xSeriCon

RAM Sample Study:
PK1000 Refrigerator System

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I. Executive Summary

A. Objective

This study evaluates the Reliability, Availability, and Maintainability (RAM) of the PK1000 Refrigerator System, a critical heat exchanger package centered on the RW cooler E-1000. The primary objectives were to predict system availability and quantify revenue losses to meet two specific targets: a minimum availability of 99.5% and annual revenue losses under USD 100,000.

B. Baseline Performance and Challenges

The baseline scenario (strategy 1), which assumes operation without any stocked spare parts, failed to meet all project objectives. Under this baseline:

- Availability: 95.42% (below the 99.5% target).
- Annual Lost Revenue: USD 803,316 (far exceeding the USD 100,000 limit).
- Primary Bottlenecks: The RW Cooler E-1000 was identified as the most significant contributor to downtime due to its 24-hour Mean Time To Restore (MTTR) and longest spares lead time, while the screw compressor is the primary driver of failures within the refrigerant control module

C. Strategic Optimization and Cost Advantages

To bridge the gap to the targets, five alternative strategies were simulated and evaluated through Cost-Benefit analysis based on Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). The strategies demonstrate that strategic spare parts stocking and targeted equipment upgrades yield substantial cost advantages:

- Strategy 3 (Top 10 contributors spares): Stocking critical spares exclusively for the top 10 bottleneck modules requires an initial investment of 66,450 USD. This single action dramatically drives full production availability up to 99.43% and slashes annual revenue losses to 99,231 USD/yr—successfully meeting the financial target with a rapid payback period of 1.1 months.

- Strategy 4 (Strategy 3 + Upgraded Screw Compressor): Building upon Strategy 3 by implementing a targeted capital upgrade to the compressor's internal components (rotor, bearings, slide valves, and sensors) raises CAPEX to 74,450 USD. This strategy successfully elevates Full Production availability to 99.79% and minimizes annual losses to 37,168 USD/yr with a highly favorable payback period of 1.2 months.
- The manpower deficit (Strategies 5 & 6): Attempts to reduce the MTTR of the RW Cooler from 24 to 12 hours by adding maintenance staff introduce an ongoing OPEX of 100,000 USD/yr. The simulation confirms that this recurring cost erodes the annual net benefit, extends the payback period, and offers no significant marginal benefit compared to component optimization.

D. Recommendations

Based on the integrated engineering simulation and financial analysis, a phased implementation plan is recommended to guarantee compliance with all system objectives:

1. Implement Strategy 3 immediately by establishing an on-site warehouse stock for the spare parts of the top 10 downtime contributors (including the RW cooler, oil filters, and pumps). This represents the most cost-effective initial boost to availability, moving the system out of the high-risk baseline zone.
2. Procure the upgraded component packages for the high-pressure propane screw compressor. This combined approach of critical spare stocking and engineering upgrades ensures the facility stabilizes at 99.79% availability, compresses annual losses to a minimum, and achieves full investment payback within 1.2 months.

II. Introduction

A. Background

The PK1000 Refrigerator is a critical heat exchanger system (RW cooler E-1000) designed to produce refrigerated water using high-pressure propane as a refrigerant. Ensuring its continuous operation is vital for processes in a target facility.

B. Objective

The primary objective of this study is to predict the system's availability, identify potential failure bottlenecks, and quantify expected revenue losses using a Monte Carlo simulation approach.

1. Target of availability: 99.5%
2. Expected revenue losses less than USD100,000/yr

C. Scope

The study covers the entire PK1000 package, including:

3. RW Cooler E-1000: exchanger E-1000, Level control loop (LT/LIC/LV 1000), and Pressure control loop (PT/PIC/PV 1000)
4. HP propane system: screw compressor, lube oil pump system and oil circulation System.

D. Terms and Abbreviations

Term	Definition
Availability	The degree to which a system is in a specified operable and committable state at the start of a mission or at a random point in time. It is the ratio of uptime to total time.
Reliability	The probability that a system will perform its intended function without failure for a specified period under stated conditions.
Redundancy	Backup components to ensure a system continues working if one part fails

Maintainability	The ease and speed with which a system can be restored to a functional state after a failure has occurred. Also, the ability to safely maintain an item of equipment while the remainder of the process is online.

Abbreviation	Definition
HP	High Pressure
LT	Level Transmitter
LIC	Level Indicating Controller
LV	Level control valve
MTTR	Mean Time To Restore
PFH	Probability of Failure per Hour
PT	Pressure Transmitter
PIC	Pressure Indicating Controller
PV	Pressure control valve
RAM	Reliability, Availability, Maintainability
RBD	Reliability Block Diagram
RW	Refrigerant Water

III. Methodology

A. Tool (xSeriCon RAM study)

The RAM study utilized xSeriCon's in-house software, a Python-based application that runs Monte Carlo simulations based on an Excel-imported Reliability Block Diagram (RBD) model. For this study, 100,000 iterations were executed to ensure statistical stability.

To perform a RAM study, the user first develops a Reliability Block Diagram (RBD) model of the system to be studied. Each block in the RBD defines one 'module' in the RAM app. The architecture of the model is defined in terms of the following objects:

1. Basic inputs
2. Modules, which have inputs, outputs, failure modes, and success conditions
3. Operating cases
4. Maintenance personnel data

5. Sensitivity analysis

Each of these is detailed below.

B. Basic inputs

Basic inputs are elements that are outside the scope of the model but required for the system to run. Typical examples are power supplies (e.g., 24VDC, 6000VAC), cooling water, instrument air, and a process control system. Typically, basic inputs affect many parts of the system and are therefore defined as inputs to multiple modules. Each basic input is defined by its name, probability of failure per hour (PFH), and mean time to restore (MTTR).

C. Modules

A module is a specific section of the overall system, containing no redundancy. Redundancy is achieved by having multiple modules providing data to a single combination module. A module should have credible failure modes which lead to operational upset. Each module is defined by its inputs (basic and process), failure modes, and success conditions for its outputs.

D. Failure modes

Each module can define numerous various failure modes, which are specific ways a module can fail, such as a "motor bearing failure" or "clogging". Each failure mode includes a name, PFH, MTTR, specific maintenance personnel requirements (discipline, headcount, and duration), and the spare parts required for repair.

E. Success conditions

Every module output must have a success condition that defines the criteria for that output to be available. This is determined by a logical combination of required basic inputs (all must be available), process inputs (using AND or OR logic), and failure modes (all must NOT have occurred). If all the requirements—basic inputs, process inputs, and failure modes—are met for a success condition, its output is successful and will be sent to other modules or operating cases.
If a success condition is not met, the tool calculates the outage time of the corresponding output. This is calculated as the maximum of:

1. The MTTR of any missing basic inputs, and

2. The outage time of process inputs. The outage time of each input is the same as the outage of the output (in another module) from which it flows. If the selected logic is ‘OR’, the overall outage time is the shortest of the outages of all process inputs (because only the quickest-to-repair input needs to come back online); if the logic is ‘AND’, it is the longest (because all inputs need to come back online); and

3. If any failure mode has failed: The maximum lead time of any required spares that are not kept in stock, plus the MTTR of the failure mode. (These times are summed because it is assumed the repair cannot start until all required spares are available.)

