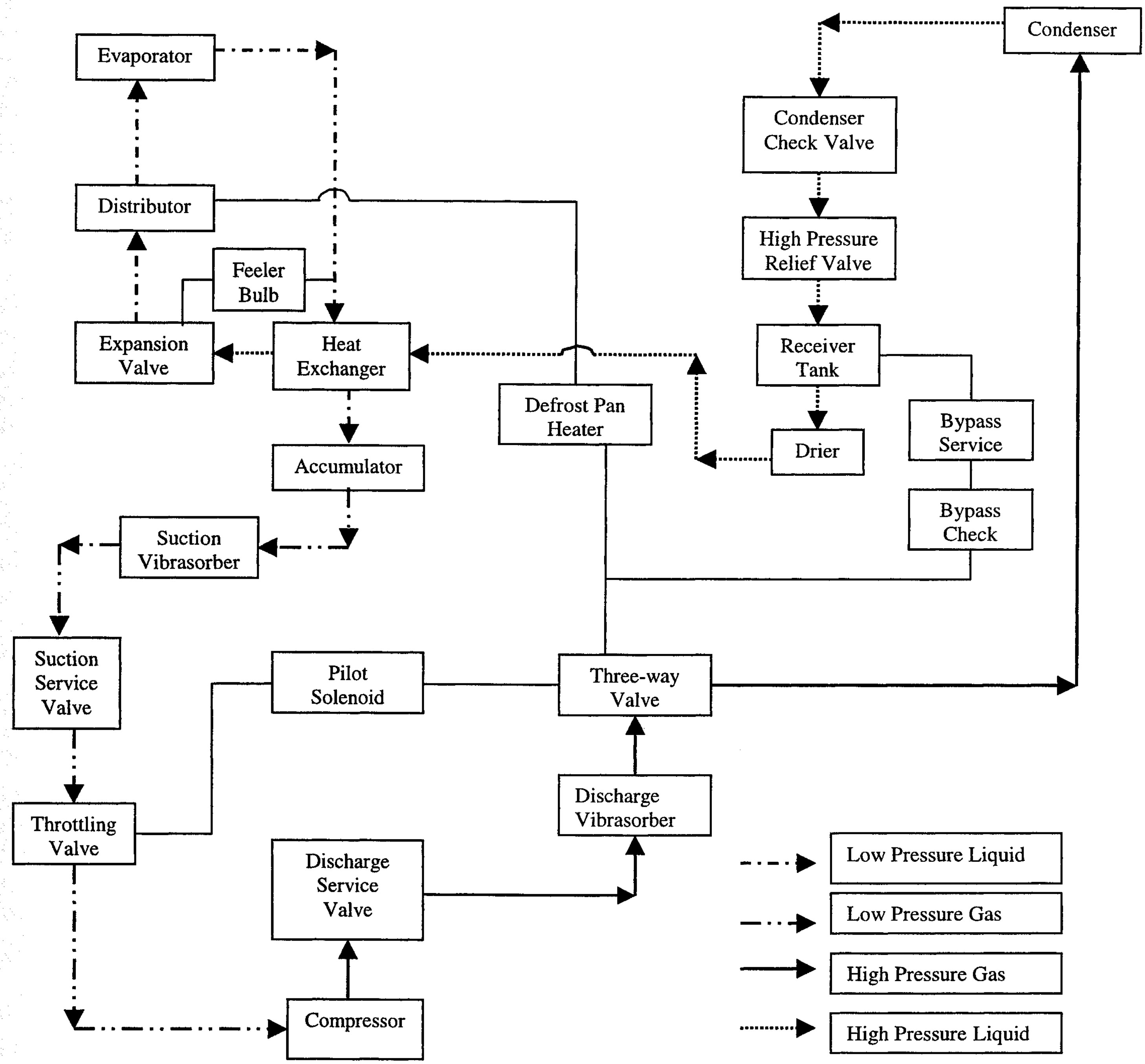

Figure 2. Functional Block Diagram – Defrost and Heating (Thermo King).

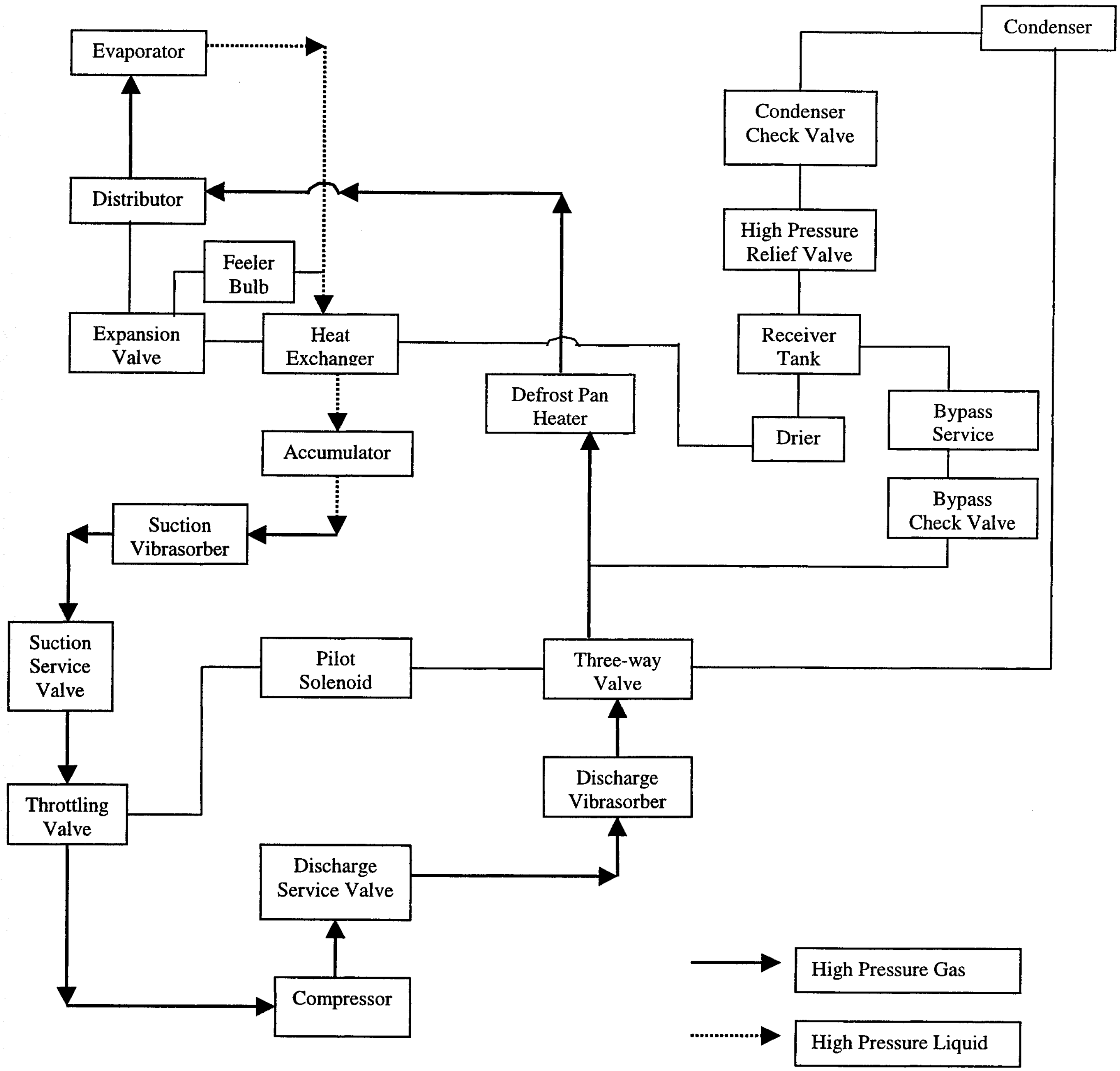

Table 1. FMEA of the trailer refrigeration system.

Component	Function	Failure Mode	Failure Effects	
			Local	System
Compressor	Moves refrigerant and increases refrigerant gas temperature and pressure	1) Bearing loose or burned out 2) Broken valve plate 3) Too much oil 4) Broken crank shaft and seals leak	Noisy compressor Low head pressure Noisy compressor Compressor not functioning	Reliability of the system decreases Unable to pump down system Unable to pull/hold vacuum on low side Unit not refrigerating System failure
Discharge service valve	Used for isolating and servicing the discharge side of the compressor	1) Leaking	Low head pressure Unable to pull vacuum on low side	System will not function properly
Discharge vibrasorber	Reduces vibration transfer allows for a flexible discharge line	1) Leaking/wear out	Flexibility decrease	Vibration will increase and damage the nearest components
Three-Way valve	Directs the flow of refrigerant to either the evaporator or condenser	1) Does not respond to pilot solenoid	The spool moves and sticks at one side	Unit cools in heat and defrost cycle or heats in refrigeration cycle Unit not refrigerating and not heating or defrosting
Condenser pressure bypass check valve	Improves three-way valve heat-to-cool response time	1) Leaks around valve	High pressure gas leaks into the unit	Unit not heating or defrosting
Condenser	Allows refrigerant to condense by transferring heat to ambient air flowing across fins and coils	1) Dirt and foreign objects in the fins 2) Idle pulley condenser fan broken	Inefficiency on air flow recirculating over the coil	Decrease efficiency of the unit
Condenser check valve	Stops refrigerant flow from the receiver tank during heat and defrost	1) Leaks / seat damage	High or low suction pressure	Unit not refrigerating and not heating or defrosting Unable to pump down system
High pressure relief valve	Relieves extremely high refrigerant pressure from the system	1) Leaks	Lost refrigerant	Decrease efficiency of the system

Table 1. FMEA of the trailer refrigeration system (continued).