The model assumes sufficient repair personnel are available to repair all applicable failure modes simultaneously, i.e. all repairs can start immediately once spares are available. However, the model calculates the percentage of 1-hour time windows during which the personnel requirement exceeds personnel availability, and reports this.

F. Operating cases

These represent the various states of the whole plant, such as "Full Production", "Half Production". A case is considered successful if all the specified module outputs required for that state are available. Each case is assigned an hourly dollar value to calculate potential financial losses during downtime.

G. Maintenance personnel data

The model can define how many maintenance personnel are available for each discipline, such as electrical and mechanical. These personnel are assumed to be continuously available and dedicated to repairing failure modes that occur, i.e. not required for preventive maintenance tasks.
This information is used to calculate the fraction of time that the requirement for maintenance personnel exceeds the available personnel. In the calculation, each iteration of the simulation is considered in isolation; no repair work is carried over from one iteration to the next, even if it takes more than 1 hour. In other words, at the start of each hour, all personnel are assumed to be available.

H. Contribution Analysis

The primary objective of the contribution analysis is to identify the root causes of system downtime. By leveraging Monte Carlo simulation, xSeriCon's RAM application automatically calculates the downtime costs of each module and generates a pie chart showcasing the top 10 critical contributors impacting overall system revenue.

I. Sensitivity Analysis

The study includes a sensitivity analysis phase to assess how changes in specific parameter values impact the overall system performance. This process involves:

1. Parameters Tested: The analysis evaluates the effects of reducing the Failure Mode PFH or MTTR of critical components by a standard margin (typically 20%).
2. Utility Impact: Variations in the reliability of basic inputs, including different voltage power supplies (24VDC, 220VAC, 380VAC, 6000VAC) and utility systems like Instrument Air (IA) and Cooling Water, are also simulated to identify external dependencies.
3. Cost-benefit analysis: This methodology identifies improvements that require minimal incremental investment while delivering the maximum potential increase in availability and reduction in downtime costs.

J. Cost-Benefit Analysis

Achieving the availability target and minimizing revenue losses requires additional investment. The purpose of this cost-benefit analysis is to quantify the potential benefits and determine the payback period associated with each alternative strategy, thereby supporting informed investment decisions.

Investments are classified into Capital Expenditures (CAPEX) or Operational Expenditures (OPEX). CAPEX represents a one-time upfront cost, whereas OPEX reflects ongoing annual expenses, such as additional manpower. Within this framework, 'benefit' refers to the cost savings derived from a given strategy's revenue, net of both the baseline revenue and any incremental OPEX. Consequently, the 'payback period' is determined by dividing CAPEX by the annual benefit, illustrating the time required to achieve a full return on investment (ROI).

$$\mathrm{Benefit} = \mathrm{Revenue}_{\mathrm{Strategy\ X}} - \mathrm{Revenue}_{\mathrm{Baseline}} - \mathrm{OPEX}_{\mathrm{Additional}}, unit\ with\ USD/yr$$

$$\text{Payback Period (Months)} = \frac{\text{CAPEX (USD)}}{\text{Benefit (USD/yr)}} \times 12$$

IV. Process Description

This section describes the physical and logical configuration of the PK1000 refrigerator system, detailing how the various components interact to achieve the plant's production objectives.

A. Operating Cases

The simulation evaluates the system's performance across three primary operating cases, which represent the plant's production states:

1. Full Production: Represents the state where the RW cooler E-1000 successfully provides 100% of the required refrigerated water supply. The value per hour of Full Production is USD2,000.
2. Half Production: Represents a partial supply state (50%). This occurs when specific modules (such as the screw compressor or refrigerant control loops) experience degradation or partial failure but can still maintain half-capacity operation. The value per hour of Half Production is USD1,000.
3. Shutdown: A total interruption of refrigerated water supply caused by the failure of critical modules or required utility inputs.

The hourly dollar value for production is estimated based on the net margin lost if the PK1000 refrigerator system fails to provide adequate cooling to the facility.

B. Subsystem

The PK1000 Refrigerator is a complex heat exchanger system centered around the RW cooler E-1000. To achieve success, the cooler relies on several interconnected subsystems (Figure 1):

1. RW cooler E-1000 itself: failure of vessel could lead to interrupt of supply.
2. Refrigerant water circulation system: An external utility treated as a basic

input for the scope of this study.

3. Refrigerant control system: The core logical process, which is further divided into three critical functional areas (Figure 2),
   - HP propane discharge: Provides the necessary high-pressure refrigerant flow, compose of screw compressor, lube oil pump system, oil circulation system.
   - Level Control Loop (LT/LIC/LV 1000): Manages refrigerant levels in the cooler.
   - Pressure Control Loop (PT/PIC/PV 1000): Manages operating pressure.

   The Refrigerant Control system successfully 100% supplies the cooler only when all three functional areas are successful. If any subsystem provides only a partial supply, the overall refrigerant control enters a "partial supply" state.

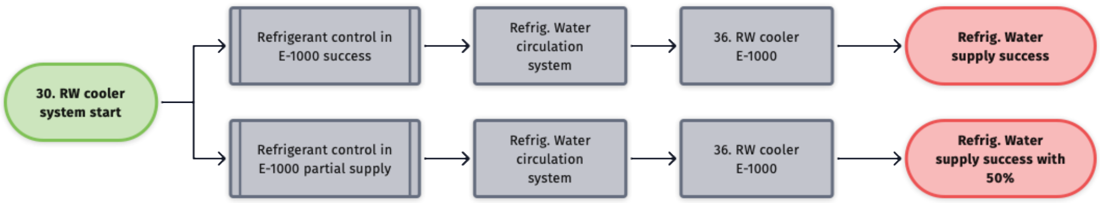


Figure 1 RBD of PK1000 refrigerant system

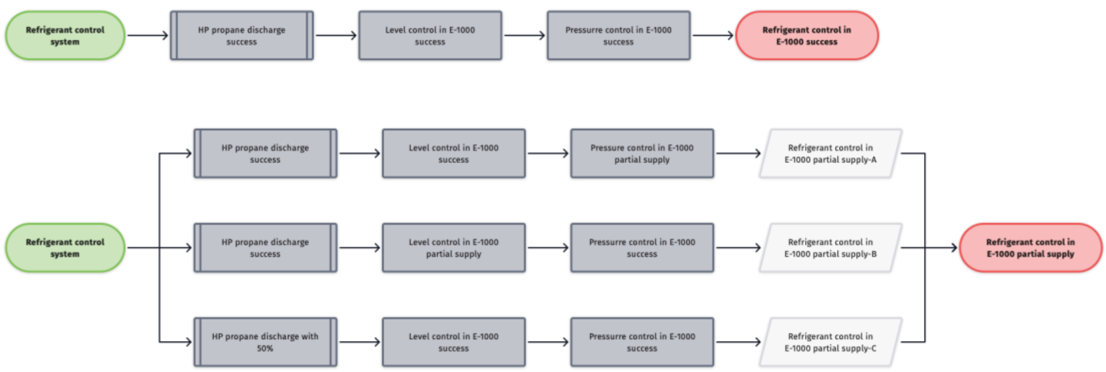


Figure 2 RBD of refrigerant control system

C. Modules, Basic Inputs, and Process Inputs/Outputs

Please see Appendix I Input Data Worksheet for more detail.

V. Results

A. Overall Review

Operation without any spare parts establishes the baseline performance (Strategy 1), under which full production availability is 95.42%, resulting in an annual lost revenue of 803,316 USD. To achieve the 99.5% availability target and reduce annual losses below 100,000 USD, five alternative strategies were evaluated through contribution (Appendix IV Contribution Analysis), sensitivity (Appendix V Sensitivity Analysis), and cost-benefit analyses.

Key findings from the strategy review are summarized below:

1. The simulation demonstrates that the lack of spare parts is the most significant contributor to production loss. Implementing Strategy 3 (stocking spares only for the top 10 contributors) significantly increases full production availability to 99.43%—nearly reaching the 99.5% target—with an additional cost of only 66,450 USD, yielding a 1.1-month payback period.
2. Both Strategy 2 (stock all spares) and Strategy 4 (upgrade the screw compressor based on Strategy 3) achieve the availability target and reduce annual lost revenue below 100,000 USD. Although Strategy 2 demonstrates the highest availability (99.82%) among all options, it also requires the highest investment (78,760 USD). In comparison, Strategy 4 is a more favorable option, offering a lower CAPEX (74,450 USD) with the equal payback period as Strategy 2 (1.2 month).

Additionally, the impact of reducing the MTTR of cooler E-1000 from 24 to 12 hours was analyzed in Strategy 5 (built on Strategy 3) and Strategy 6 (built on Strategy 4). While both strategies successfully meet the availability target, neither outperforms Strategy 4. Furthermore, considering the increased OPEX from additional manpower—which reduces the annual net benefit and extends the payback period—there is no significant marginal benefit to pursuing these options.

Table 1 Cost-Benefit Analysis

Input data			Results						
#	Strategy	Operating case	Revenue achieved (USD/yr)	Availability	Lost revenue (USD/yr)	CAPEX* (USD)	OPEX* (USD/yr)	Benefit (USD/yr)	Payback Period (Months)
1	Run without spare parts (Baseline)	Full production Half production	16,728,684 8,497,936	95.42% 96.94%	803,316 268,064	-	-	- -	-
2	Run with all spare parts	Full production Half production	17,499,916 8,752,413	99.82% 99.84%	32,084 13,587	78,760	-	771,232 254,477	1.2
3	Run with spare parts of top 10 contributors	Full production Half production	17,432,769 8,720,417	99.43% 99.48%	99,231 45,583	66,450	-	704,085 222,481	1.1
4	Strategy 3+ Upgraded screw compressor	Full production Half production	17,494,832 8,745,312	99.79% 99.76%	37,168 20,688	74,450	-	766,148 252,461	1.2
5	Strategy 3+ reduce MTTR of E-1000 to 12hrs	Full production Half production	17,459,418 8,732,514	99.59% 99.62%	72,582 33,486	66,450	100,000	630,734 134,578	1.3
6	Strategy 3+ Upgraded screw compressor AND reduce MTTR of E-1000 to 12hrs	Full production Half production	17,495,007 8,750,835	99.79% 99.83%	36,993 15,165	74,450	100,000	666,323 152,899	1.3

Note*: additional investment is described in Appendix VI Additional Investment of Strategies

B. Recommendations

Based on the simulation results and cost-benefit analysis, the following recommendations are provided to ensure the PK1000 refrigerator system meets its availability (99.5%) and financial (<$100,000 loss/yr) targets:

1. As an immediate first step, the facility should implement Strategy 3 by stocking spares for the top 10 bottlenecks (e.g., RW Cooler, filters, and pumps). This provides the most significant initial boost in availability, elevating the system from a baseline of 95.42% to 99.43%.2.
2. Investing in and upgrading critical components of the screw compressor (e.g., rotor, bearings, and slide valve) will achieve 99.79% availability and keep annual revenue losses at $37,168. This approach not only successfully meets all project objectives but also demonstrates a favorable 1.2-month payback period.

Appendix I Input Data Worksheet

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
1	Motor MP-1622A		Winding/Insulation Fail	1.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor Stress Cone, No, 250, 5		Power 380VAC	Motor MP-1622A success	Power 380VAC, local control system	AND	1.1, 1.2, 1.3	4	8	Electrical, 1, 8	No
			Bearing failure	1.2		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor bearing, No, 300, 5		local control system								
			Electrical fault	1.3		2.28E-05	2	Electrical, 1, 2 Mechanical, 1, 2	Motor Terminal Board, No, 150,1 Motor CT, No, 450, 1										
2	Lube oil pump P-1622A		shaft seal leakage	2.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump mechanical seal, No, 800, 3 lube oil pump Packing, No, 100, 1	Motor MP-1622A success	Power 380VAC	Lube oil pump P-1622A success	Motor MP-1622A success, Power 380VAC, local control system, IA supply, cooling water supply	AND	2.1, 2.2, 2.3	4	8	Electrical, 1, 8	No
			coupling failure	2.2		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	lube oil pump Flexible Inserts, No, 60, 5		local control system								
			bearing lock	2.3		2.28E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump bearing, No, 120, 5		IA supply								
											cooling water supply								
3	Motor MP-1622B		Winding/Insulation Fail	3.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor Stress Cone, No, 250, 5		Power 380VAC	Motor MP-1622B success	Power 380VAC, local control system	AND	3.1, 3.2, 3.3	4	8	Electrical, 1, 8	No
			Bearing failure	3.2		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor bearing, No, 300, 5		local control system								
			Electrical fault	3.3		2.28E-05	2	Electrical, 1, 2 Mechanical, 1, 2	Motor Terminal Board, No, 150,1 Motor CT, No, 450, 1										
4	Lube oil pump P-1622B		shaft seal leakage	4.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump mechanical seal, No, 800, 3 lube oil pump Packing, No, 100, 1	Motor MP-1622B success	Power 380VAC	Lube oil pump P-1622B success	Motor MP-1622B success, Power 380VAC, local control system, IA	AND	4.1, 4.2, 4.3	4	8	Electrical, 1, 8	No

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
													supply, cooling water supply						
			coupling failure	4.2		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	lube oil pump Flexible Inserts, No, 60, 5		local control system								
			bearing lock	4.3		2.28E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump bearing, No, 120, 5		IA supply								
											cooling water supply								
	lube oil system									Lube oil pump P-1622A success	Power 380VAC	lube oil system success	Lube oil pump P-1622A success, Lube oil pump P-1622B success	OR		4	8	Electrical, 1, 8	No
										Lube oil pump P-1622B success									
10	oil filter F-6162A		clogging	10.1		2.28E-04	1	Mechanical, 1, 1	Filters Cartridges, No, 150, 1		nothing	oil filter F-6162A success	nothing	AND	10.1, 10.2	0.5	1	Electrical, 1, 1	No
			Housing/Seal Leakage	10.2		2.28E-04	2	Mechanical, 1, 2	O-ring, No, 10, 0.5										
11	oil filter F-6162B		clogging	11.1		2.28E-04	1	Mechanical, 1, 1	Filters Cartridges, No, 150, 1		nothing	oil filter F-6162B success	nothing	AND	11.1, 11.2	0.5	1	Electrical, 1, 1	No
			Housing/Seal Leakage	11.2		2.28E-04	2	Mechanical, 1, 2	O-ring, No, 10, 0.5										
	LP filtered oil									oil filter F-6162A success	nothing	LP filtered oil success	oil filter F-6162A success, oil filter F-6162B success	OR		0.5	1	Electrical, 1, 1	No
										oil filter F-6162B success									
12	Motor MP-1621A		Winding/Insulation Fail	12.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor Stress Cone, No, 250, 5	LP filtered oil success	Power 380VAC	Motor MP-1621A success	LP filtered oil success, Power	AND	12.1, 12.2, 12.3	0.5	1	Electrical, 1, 1	No