Component	Function	Failure Mode	Failure Effects	
			Local	System
Receiver tank outlet valve	Allows refrigerant to flow from the receiver tank and is used for servicing the low side	1) Leaks	Refrigerant flows out	Unable to pump down system
Expansion valve	Meters the liquid refrigerant to the evaporator in the cool mode	1) Opened too much 2) Closed too much 3) Needle eroded or leaking 4) Partially closed by ice, dirt or wax	High suction pressure Low suction pressure High suction pressure Low suction pressure	Suction line frosting back Unit not refrigerating Suction line frosting back Unit not refrigerating Unit operating in a vacuum
Expansion valve feeler bulb	Senses temperature at the evaporator outlet and assists in controlling refrigerant flow	1) Improperly mounted 2) Making pure contact	High suction pressure High suction pressure	Suction line frosting back Suction line frosting back Unit not refrigerating
Evaporator	Transfers heat between refrigerated compartment air and refrigerant moving through its coils	1) Dirty or plugged coils 2) Plugged passes in the coils distribution 3) Tubes damaged 4) Insufficient circulation		Gradual reduction in capacity Gradual reduction in capacity Gradual reduction in capacity Rapid cycling between cool and heat
Suction vibrasorber	Reduces vibration transfer and allows for a flexible suction line	1) Leaking/wear out	Flexibility decrease	Vibration will increase and damage the nearest components

Table 1. FMEA of the trailer refrigeration system (continued).

Component	Function	Failure Mode	Failure Effects	
			Local	System
Suction service valve	Used for isolating and servicing the suction side of the compressor	1) Leaks	High suction pressure	Unable to pump down system
Throttling valve	Regulates refrigerant vapor pressure entering the compressor	1) Leaks	Refrigerant flows out	Overload the motor or engine Decrease efficiency of the unit Unit not refrigerating and not heating or defrosting
Pilot solenoid	When energized, this electrically-controlled valve permits the three-way valve to shift from cool to heat	1) Coil, needle, and seat failures or malfunction		Unit not refrigerating Unit not heating or defrosting Unable to pump down system Unit cools in heat and defrost cycle Unit heats in refrigerating cycle
Bypass check valve	Prevents refrigerant from flowing into the bypass line when the unit is in the cool cycle	1) Leaks or malfunction	Refrigerant flows into bypass line when the unit is in the cool cycle	Unable to pump down system
Bypass service valve	Provides for checking and servicing of the bypass line and bypass check valve	1) Leakage around the stem	Refrigerant flows into bypass line when the unit is in the cool cycle	Unable to pump down system

Fault Tree Analysis (FTA)

The second method used to identify failure modes was Fault Tree Analysis (FTA). A Fault Tree Analysis is a graphical representation of logical relationships between events (usually failure events). This method has long been used for the qualitative and quantitative analysis of the failure modes of critical systems (Koren and Childs, 1995). A fault tree provides a mathematical and graphical representation of the combination of events, which can lead to system failure. The construction of a fault tree model can provide insight into the system by illuminating potential weaknesses with respect to reliability or safety. A fault tree can help with the diagnosis of failure symptoms (modes) by illustrating which combinations of events could lead to the observed failure symptoms. The quantitative analysis of a fault tree is used to determine the probability of system failure, given the probability of occurrence for failure events (Koren and Childs, 1995).

If performed manually, the construction of a fault tree provides a systematic method for analyzing and documenting the potential causes of system failure. The analyst begins with the failure scenario being considered and decomposes the failure system into its possible causes. Each possible cause is then investigated and further refined until the basic causes of the failure are understood. In other words, FTA provides a logical framework for understanding the way in which a system can fail, which is often as important as understanding how a system operates.

A fault tree consists of the undesired top events (system or subsystem failures), linked to more basic events by logic gates. The top events are resolved into their constituent causes, connected by "AND" or "OR" logic gates, which are then further resolved until basic events are identified. The basic events represent basic causes for the failures, and represent the limit of resolution of the fault tree (Koren and Childs, 1995).

In this project, FTA was used to identify the potential causes of reefer failures. Figures 3 and 4 show the refrigeration cycle FTA and defrost/heating cycle FTA for the Thermo King reefer units, respectively. The FTA process began with the scenario where the reefer system failed to operate followed by the decomposition of the failed system into its possible causes. Each possible cause was then investigated and further refined until the basic causes of the failure were understood.

The FMEA and FTA identified the following possible reefer component failures:

1. Compressor
2. Discharge Vibrasorber
3. Suction Vibrasorber
4. Three-Way Valve
5. Pilot Solenoid
6. Throttling Valve
7. Bypass Check Valve
8. Evaporator
9. Expansion Valve
10. Condenser
11. Sub-cooler Heat Exchanger
12. Receiver Tank
13. Accumulator

After identifying the reefer failures types, failure data was collected for appoximately 30 trailers from each of six fleet years (1990-1995). These data are shown in Tables 2-7.

Pareto Analysis

Pareto Analysis was used to determine the percentage of failures for each failure type. The Pareto Analysis for each fleet year can be seen in Figures 5-10. It was found that compressor failures caused 56% of all system failures, followed by the malfunction of the discharge vibrasorber (18%) and suction vibrasorber (11%).

Figure 3. Fault Tree Analysis – Refrigeration Cycle (Thermo King).

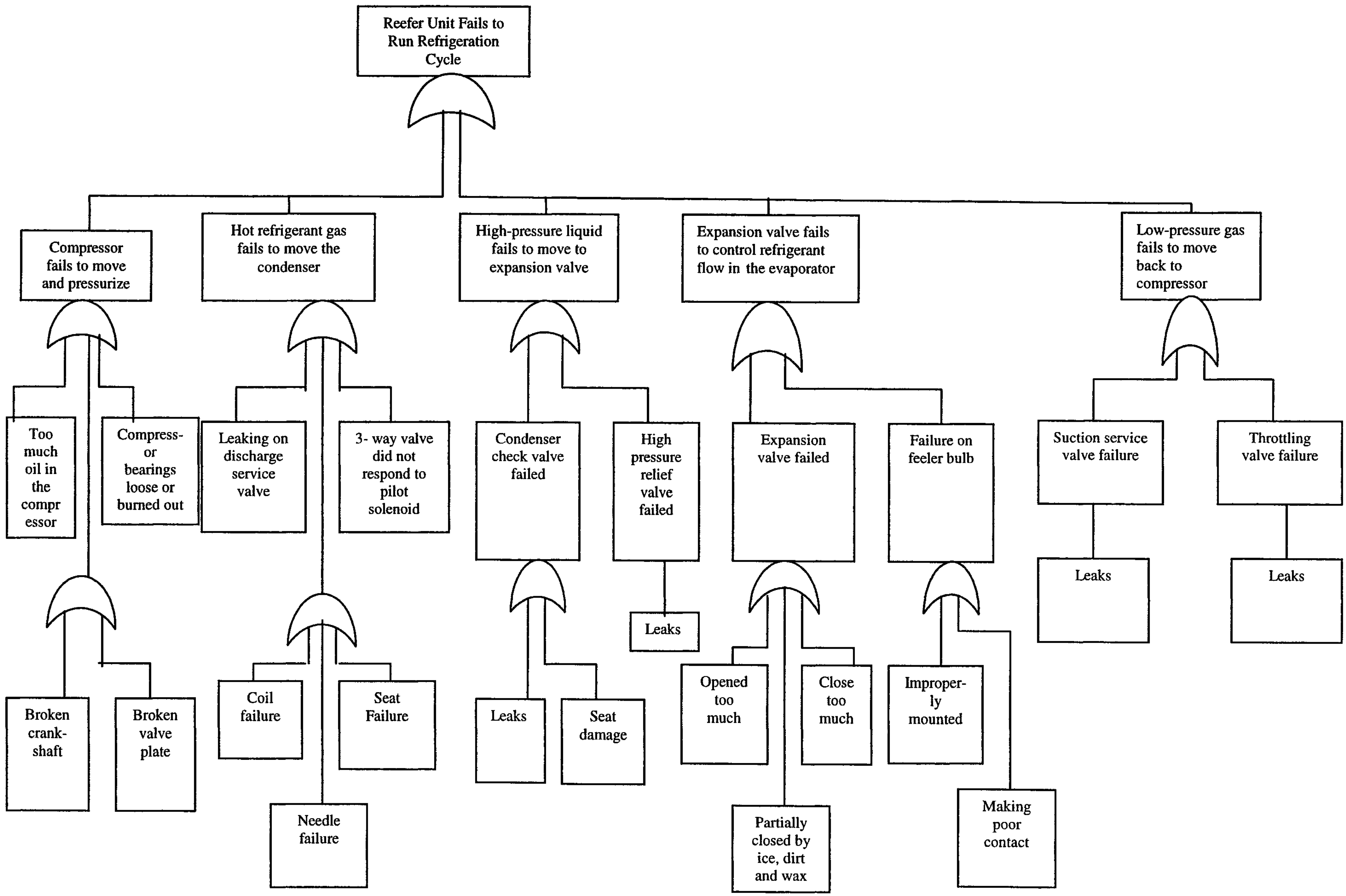

Figure 4. Fault Tree Analysis – Heating/Defrost Cycle (Thermo King).