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
													380VAC, local control system						
			Bearing failure	12.2		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor bearing, No, 300, 5		local control system								
			Electrical fault	12.3		2.28E-05	2	Electrical, 1, 2 Mechanical, 1, 2	Motor Terminal Board, No, 150,1 Motor CT, No, 450, 1										
13	oil pump P-1621A		shaft seal leakage	13.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump mechanical seal, No, 800, 3 lube oil pump Packing, No, 100, 1	Motor MP-1621A success	Power 380VAC	oil pump P-1621A success	Motor MP-1621A success, Power 380VAC, local control system, IA supply, cooling water supply	AND	13.1, 13.2, 13.3	4	8	Electrical, 1, 8	No
			coupling failure	13.2		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	lube oil pump Flexible Inserts, No, 60, 5		local control system								
			bearing lock	13.3		2.28E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump bearing, No, 120, 5		IA supply								
											cooling water supply								
14	Motor MP-1621B		Winding/Insulation Fail	14.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor Stress Cone, No, 250, 5	LP filtered oil success	Power 380VAC	Motor MP-1621B success	LP filtered oil success, Power 380VAC, local control system	AND	14.1, 14.2, 14.3	4	8	Electrical, 1, 8	No
			Bearing failure	14.2		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor bearing, No, 300, 5		local control system								
			Electrical fault	14.3		2.28E-05	2	Electrical, 1, 2 Mechanical, 1, 2	Motor Terminal Board, No, 150,1 Motor CT, No, 450, 1										
15	oil pump P-1621B		shaft seal leakage	15.1		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump mechanical seal, No, 800, 3	Motor MP-1621B success	Power 380VAC	oil pump P-1621B success	Motor MP-1621B success, Power 380VAC, local	AND	15.1, 15.2, 15.3	4	8	Electrical, 1, 8	No

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
									lube oil pump Packing, No, 100, 1				control system, IA supply, cooling water supply						
			coupling failure	15.2		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	lube oil pump Flexible Inserts, No, 60, 5		local control system								
			bearing lock	15.3		2.28E-05	4	Electrical, 1, 4 Mechanical, 1, 4	lube oil pump bearing, No, 120, 5		IA supply								
											cooling water supply								
	HP oil									oil pump P-1621A success	Power 380VAC	HP oil discharge	oil pump P-1621A success, oil pump P-1621B success	OR		4	8	Electrical, 1, 8	No
										oil pump P-1621B success									
16	oil filter F-6163A		clogging	16.1		2.28E-04	1	Mechanical, 1, 1	Filters Cartridges, No, 150, 1	HP oil discharge	nothing	oil filter F-6163A success	HP oil discharge	AND	16.1, 16.2	0.5	1	Electrical, 1, 1	No
			Housing/Seal Leakage	16.2		2.28E-04	2	Mechanical, 1, 2	O-ring, No, 10, 0.5										
17	oil filter F-6163B		clogging	17.1		2.28E-04	1	Mechanical, 1, 1	Filters Cartridges, No, 150, 1	HP oil discharge	nothing	oil filter F-6163B success	HP oil discharge	AND	17.1, 17.2	0.5	1	Electrical, 1, 1	No
			Housing/Seal Leakage	17.2		2.28E-04	2	Mechanical, 1, 2	O-ring, No, 10, 0.5										
	HP filtered oil									oil filter F-6163A success	nothing	HP filtered oil success	oil filter F-6163A success, oil filter F-6163B success	OR		0.5	1	Electrical, 1, 1	No
										oil filter F-6163B success									
20	Motor MC-1621		Winding/Insulation Fail	20.1		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	Motor 6kV Stress Cone, No, 1200, 5		Power 6000VAC	Motor MC-1621 success	Power 6000VAC, local control system	AND	20.1, 20.2, 20.3	1	8	Electrical, 1, 8	No
			Bearing failure	20.2		1.43E-05	8	Electrical, 1, 8 Mechanical, 1, 8	Motor 6kV bearing, No, 3000, 5		local control system								

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
			Electrical fault	20.3		2.28E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Motor 6kV Terminal Board, No, 900,1 Motor CT, No, 450, 1										
21	screw compressor C-1621		seal failure	21.1		2.28E-05	8	Electrical, 1, 8 Mechanical, 1, 8	screw compressor Mechanical Seal Assembly, No, 2500, 5 O-ring kit, No, 250, 3	Motor MC-1621 success	Power 6000VAC	HP propane discharge	Motor MC-1621 success, lube oil system success,HP filtered oil success, Power 6000VAC, local control system, IA supply, cooling water supply	AND	21.1, 21.2, 21.3, 21.4, 21.5, 21.6	1	12	Electrical, 1, 12	No
			Bearing failure	21.2		1.14E-05	8	Electrical, 1, 8 Mechanical, 1, 8	screw compressor Thrust Bearings, No, 3500, 5 screw compressor Radial Bearings, No, 2800, 5	lube oil system success	local control system	HP propane discharge with 50%	Motor MC-1621 success, lube oil system success,HP filtered oil success, Power 6000VAC, local control system, IA supply, cooling water supply	AND	21.1, 21.2, 21.3, 21.4, 21.5				
			slide valve broken	21.3		1.14E-05	4	Electrical, 1, 4 Mechanical, 1, 4	Slide Valve Repair Kit, No, 2000, 5 Solenoid Valves, No, 400, 3	HP filtered oil success	IA supply								
			rotor broken	21.4		2.28E-05	8	Electrical, 1, 8 Mechanical, 1, 8	rotor, No, 25000, 1		cooling water supply								
			vibration/sensor faiulure	21.5		3.81E-05	2	Electrical, 1, 2 Mechanical, 1, 2	Vibration Probes, No, 500, 1 sensors, No, 300, 1										
			Degradation with lower pressure/flow	21.6		1.14E-04	2	Electrical, 1, 2 Mechanical, 1, 2	O-ring kit, No, 250, 3										

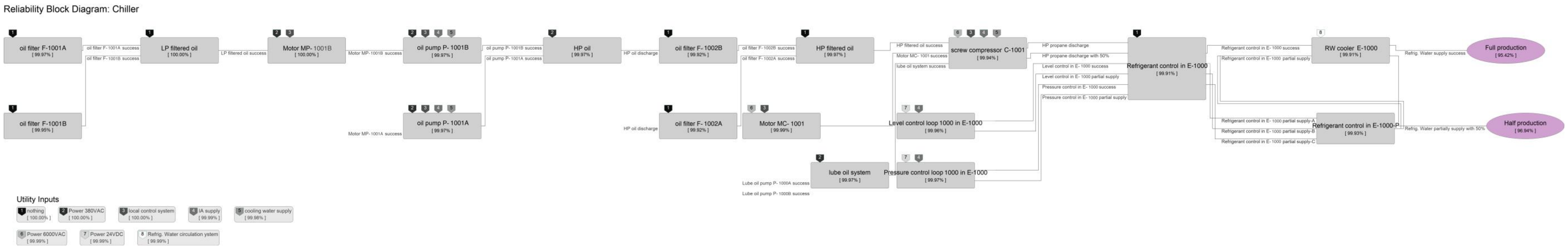
Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
30	Level control loop 6164 in E-1622		LT 6164 failure	30.1		1.14E-05	2	Electrical, 1, 2 Mechanical, 1, 2	level transmitter, No, 2200,1		Power 24VDC	Level control in E-1622 success	Power 24VDC, IA supply	AND	30.1, 30.2, 30.3, 30.4	3	2	Electrical, 1, 2	No
			LIC 6164 failure	30.2		5.71E-06	2	Electrical, 1, 2 Mechanical, 1, 2	AI/AO card, No, 1500, 1		IA supply	Level control in E-1622 partial supply	Power 24VDC, IA supply	AND	30.1, 30.2, 30.3				
			LV 6164 failure	30.3		1.14E-05	3	Electrical, 1, 2 Mechanical, 1, 3	LCV repair kit, No, 800, 5										
			signal shift	30.4		3.81E-05	2	Electrical, 1, 2 Mechanical, 0, 0	level transmitter, No, 2200,1 AI/AO card, No, 1500, 1 LCV repair kit, No, 800, 5										
31	Pressure control loop 6193 in E-1622		PT 6193 failure	31.1		1.14E-05	2	Electrical, 1, 2 Mechanical, 1, 2	pressure transmitter, No, 1200,1		Power 24VDC	Pressure control in E-1622 success	Power 24VDC, IA supply	AND	31.1, 31.2, 31.3, 31.4	3	2	Electrical, 1, 2	No
			PIC 6193 failure	31.2		5.71E-06	2	Electrical, 1, 2 Mechanical, 1, 2	AI/AO card, No, 1500, 1		IA supply	Pressure control in E-1622 partial supply	Power 24VDC, IA supply	AND	31.1, 31.2, 31.3				
			PV6193 failure	31.3		1.14E-05	3	Electrical, 1, 2 Mechanical, 1, 3	PCV repair kit, No, 800, 5										
			signal shift	31.4		3.81E-05	2	Electrical, 1, 2 Mechanical, 0, 0	pressure transmitter, No, 1200,1 AI/AO card, No, 1500, 1 PCV repair kit, No, 800, 5										
	Refrigerant control in E-1622									Level control in E-1622 success	nothing	Refrigerant control in E-1622 success	HP propane discharge, Level control in E-1622 success, Pressure control in E-1622 success	AND		3	2	Electrical, 1, 2	No

Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
										Pressure control in E-1622 success		Refrigerant control in E-1622 partial supply-A	HP propane discharge, Level control in E-1622 success, Pressure control in E-1622 partial supply	AND					
										Level control in E-1622 partial supply		Refrigerant control in E-1622 partial supply-B	HP propane discharge, Pressure control in E-1622 success, Level control in E-1622 partial supply	AND					
										Pressure control in E-1622 partial supply		Refrigerant control in E-1622 partial supply-C	Level control in E-1622 success, Pressure control in E-1622 success, HP propane discharge with 50%	AND					
										HP propane discharge									
										HP propane discharge with 50%									
	Refrigerant control in E-1622-P									Refrigerant control in E-1622 partial supply-A		Refrigerant control in E-1622 partial supply	Refrigerant control in E-1622 partial supply-A, Refrigerant control in E-1622 partial supply-B, Refrigerant control in E-1622 partial supply-C	OR		3	2	Electrical, 1, 2	No

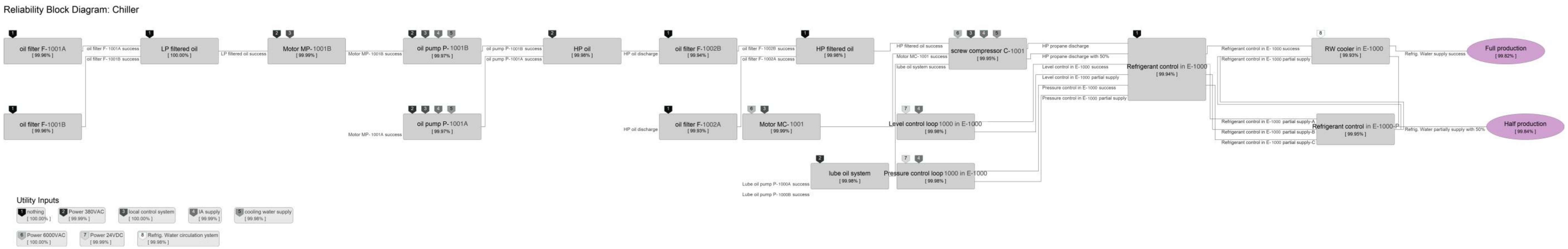
Module number	Module name	Module description	Failure mode name	Failure mode number	Failure mode description	Failure mode PFH	Failure mode MTTR (hr)	Failure mode personnel: discipline, headcount, duration (hr)	Failure mode spares: name, in stock, cost, leadtime (days)	Input (process)	basic inputs	Output	Success: Inputs	Success: input logic	success: failure modes	PM interval (years)	PM duration (hours)	PM personnel: discipline, headcount, duration (hr)	PM only during shutdown
										Refrigerant control in E-1622 partial supply-B									
										Refrigerant control in E-1622 partial supply-C									
36	RW cooler E-1622		tube/shell leakage	36.1		4.57E-06	24	Electrical, 1, 12 Mechanical, 2, 24	Flange, No, 150, 5 tube, No, 10000, 30	Refrigerant control in E-1622 success	Refrig. Water circulation ystem	Refrig. Water supply success	Refrigerant control in E-1622 success, Refrig. Water circulation ystem	AND	36.1	5	8	Electrical, 1, 8	No
										Refrigerant control in E-1622 partial supply		Refrig. Water partially supply with 50%	Refrigerant control in E-1622 partial supply, Refrig. Water circulation ystem	AND	36.1				