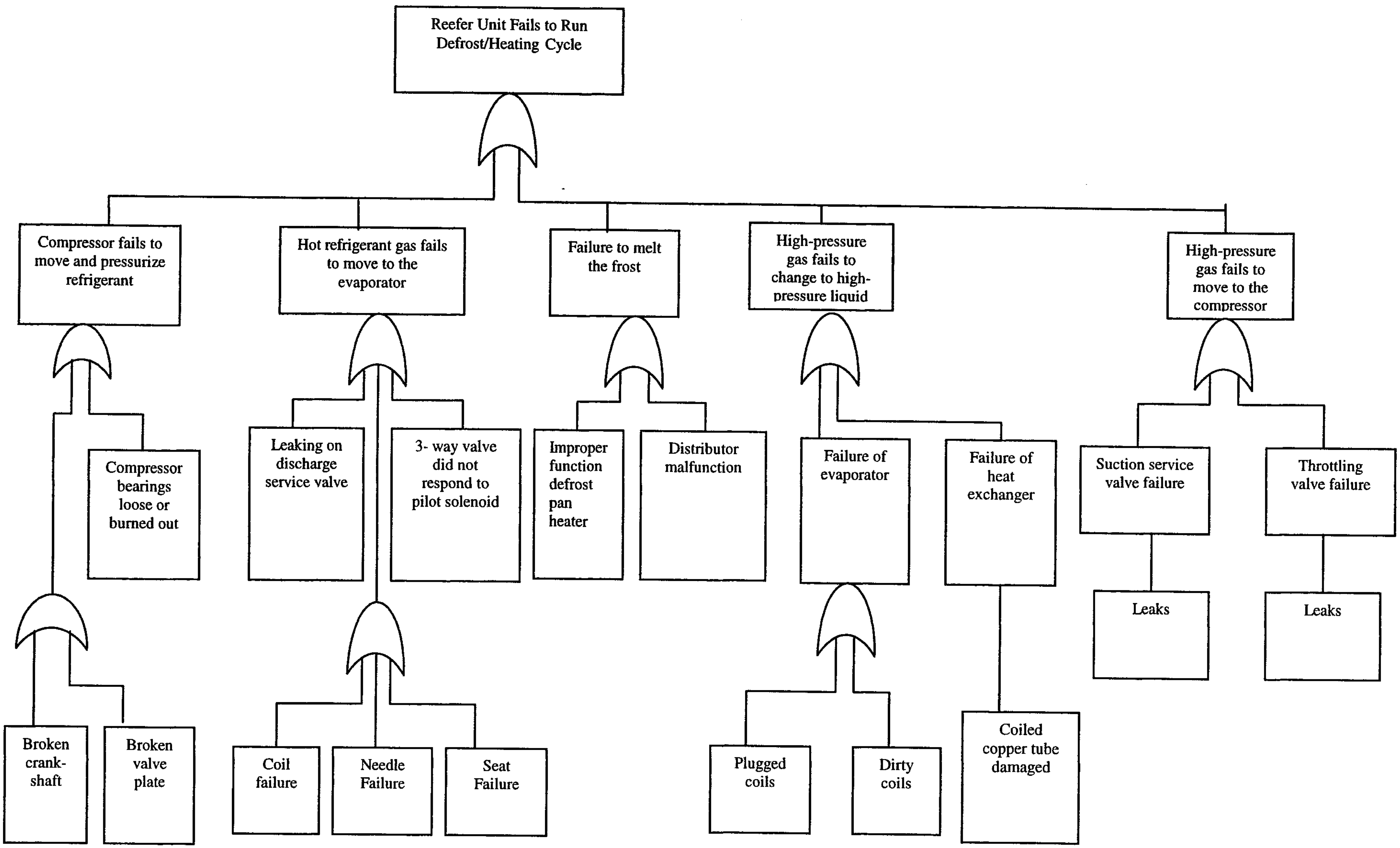

Table 2. 1990 Trailers Failure Data.

Year = 90
Total Trailers = 27

Failure Type	**Number of Failures**	**% of Trailer Failures**
Compressor	43	68%
Discharge Vibrasorber	5	8%
Suction Vibrasorber	9	14%
3-Way-Valve	2	3%
Pilot Solenoid	0	0%
Throttling Valve	1	2%
By-pass Check Valve	3	5%
Evaporator	0	0%
Expansion Valve	0	0%
Condenser	0	0%
Heat Exchanger	0	0%
Receiver Tank	0	0%
Accumulator	0	0%
Total Failures	**63**	100%

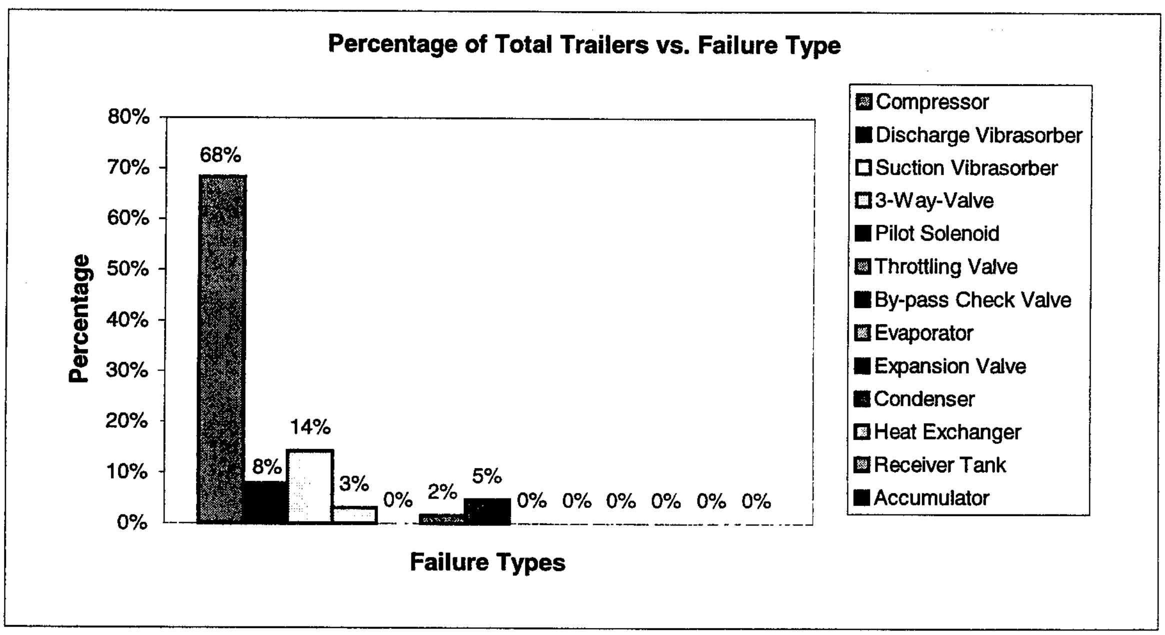

Figure 5. 1990 Trailers Pareto Analysis.

Table 3. 1991 Trailers Failure Data.