Appendix II Reliability Block Diagram

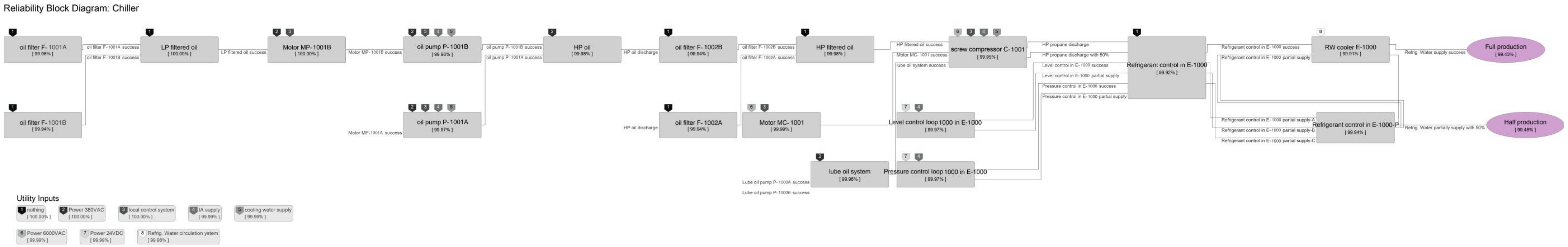
Reliability Block Diagram of strategy 1



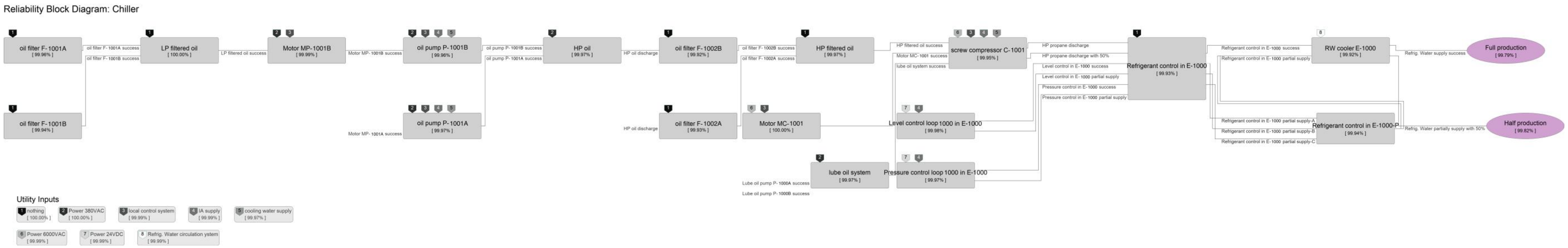
Reliability Block Diagram of strategy 2



Reliability Block Diagram of strategy 3



Reliability Block Diagram of strategy 4



Appendix III Cost of Downtime

PROCESS MODULES					
#	Name	Description	Availability	Time to repair (hr)[1]	Cost of downtime (USD/yr)
1	Motor MP-1000A	Lube oil pump motor	99.99%	4	1,403
2	Lube oil pump P-1000A	Lube oil pump	99.96%	8	6,312
3	Motor MP-1000B	Lube oil pump motor	99.99%	4	1,227
4	Lube oil pump P-1000B	Lube oil pump	99.96%	8	6,487
5	lube oil system	Discharge lube oil	99.97%	0	4,558
6	oil filter F-1001A	Oil filter, φ0.37X1.5 m	99.97%	2	5,260
7	oil filter F-1001B	Oil filter, φ0.37X1.5 m	99.95%	2	8,941
8	LP filtered oil	Suction oil of oil pump	100.00%	0	0
9	Motor MP-1001A	Oil pump motor	99.99%	4	1,052
10	oil pump P-1001A	Oil pump	99.97%	8	5,961
11	Motor MP-1001B	Oil pump motor	100.00%	4	877
12	oil pump P-1001B	Oil pump	99.97%	8	5,961
13	HP oil	Discharge oil of oil pump	99.97%	0	4,558
14	oil filter F-1002A	Oil filter, φ0.37X1.5 m	99.92%	2	14,727
15	oil filter F-1002B	Oil filter, φ0.37X1.5 m	99.92%	2	14,376
16	HP filtered oil	Discharge oil after filters	99.97%	0	4,734
17	Motor MC-1001	Refrigerator compressor motor	99.99%	8	1,403
18	screw compressor C-1001	High pressure propane screw compressor	99.94%	8	10,519
19	Level control loop 1000 in E-1000	Level control of RW cooler E-1000	99.96%	3	6,312
20	Pressure control loop 1000 in E-1000	Pressure control of RW cooler E-1000	99.97%	3	5,610
21	Refrigerant control in E-1000	Define refrigerant control in E-1000 is successful, partial supply or failure	99.91%	0	15,253
22	Refrigerant control in E-1000-P	Define refrigerant control in E-1000 is partial supply by	99.93%	0	6,049

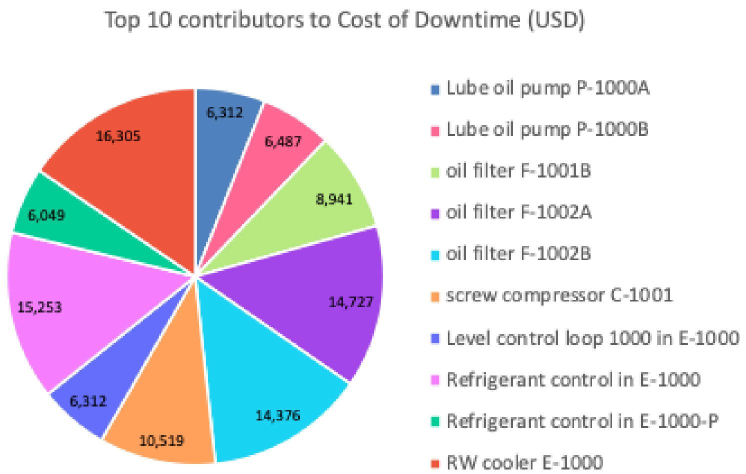
PROCESS MODULES					
#	Name	Description	Availability	Time to repair (hr)[1]	Cost of downtime (USD/yr)
		OR gate identification from module #21			
23	RW cooler E-1000	Identify the final status of refrigerator system	99.91%	24	16,305
Notes:					
1	The longest time to restore a fault, considering lead time of unstocked spare parts				

Appendix IV Contribution Analysis

Contribution analysis

Contribution analysis was simulated under strategy 1. We calculated cost of downtime of each module (Appendix III Cost of Downtime) and listed top 10 contributors in **Error! Reference source not found.**.

- RW Cooler E-1000 is identified as the most significant contributor to downtime. Despite its low failure rate (PFH), its 24-hour MTTR and longest lead time of spares results in the highest financial impact.
- Another significant impact on downtime is driven by the refrigerant control module, which is composed of a level control loop, a pressure control loop, and a screw compressor. Within this module, the screw compressor is the primary component impacting its availability (see Appendix III).
- The rest of top 10 contributors are oil filters and oil pumps with redundancy. While these components need higher maintenance frequency, they have a lower impact on system availability compared to the screw compressor.

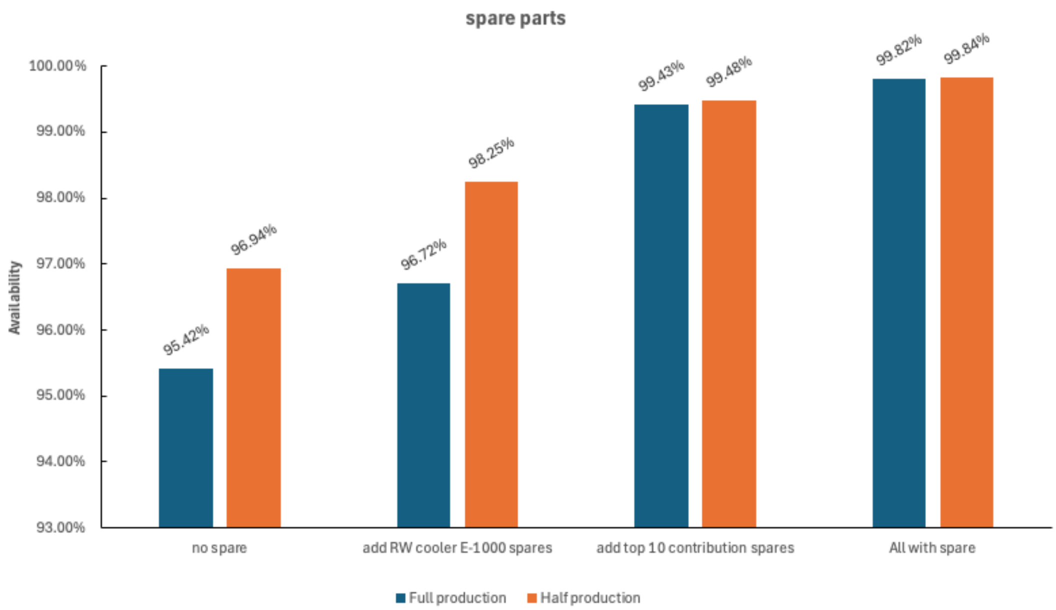


Appendix V Sensitivity Analysis

Sensitivity Analysis

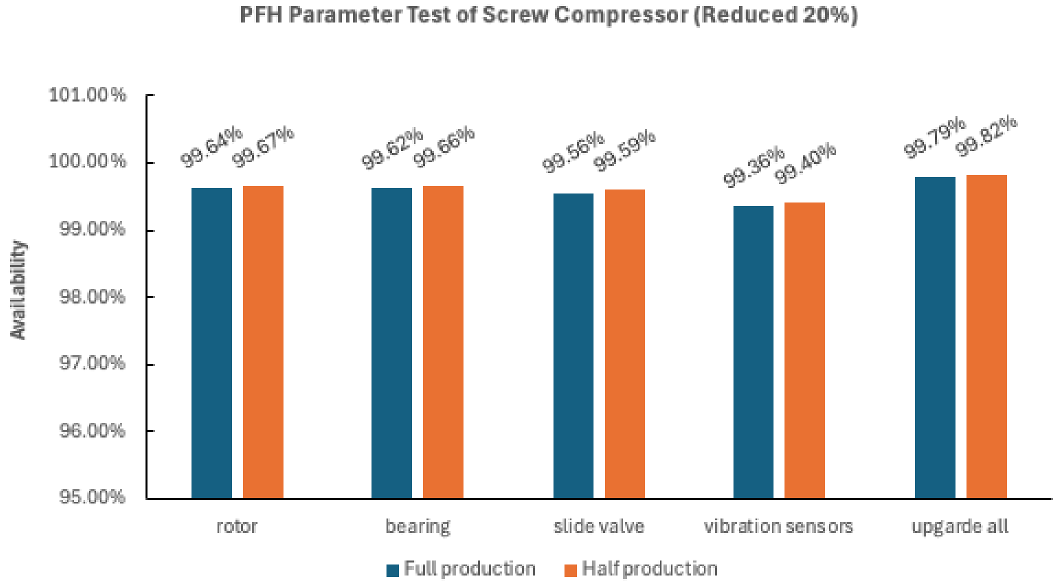
1. Spare parts

   Considering that cooler E-1000 is the primary contributor, we found that availability improves by 1.3% when its spares are stocked; however, a gap remains relative to the 99.5% target. Furthermore, we simulated scenarios for stocking spares for both the top 10 contributors and all components, with both results demonstrating significant improvements to 99.43% and 99.82%, separately.



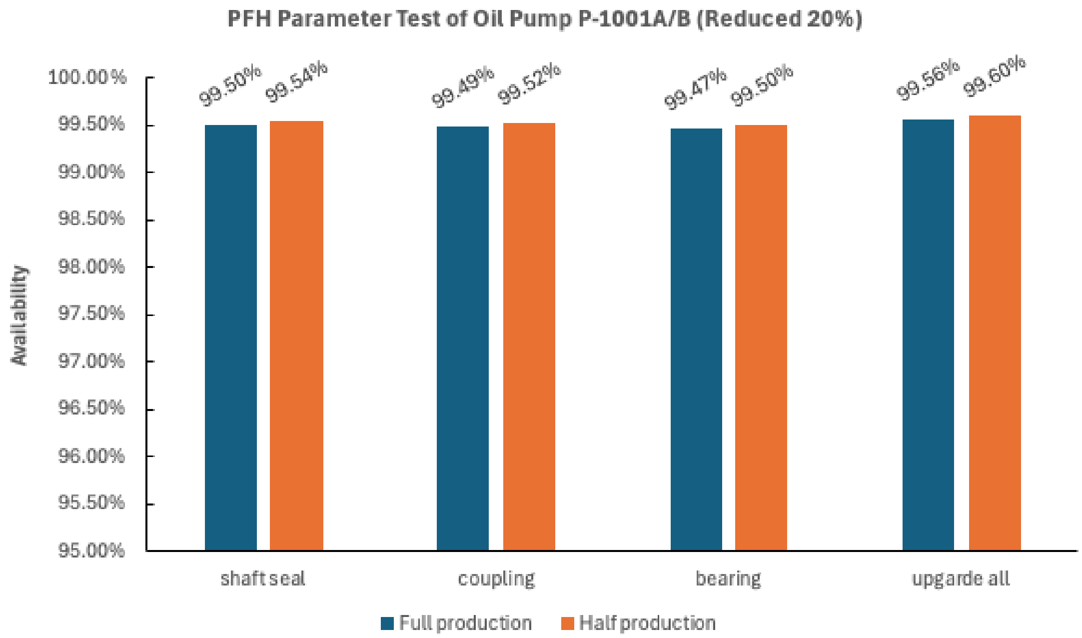
2. PFH-Screw Compressor

   A sensitivity test on the PFH parameters of the screw compressor was conducted under strategy 3 conditions (99.43% availability). By reducing the failure rate of each component by 20%, we analyzed the impact on total system availability. The results indicate that improving the reliability of the rotor—which has the highest failure rate and longest MTTR—yields better availability; however, the difference is not significant when compared to improvements in the bearing or slide valve. Instead, a significant increase in overall availability (99.79%) is only observed when upgrading all components of the screw compressor.