Year = 91
Total Trailers = 30

Failure Type	Number of Failure	% of Total Failures
Compressor	55	75%
Discharge Vibrasorber	7	10%
Suction Vibrasorber	3	4%
3-Way-Valve	2	3%
Pilot Solenoid	2	3%
Throttling Valve	0	0%
By-pass Check Valve	0	0%
Evaporator	0	0%
Expansion Valve	1	1%
Condenser	2	3%
Heat Exchanger	0	0%
Receiver Tank	1	1%
Accumulator	0	0%
Total Failures	**73**	100%

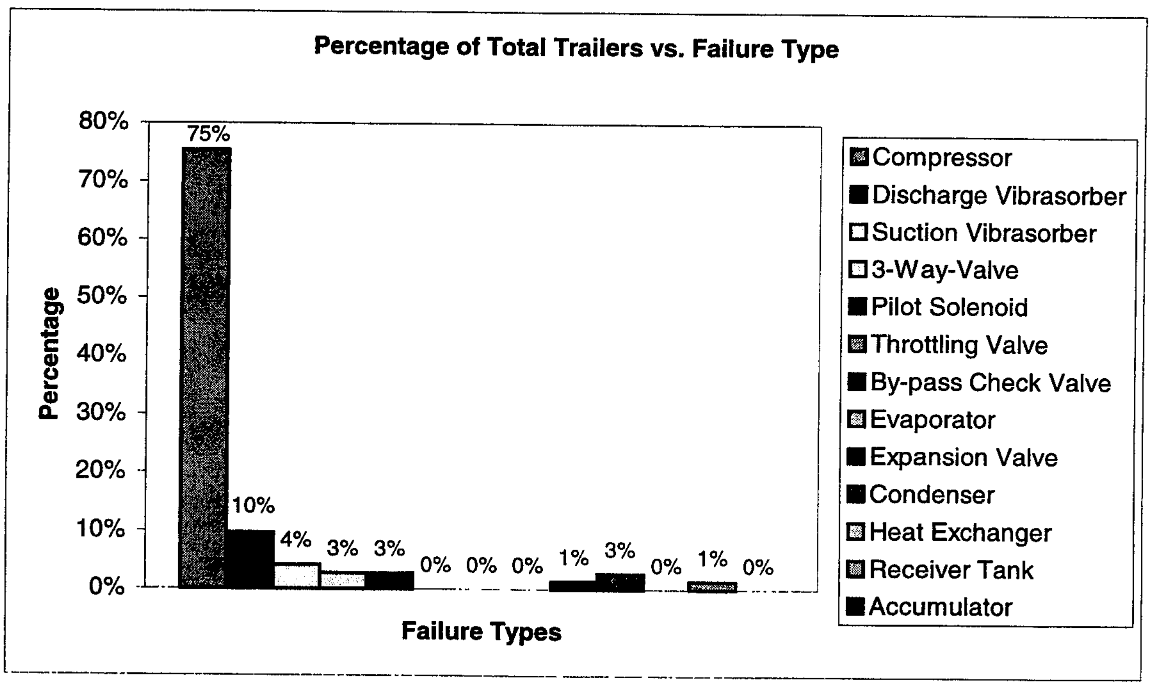

Figure 6. 1991 Trailers Pareto Analysis.

Table 4. 1992 Trailers Failure Data.

Year = 92
Total Trailers = 90

Failure Type	Number of Failure	% of Total Failures
Compressor	25	48%
Discharge Vibrasorber	10	19%
Suction Vibrasorber	4	8%
3-Way-Valve	1	2%
Pilot Solenoid	4	8%
Throttling Valve	2	4%
By-pass Check Valve	1	2%
Evaporator	1	2%
Expansion Valve	1	2%
Condenser	1	2%
Heat Exchanger	1	2%
Receiver Tank	0	0%
Accumulator	1	2%
Total Failures	**52**	100%

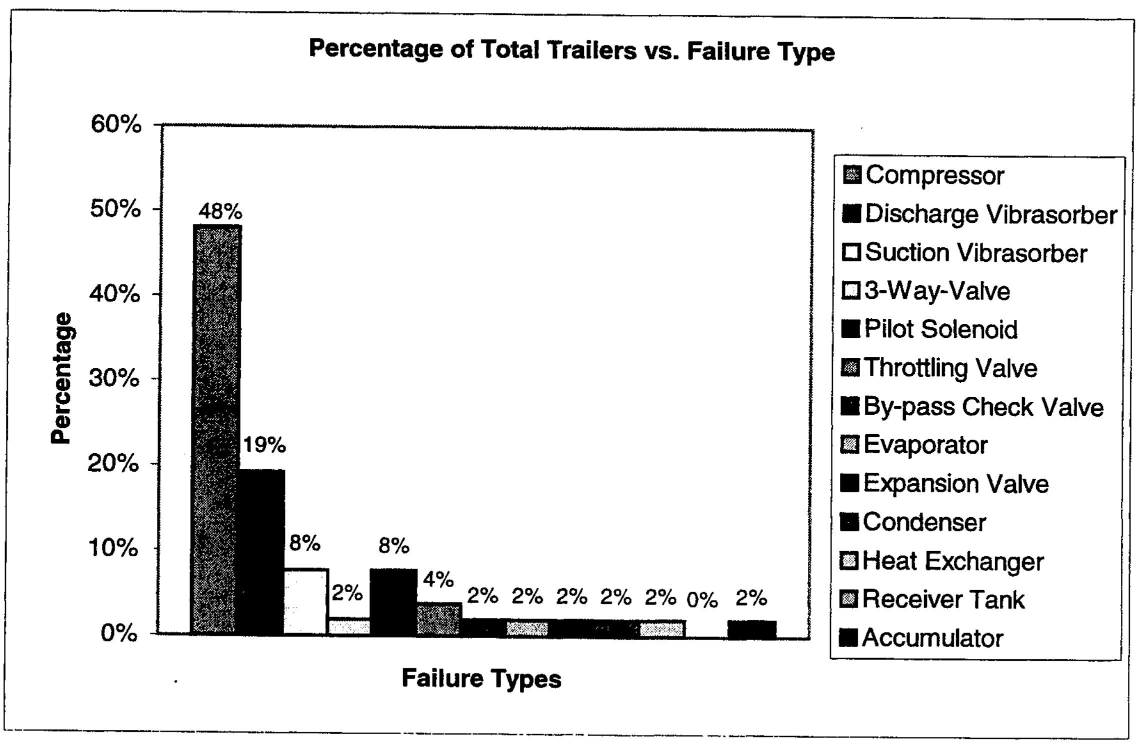

Figure 7. 1992 Trailers Pareto Analysis.

Table 5. 1993 Trailers Failure Data.

Year = 93
Total Trailers = 26

Failure Type	Number of Failure	% of Total Failures
Compressor	19	48%
Discharge Vibrasorber	11	28%
Suction Vibrasorber	2	5%
3-Way-Valve	3	8%
Pilot Solenoid	1	3%
Throttling Valve	0	0%
By-pass Check Valve	0	0%
Evaporator	0	0%
Expansion Valve	1	3%
Condenser	3	8%
Heat Exchanger	0	0%
Receiver Tank	0	0%
Accumulator	0	0%
Total Failures	**40**	100%

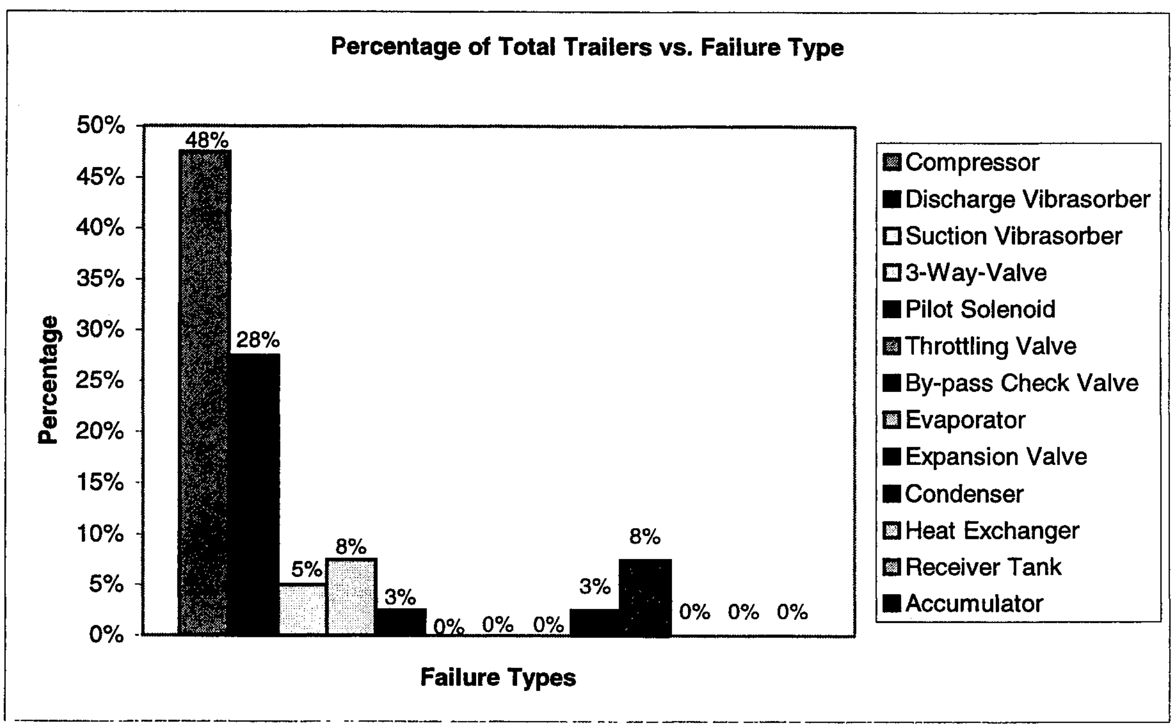

Figure 8. 1993 Trailers Pareto Analysis.

Table 6. 1994 Trailers Failure Data.

Year = 94
Total Trailers = 30

Failure Type	Number of Failure	% of Total Failures
Compressor	26	44%
Discharge Vibrasorber	19	32%
Suction Vibrasorber	9	15%
3-Way-Valve	0	0%
Pilot Solenoid	1	2%
Throttling Valve	2	3%
By-pass Check Valve	2	3%
Evaporator	0	0%
Expansion Valve	0	0%
Condenser	0	0%
Heat Exchanger	0	0%
Receiver Tank	0	0%
Accumulator	0	0%
Total Failures	**59**	100%

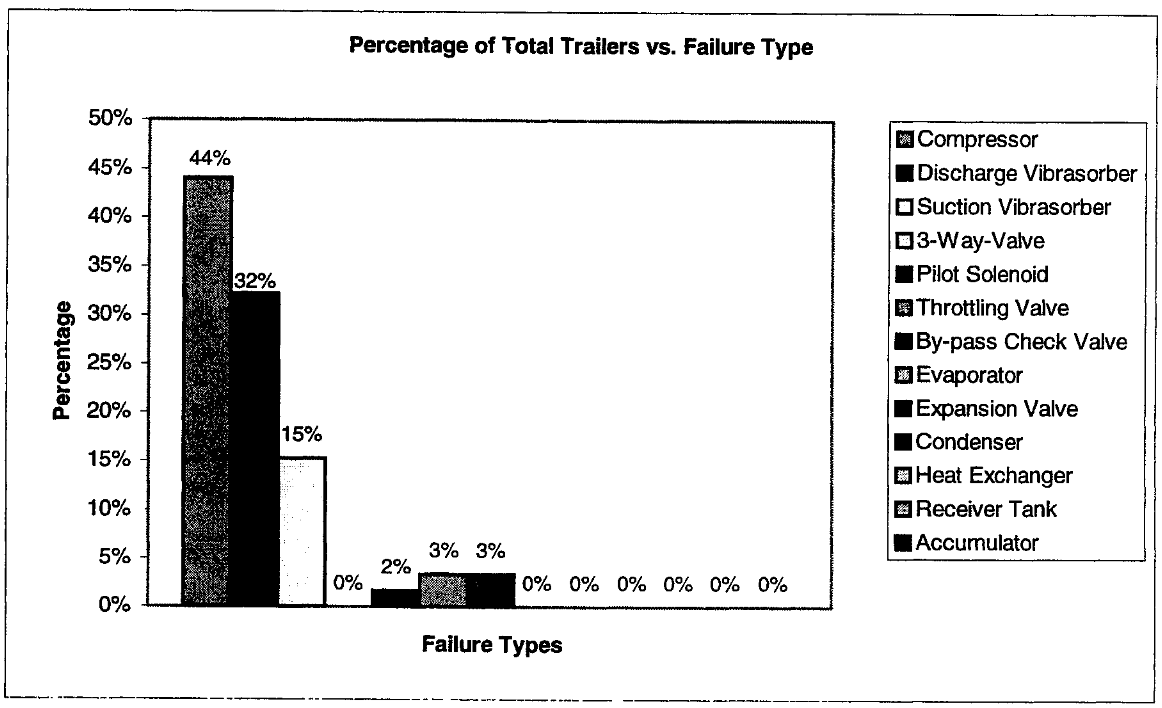

Figure 9. 1994 Trailers Pareto Analysis.

Table 7. 1995 Trailers Failure Data.

Year = 95
Total Trailers = 28

Failure Type	Number of Failure	% of Total Failures
Compressor	9	31%
Discharge Vibrasorber	5	17%
Suction Vibrasorber	2	7%
3-Way-Valve	5	17%
Pilot Solenoid	5	17%
Throttling Valve	0	0%
By-pass Check Valve	0	0%
Evaporator	0	0%
Expansion Valve	2	7%
Condenser	1	3%
Heat Exchanger	0	0%
Receiver Tank	0	0%
Accumulator	0	0%
Total Failures	**29**	100%

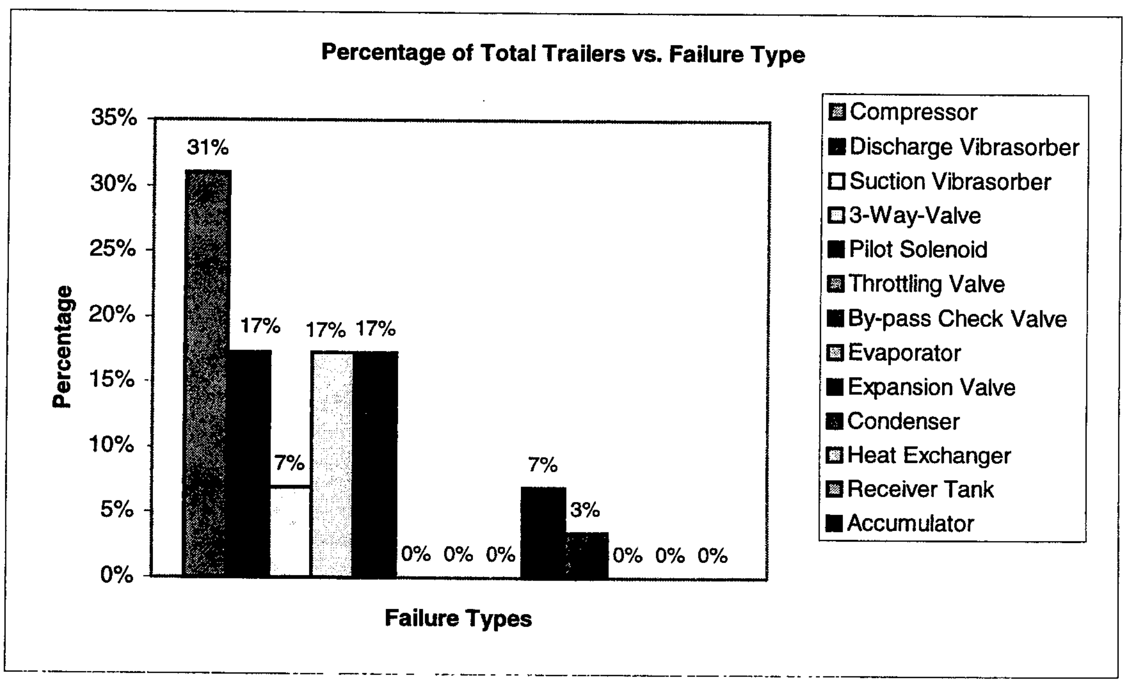

Figure 10. 1995 Trailers Pareto Analysis.

Reliability Analysis

The next step in the project was to characterize the gathered failure data into a useful form. *Reliability Analysis Software* (Elsayed, 1996) was used to generate both a best-fit probability distribution and the mean time between failures (MTBF) for each failure type. Due to the infrequent number of failures for failure types other than compressors, it was determined necessary to group them into two sets, "compressor" failures and the remaining "other" failures. Also, trailer fleet years 1990-1992 were considered "old" and trailers 1993-1995 considered "new". For each combination of old/new and compressor/other, an exponential distribution was used to model the time to failure. The following MTBFs were computed:

- Old compressor = 520 hours
- New compressor = 799 hours
- Old others = 1083 hours
- New others = 585 hours

Note that all failure data were based on calendar time, not system run time.

PHASE II: GENERALIZED SIMULATION MODEL

Simulation Model

A simulation model of inbound and outbound trailer movement at Tyson's Berryville facility was constructed using the simulation language *SIMNET II*. Trailers were categorized as either old or new. Failures were classified as either compressor failures or other. A key assumption in the model is that no trailer shortages occur. Testing of the simulation model indicated that a simulation run length of 7 years was appropriate for generating accurate results and 20 replications of the model provided adequate precision in performance estimates. The performance measures estimated from the output included: repair costs, delay costs, total costs (the sum of repair and delay costs), and the number of failures. A flowchart of the simulation code is shown in Figure 11.

Experimental Design

Having tested the simulation model, the next phase of the analysis was to determine the effect of certain factors on the performance of the distribution system under consideration. Five factors were chosen for consideration:

A: frequency of occurrence for delay

This value is a percentage which represents the probability that a failure results in substantial delay of a product shipment. These delays could result in charges to the trucking division (i.e., cost penalty). Input values for this factor range between 3-10%.

B: MTBF multiplier

This factor is used to adjust MTBF values. For example, if the estimated MTBF values are to be used, then this factor would have a value of 1. A value of less than 1 would correspond to a degradation in the failure rate of trailers. For example, a value of 0.25 would imply a MTBF 4 times greater than the estimated value.

C: repair time multiplier

This factor is used to adjust the time required to perform trailer repairs. Note that in this case, slower repair procedures would imply that this factor has a value of greater than 1. A value of 1.0 utilizes the projected repair times provided by Tyson Foods.

D: old trailer percentage

This factor designates the percentage of trailers in the system fleet that are categorized as old. Input values for this factor range between 25-75%.

E: delay time multiplier

This factor is used to adjust the amount of time consumed by substantial delays. A value of 1.0 will utilize the delay times provided by Tyson Foods.

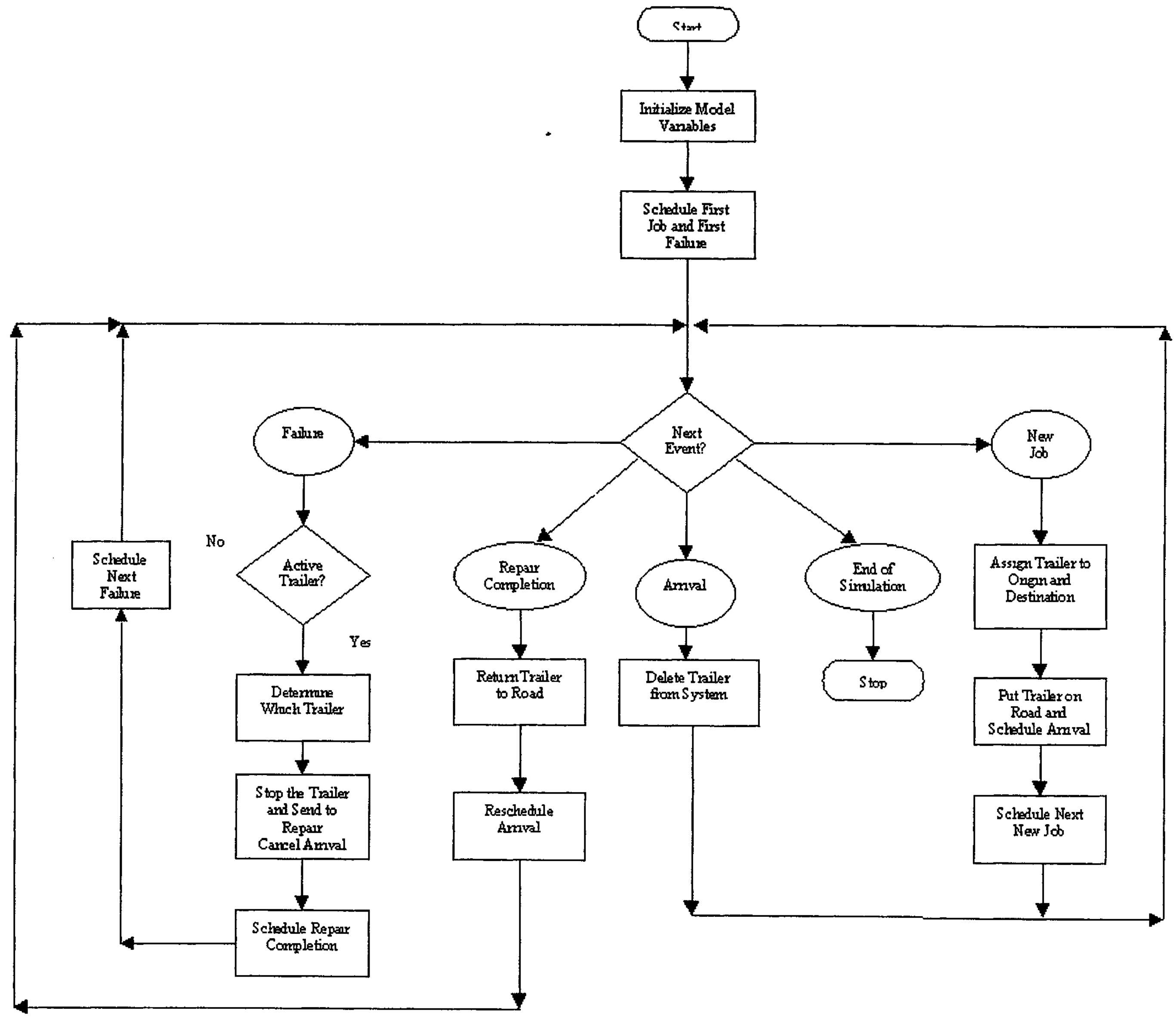

Figure 11. Flowchart showing simulation logic excluding data collection and output.

The objective of the experimental design and analysis was to determine which of these factors and which interactions between factors have a significant effect on the performance of the system. The experimental design used in this analysis was a 2^5 factorial design. Therefore, low and high values for each of the five factors were chosen for experimentation. These values are summarized in the table below.

Table 8. Summary of five factors.

FACTOR	Low Value (−1)	High Value (+1)
A: frequency of occurrence for delay	3%	10%
B: MTBF multiplier	1.0	0.25
C: repair time multiplier	1.0	4.0
D: old trailer percentage	25%	75%
E: delay time multiplier	1.0	4.0

Thirty-two (32) experiments were conducted by simulating the distribution system using each combination of the low and high values for the five factors. Each of the 32 experiments was replicated 20 times.

Results and Analysis

Primary results of the simulation experiments are captured in Tables 9-12. An analysis of variance (ANOVA) was performed to determine which effects and which interactions between factors have a statistically significant effect on the system performance measures. There are 31 potential main effects and interactive effects:

- 5 main effects (A, B, C, D and E)
- 10 two-way interactive effects (AB, AC, … , DE)
- 10 three way interactive effects (ABC, ABD, … , CDE)
- 5 four-way interactive effects (ABCD, ABCE, ABDE, ACDE, BCDE)
- 1 five-way interactive effects (ABCDE)

Note that to complete the ANOVA, some subset of these factors must be assumed to be insignificant. Results from each ANOVA and the models derived from each are described below. ANOVA and models for individual performance measures were also developed. Experimental results are shown in Tables 9-12 while Tables 13-16 contain the main and interactive effects that were found to be significant for each individual performance measure.

Repair Costs ANOVA

Factors assumed to be insignificant:

A: frequency of occurrence of delay
E: delay time multiplier
all interactive effects containing A and/or E

Factors found to be significant:

B: MTBF multiplier
C: repair time multiplier
D: old trailer percentage
BC, BD, CD, BCD

Model of 7-Year Total Repair Cost:

$$\begin{aligned}\text{Total Repair Cost} = {} & \$30521 + \$18444\, X_B + \$18327\, X_C - \$902\, X_D \\ & + \$11111\, X_B X_C - \$520\, X_B X_D - \$648\, X_C X_D \\ & - \$384\, X_B X_C X_D\end{aligned}$$

Note that:

$$X_B = 2\left(\frac{\text{MTBF multiplier} - 1}{-0.75}\right) - 1$$

$$X_C = 2\left(\frac{\text{repair time multiplier} - 1}{3}\right) - 1$$

$$X_D = 2\left(\frac{\text{old trailer percentage} - 25\%}{50\%}\right) - 1$$

The model is only valid for values of X_B, X_C and X_D between -1 and 1.

Delay Costs ANOVA

Factors assumed to be insignificant:

C: repair time multiplier
all interactive effects containing C

Factors found to be significant:

A: frequency of occurrence of delay
B: MTBF multiplier
AB

Model of 7-Year Total Delay Cost:

Total Delay Cost = \$6601 + \$3488 X_A + \$4080 X_B + \$2174 $X_A X_B$

Note that:

$$X_A = 2\left(\frac{\text{frequency of occurrence of delay} - 3\%}{7\%}\right) - 1$$

The model is only valid for values of X_A and X_B between −1 and 1.

Total Costs ANOVA

Factors assumed to be insignificant:

interactive effects not found to be significant during any portion of repair and delay cost analysis

Factors found to be significant:

A: frequency of occurrence of delay
B: MTBF multiplier
C: repair time multiplier
D: old trailer percentage
E: delay time multiplier
AB, BC, BD, BE, CD, BCD

Model of 7-Year Total Cost:

$$\begin{aligned}\text{Total Cost} = {} & \$37122 + \$3385\, X_A + \$22524\, X_B + \$18471\, X_C - \$917\, X_D - \$310\, X_E \\ & + \$2226\, X_A X_B + \$11201\, X_B X_C - \$569\, X_B X_D - \$445\, X_B X_E \\ & - \$819\, X_C X_D - \$617\, X_B X_C X_D\end{aligned}$$

Note that:

$$X_E = 2\left(\frac{\text{delay time multiplier} - 1}{3}\right) - 1$$

The model is only valid for values of X_A, X_B, X_C, XD and X_E between −1 and 1.

Number of Failures ANOVA

Factors assumed to be insignificant:

A: frequency of occurrence of delay
C: repair time multiplier
E: delay time multiplier
all interactive effects including one or more of A, C and E

Factors found to be significant:

B: MTBF multiplier

Model of 7-Year Total Number of Failures:

Total Number of Failures = 144 + 87 X_B

Note that the model is only valid for values of X_B between −1 and 1.

Analysis Tool

A spreadsheet was created which allows the user to input actual values for the five experimental factors. The spreadsheet then estimates each of the system performance measures using the models derived from the ANOVA. Figure 12 contains a screen capture of this spreadsheet.

Table 9. Repair cost simulation results.

	A	B	C	D	E	Repair Cost ($)				
Expt.	Fr_Occ	MTBF	Repair T.	Old T. %	Delay T.	Old Compressor	New Compressor	Old Other	New Other	Total
1	-1	-1	-1	-1	-1	635.10	1132.74	619.84	2572.67	4960.35
2	-1	-1	-1	-1	+1	605.55	1274.62	532.57	2701.31	5114.05
3	-1	-1	-1	+1	-1	1859.52	445.89	1338.06	792.72	4436.19
4	-1	-1	-1	+1	+1	2022.34	433.79	1743.35	905.08	5104.56
5	-1	-1	+1	-1	-1	2581.92	5255.77	2007.87	10344.67	20190.23
6	-1	-1	+1	-1	+1	2682.51	4850.36	2017.72	10711.34	20261.93
7	-1	-1	+1	+1	-1	7446.60	1628.77	5784.07	3837.62	18697.06
8	-1	-1	+1	+1	+1	7837.94	1643.22	5877.27	3730.91	19089.34
9	-1	+1	-1	-1	-1	2496.37	4928.48	2092.67	10577.67	20095.19
10	-1	+1	-1	-1	+1	2406.88	4839.28	1996.56	10541.43	19784.15
11	-1	+1	-1	+1	-1	7725.71	1715.95	6422.63	3584.83	19449.12
12	-1	+1	-1	+1	+1	7381.67	1721.19	6259.87	3498.80	18861.53
13	-1	+1	+1	-1	-1	10272.87	19959.09	8389.45	44494.64	83116.05
14	-1	+1	+1	-1	+1	10040.27	18952.67	8181.92	42695.33	79870.19
15	-1	+1	+1	+1	-1	30584.81	6698.69	24912.04	13820.53	76016.07
16	-1	+1	+1	+1	+1	30511.23	6200.88	24101.00	14132.11	74945.22
17	+1	-1	-1	-1	-1	598.79	1224.04	487.67	2668.16	4978.66
18	+1	-1	-1	-1	+1	635.38	1134.59	501.41	2590.58	4861.96
19	+1	-1	-1	+1	-1	1849.85	386.34	1476.91	779.94	4493.04
20	+1	-1	-1	+1	+1	2011.39	435.44	1500.26	992.75	4939.84
21	+1	-1	+1	-1	-1	2786.20	4822.56	1751.80	10110.52	19471.08
22	+1	-1	+1	-1	+1	2382.95	4853.81	1760.15	10836.68	19833.59
23	+1	-1	+1	+1	-1	7691.20	1575.68	5683.35	3649.59	18599.82
24	+1	-1	+1	+1	+1	7703.63	1438.93	6123.92	2930.75	18197.23
25	+1	+1	-1	-1	-1	2419.85	4906.69	1753.37	10911.87	19991.78
26	+1	+1	-1	-1	+1	2553.54	4776.63	2058.80	10413.24	19802.21
27	+1	+1	-1	+1	-1	7564.83	1742.98	6143.72	3780.25	19231.78
28	+1	+1	-1	+1	+1	7850.31	1639.78	6111.35	3399.96	19001.40
29	+1	+1	+1	-1	-1	9654.20	20257.04	8726.41	41876.44	80514.09
30	+1	+1	+1	-1	+1	10346.37	19420.24	7887.49	42276.97	79931.07
31	+1	+1	+1	+1	-1	30457.27	6293.08	25121.43	15168.73	77040.51
32	+1	+1	+1	+1	+1	30560.10	6508.15	24324.55	14402.29	75795.09

low (-1)	3%	1	1	25%	1
high (+1)	10%	0.25	4	75%	4

Table 10. Delay costs simulation results.

	A	B	C	D	E	Delay Cost ($)				
Expt.	Fr_Occ	MTBF	Repair T.	Old T. %	Delay T.	Old Compressor	New Compressor	Old Other	New Other	Total
1	-1	-1	-1	-1	-1	134.29	484.67	37.56	299.24	955.76
2	-1	-1	-1	-1	+1	276.39	314.76	88.14	505.30	1184.59
3	-1	-1	-1	+1	-1	623.11	128.71	96.32	169.90	1018.04
4	-1	-1	-1	+1	+1	528.15	148.30	466.87	163.57	1306.89
5	-1	-1	+1	-1	-1	213.84	303.39	42.15	525.75	1085.13
6	-1	-1	+1	-1	+1	231.16	394.70	97.10	503.75	1226.71
7	-1	-1	+1	+1	-1	658.25	87.46	437.07	209.16	1391.94
8	-1	-1	+1	+1	+1	754.16	102.71	382.08	249.84	1488.79
9	-1	+1	-1	-1	-1	655.56	1605.45	263.42	2229.79	4754.22
10	-1	+1	-1	-1	+1	1072.28	1200.99	200.16	2348.09	4821.52
11	-1	+1	-1	+1	-1	2668.43	630.26	1103.91	1141.43	5544.03
12	-1	+1	-1	+1	+1	2177.68	501.88	1318.24	493.14	4490.94
13	-1	+1	+1	-1	-1	654.50	2112.43	500.23	2748.39	6015.55
14	-1	+1	+1	-1	+1	761.41	1428.90	301.67	2436.77	4928.75
15	-1	+1	+1	+1	-1	2448.85	513.81	1225.75	739.77	4928.18
16	-1	+1	+1	+1	+1	2470.42	351.07	1122.72	718.38	4662.59
17	+1	-1	-1	-1	-1	672.41	1704.54	308.86	1481.93	4167.74
18	+1	-1	-1	-1	+1	520.42	1216.13	256.34	1680.89	3673.78
19	+1	-1	-1	+1	-1	2153.90	421.86	720.03	420.08	3715.87
20	+1	-1	-1	+1	+1	1610.07	678.43	893.45	525.45	3707.40
21	+1	-1	+1	-1	-1	575.06	963.54	180.41	1795.05	3514.06
22	+1	-1	+1	-1	+1	542.70	1307.29	468.24	1768.13	4086.36
23	+1	-1	+1	+1	-1	2156.17	639.38	790.09	445.37	4031.01
24	+1	-1	+1	+1	+1	1818.07	408.15	1038.17	513.31	3777.70
25	+1	+1	-1	-1	-1	2593.99	4215.48	1337.01	6881.49	15027.97
26	+1	+1	-1	-1	+1	3066.84	4695.91	1158.65	6895.06	15816.46
27	+1	+1	-1	+1	-1	8276.80	2024.32	3875.96	3420.07	17597.15
28	+1	+1	-1	+1	+1	7847.87	2103.12	3413.38	2150.69	15515.06
29	+1	+1	+1	-1	-1	3254.04	5882.26	1530.30	7058.00	17724.60
30	+1	+1	+1	-1	+1	2751.05	5419.31	1532.06	7162.09	16864.51
31	+1	+1	+1	+1	-1	7998.34	1584.41	4167.23	2409.52	16159.50
32	+1	+1	+1	+1	+1	8215.49	1635.84	3543.62	2642.06	16037.01

low (-1)	3%	1	1	25%	1
high (+1)	10%	0.25	4	75%	4

Table 11. Total costs simulation results.

	A	B	C	D	E	Total Cost ($)				
Expt.	Fr_Occ	MTBF	Repair T.	Old T. %	Delay T.	Old Compressor	New Compressor	Old Other	New Other	Total
1	-1	-1	-1	-1	-1	769.39	1617.41	657.40	2871.91	5916.11
2	-1	-1	-1	-1	+1	881.93	1589.39	620.71	3206.61	6298.64
3	-1	-1	-1	+1	-1	2482.62	574.60	1434.38	962.61	5454.21
4	-1	-1	-1	+1	+1	2550.50	582.08	2210.22	1068.65	6411.45
5	-1	-1	+1	-1	-1	2795.76	5559.16	2050.02	10870.42	21275.36
6	-1	-1	+1	-1	+1	2913.67	5245.06	2114.81	11215.09	21488.63
7	-1	-1	+1	+1	-1	8104.84	1716.23	6221.14	4046.79	20089.00
8	-1	-1	+1	+1	+1	8592.09	1745.93	6259.36	3980.75	20578.13
9	-1	+1	-1	-1	-1	3151.93	6533.92	2356.09	12807.46	24849.40
10	-1	+1	-1	-1	+1	3479.16	6040.27	2196.72	12889.53	24605.68
11	-1	+1	-1	+1	-1	10394.14	2346.21	7526.54	4726.54	24993.43
12	-1	+1	-1	+1	+1	9559.35	2223.06	7578.11	3991.94	23352.46
13	-1	+1	+1	-1	-1	10927.37	22071.53	8889.68	47243.03	89131.61
14	-1	+1	+1	-1	+1	10801.68	20381.57	8483.58	45132.09	84798.92
15	-1	+1	+1	+1	-1	33033.65	7212.49	26137.79	14560.29	80944.22
16	-1	+1	+1	+1	+1	32981.65	6551.95	25223.72	14850.49	79607.81
17	+1	-1	-1	-1	-1	1271.20	2928.58	796.53	4150.09	9146.40
18	+1	-1	-1	-1	+1	1155.80	2350.72	757.75	4271.47	8535.74
19	+1	-1	-1	+1	-1	4003.75	808.20	2196.93	1200.01	8208.89
20	+1	-1	-1	+1	+1	3621.46	1113.87	2393.71	1518.20	8647.24
21	+1	-1	+1	-1	-1	3361.26	5786.10	1932.21	11905.57	22985.14
22	+1	-1	+1	-1	+1	2925.65	6161.10	2228.39	12604.81	23919.95
23	+1	-1	+1	+1	-1	9847.37	2215.05	6473.44	4094.96	22630.82
24	+1	-1	+1	+1	+1	9521.70	1847.09	7162.09	3444.06	21974.94
25	+1	+1	-1	-1	-1	5013.85	9122.18	3090.38	17793.37	35019.78
26	+1	+1	-1	-1	+1	5620.38	9472.54	3217.45	17308.31	35618.68
27	+1	+1	-1	+1	-1	15841.63	3767.31	10019.68	7200.33	36828.95
28	+1	+1	-1	+1	+1	15698.17	3742.90	9524.73	5550.64	34516.44
29	+1	+1	+1	-1	-1	12908.25	26139.30	10256.72	48934.43	98238.70
30	+1	+1	+1	-1	+1	13097.42	24839.55	9419.55	49439.07	96795.59
31	+1	+1	+1	+1	-1	38455.61	7877.49	29288.67	17578.25	93200.02
32	+1	+1	+1	+1	+1	38775.59	8143.99	27868.17	17044.35	91832.10

low (-1)	3%	1	1	25%	1
high (+1)	10%	0.25	4	75%	4

Table 12. Number of failures simulation results.

	A	B	C	D	E	Number of Failures				
Expt.	Fr_Occ	MTBF	Repair T.	Old T. %	Delay T.	Old Compressor	New Compressor	Old Other	New Other	Total
1	-1	-1	-1	-1	-1	9.65	17.10	5.40	24.20	56.35
2	-1	-1	-1	-1	+1	9.15	19.40	4.75	25.50	58.80
3	-1	-1	-1	+1	-1	27.90	6.75	12.55	7.85	55.05
4	-1	-1	-1	+1	+1	30.55	6.50	15.30	8.45	60.80
5	-1	-1	+1	-1	-1	9.75	19.90	4.55	24.60	58.80
6	-1	-1	+1	-1	+1	10.15	18.35	4.40	25.25	58.15
7	-1	-1	+1	+1	-1	28.20	6.15	13.15	8.95	56.45
8	-1	-1	+1	+1	+1	29.65	6.20	13.85	8.75	58.45
9	-1	+1	-1	-1	-1	37.70	75.10	18.45	99.75	231.00
10	-1	+1	-1	-1	+1	36.70	73.30	18.30	100.05	228.35
11	-1	+1	-1	+1	-1	117.50	25.90	57.40	33.45	234.25
12	-1	+1	-1	+1	+1	111.65	26.20	55.95	33.75	227.55
13	-1	+1	+1	-1	-1	38.85	75.70	18.45	105.10	238.10
14	-1	+1	+1	-1	+1	38.10	71.80	18.00	101.15	229.05
15	-1	+1	+1	+1	-1	115.85	25.35	56.65	33.15	231.00
16	-1	+1	+1	+1	+1	115.75	23.60	54.35	33.65	227.35
17	+1	-1	-1	-1	-1	8.95	18.85	4.20	25.10	57.10
18	+1	-1	-1	-1	+1	9.65	16.95	4.35	24.60	55.55
19	+1	-1	-1	+1	-1	27.90	5.70	12.90	7.55	54.05
20	+1	-1	-1	+1	+1	30.20	6.60	13.40	8.80	59.00
21	+1	-1	+1	-1	-1	10.50	18.25	3.90	23.20	55.85
22	+1	-1	+1	-1	+1	9.05	18.45	4.40	25.30	57.20
23	+1	-1	+1	+1	-1	29.10	6.00	13.50	8.30	56.90
24	+1	-1	+1	+1	+1	29.20	5.50	13.45	7.10	55.25
25	+1	+1	-1	-1	-1	36.65	74.90	15.55	103.70	230.80
26	+1	+1	-1	-1	+1	38.80	72.25	17.95	98.20	227.20
27	+1	+1	-1	+1	-1	114.40	26.20	55.65	35.75	232.00
28	+1	+1	-1	+1	+1	119.35	25.25	54.90	32.15	231.65
29	+1	+1	+1	-1	-1	36.40	76.75	19.55	99.25	231.95
30	+1	+1	+1	-1	+1	39.15	73.70	17.75	100.15	230.75
31	+1	+1	+1	+1	-1	115.25	23.85	55.45	36.10	230.65
32	+1	+1	+1	+1	+1	115.70	24.60	54.85	33.80	228.95

low (-1)	3%	1	1	25%	1
high (+1)	10%	0.25	4	75%	4

Table 13. Repair cost ANOVA results.

Effect	Old Compressor	New Compressor	Old Other	New Other
B	significant	significant	significant	significant
C	significant	significant	significant	significant
D	significant	significant	significant	significant
BC	significant	significant	significant	significant
BD	significant	significant	significant	significant
BE	significant	significant	significant	significant
BCD	significant	significant	significant	significant

Table 14. Delay cost ANOVA results.

Effect	Old Compressor	New Compressor	Old Other	New Other
A	significant	significant	significant	significant
B	significant	significant	significant	significant
D	significant	significant	significant	significant
E				
AB	significant	significant	significant	significant
AD	significant	significant	significant	significant
AE				
BD	significant	significant	significant	significant
BE			significant	
DE				
ABD	significant	significant	significant	significant
ABE				
ADE				
BDE				
ABDE				

Table 15. Total cost ANOVA results.

Effect	Old Compressor	New Compressor	Old Other	New Other
A	significant	significant	significant	significant
B	significant	significant	significant	significant
C	significant	significant	significant	significant
D	significant	significant	significant	significant
E				
AB	significant	significant	significant	significant
AD	significant	significant	significant	significant
AE				
BC	significant	significant	significant	significant
BD	significant	significant	significant	significant
BE			significant	
CD	significant	significant	significant	significant
DE				
ABD	significant	significant	significant	
ABE	significant			
ADE				
BCD	significant	significant	significant	significant
BDE				
ABDE				

Table 16. Number of failures ANOVA results.

Effect	Old Compressor	New Compressor	Old Other	New Other
B	significant	significant	significant	significant
D	significant	significant	significant	significant
BD	significant	significant	significant	significant

Please Enter the Desired Factor Values

	-1 Min.	Actual	+1 Max.	(-1 , +1)	
Frequency of Occurrence for Delay	3%	**5.0%**	10%	-0.429	$= X_A$
Mean Time Between Failure	1.00	**0.75**	0.25	-0.333	$= X_B$
Repair Time	1.0	**2.0**	4.0	-0.333	$= X_C$
Old Trailer %	25%	**50%**	75%	0.000	$= X_D$
Delay Time	1.0	**2.0**	4.0	-0.333	$= X_E$

Estimated Total Repair Cost	$19,498
Old Compressor	$5,087
New Compressor	$3,261
Old Other	$4,057
New Other	$7,091

Estimated Total Cost	$23,622
Old Compressor	$6,426
New Compressor	$4,138
Old Other	$4,666
New Other	$8,311

Estimated Total Delay Cost	$4,056
Old Compressor	$1,350
New Compressor	$868
Old Other	$624
New Other	$1,204

Estimated Total Number of Failures	115
Old Compressor	38
New Compressor	25
Old Other	18
New Other	33

Figure 12. Screen shot of spreadsheet analysis tool with example input values.

Reference

Bowles, J.B. and Bonnell, R.D. (1998), "Failure Mode, Effects, and Criticality Analysis," *1998 Annual Reliability and Maintainability Symposium Tutorial Notes*, pp. Bowles 1-23, Anaheim, California, January 19-22.

Elsayed, A.E. (1996), *Reliability Engineering*, Addison Wesley Longman, Inc., Massachusetts, pp. 259-351.

Koren, J. and Childs, C. (1995), "Basic Fault Tree Analysis," *1995 Annual Reliability and Maintainability Symposium Tutorial Notes*, pp. Koren 1-8, Washington, DC, January 16-19.

Taha, H.A. (1992), "Introduction to Linear Programming," *Operation Research An Introduction*, 6th Edition, Prentice Hall, Upper Saddle River, New Jersey, pp 11-53.

Taha, H.A. (1992), *Simulation With SIMNET II*, SimTec, Inc., Fayetteville, AR 72701.

Taylor, G.D. and English, R.J., "A Flexible Simulation Framework for Electronics Assemble," *NEPCO West '97 Conference Paper*, Proceedings of NEPCON West '97, pp 1-10, Troy, New York, October 31, 1997.