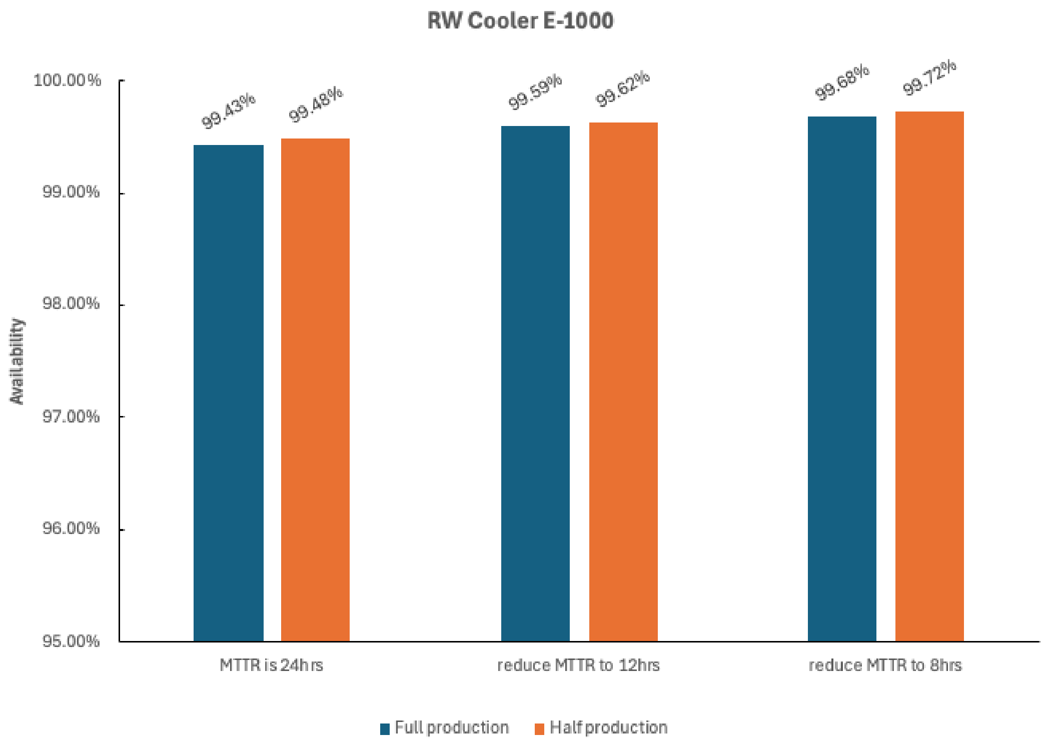
3. PFH- Oil Pump P-1001A/B

   Another sensitivity test on the PFH parameters of the oil pumps P-1001A/B was conducted (it is still based on strategy 3). While availability increases when improving any individual component, the results show no significant difference between the various scenarios. Even with a 20% reduction in all PFH values, the availability across all conditions remains consistently close to 99.5%.



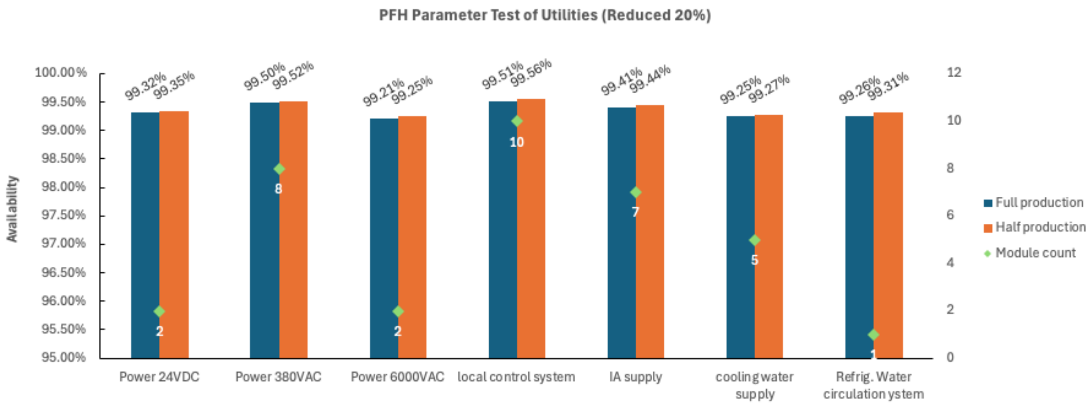
4. Reduce MTTR of RW cooler E-1000

   The MTTR of the RW cooler is the longest among all components in this study, reaching up to 24 hours. Even though its failure rate is low, it significantly impacts operations when a failure occurs. We simulated MTTR at 12 and 8 hours; the results show that availability slightly improved by 0.16% and 0.25%, respectively. Both solutions achieve availability target.



5. PFH-Utilities

We analyzed the impact of utilities on PFH sensitivity. Greater utilization across modules results in significant overall improvement. local control system and power 380VAC only barely meet the availability target, despite being integrated across 10 and 8 modules, respectively. However, upgrading every local control panel in the field would be impractical due to the diverse vendor landscape and the inherent complexities of system integration. Furthermore, estimating the cost of upgrading the power system in an existing plant is challenging, as it must account for not only the hardware refreshment costs but also the impact of facility-wide downtime during modification. Consequently, these may not be the most viable solutions.



Appendix VI Additional Investment of Strategies

1. Cost of spares

Information of spares are showed as table below. The total annual cost for all spares is 78,760 USD, while the cost for spares (marked with blue) associated with the top 10 contributors is 66,450 USD.

#	Name	In module	Price (USD)	Lead time (days)	Probability used per year	Time between usages (yr)
1	Motor Stress Cone	Motor MP-1000A	250	5	0.10%	10
2	Motor bearing	Motor MP-1000A	300	5	0.10%	10
3	Motor Terminal Board	Motor MP-1000A	150	1	0.20%	5
4	Motor CT	Motor MP-1000A	450	1	0.20%	5
5	lube oil pump mechanical seal	Lube oil pump P-1000A	800	3	0.10%	10
6	lube oil pump Packing	Lube oil pump P-1000A	100	1	0.10%	10
7	lube oil pump Flexible Inserts	Lube oil pump P-1000A	60	5	0.10%	10
8	lube oil pump bearing	Lube oil pump P-1000A	120	5	0.20%	5
9	Motor Stress Cone	Motor MP-1000B	250	5	0.10%	10
10	Motor bearing	Motor MP-1000B	300	5	0.10%	10
11	Motor Terminal Board	Motor MP-1000B	150	1	0.20%	5
12	Motor CT	Motor MP-1000B	450	1	0.20%	5
13	lube oil pump mechanical seal	Lube oil pump P-1000B	800	3	0.10%	10
14	lube oil pump Packing	Lube oil pump P-1000B	100	1	0.10%	10
15	lube oil pump Flexible Inserts	Lube oil pump P-1000B	60	5	0.10%	10
16	lube oil pump bearing	Lube oil pump P-1000B	120	5	0.20%	5
17	Filters Cartridges	oil filter F-1001A	150	1	2.00%	0.5
18	O-ring	oil filter F-1001A	10	0	2.00%	0.5
19	Filters Cartridges	oil filter F-1001B	150	1	2.00%	0.5

#	Name	In module	Price (USD)	Lead time (days)	Probability used per year	Time between usages (yr)
20	O-ring	oil filter F-1001B	10	0	2.00%	0.5
21	Motor Stress Cone	Motor MP-1001A	250	5	0.10%	10
22	Motor bearing	Motor MP-1001A	300	5	0.10%	10
23	Motor Terminal Board	Motor MP-1001A	150	1	0.20%	5
24	Motor CT	Motor MP-1001A	450	1	0.20%	5
25	lube oil pump mechanical seal	oil pump P-1001A	800	3	0.10%	10
26	lube oil pump Packing	oil pump P-1001A	100	1	0.10%	10
27	lube oil pump Flexible Inserts	oil pump P-1001A	60	5	0.10%	10
28	lube oil pump bearing	oil pump P-1001A	120	5	0.20%	5
29	Motor Stress Cone	Motor MP-1001B	250	5	0.10%	10
30	Motor bearing	Motor MP-1001B	300	5	0.10%	10
31	Motor Terminal Board	Motor MP-1001B	150	1	0.20%	5
32	Motor CT	Motor MP-1001B	450	1	0.20%	5
33	lube oil pump mechanical seal	oil pump P-1001B	800	3	0.10%	10
34	lube oil pump Packing	oil pump P-1001B	100	1	0.10%	10
35	lube oil pump Flexible Inserts	oil pump P-1001B	60	5	0.10%	10
36	lube oil pump bearing	oil pump P-1001B	120	5	0.20%	5
37	Filters Cartridges	oil filter F-1002A	150	1	2.00%	0.5
38	O-ring	oil filter F-1002A	10	0	2.00%	0.5
39	Filters Cartridges	oil filter F-1002B	150	1	2.00%	0.5
40	O-ring	oil filter F-1002B	10	0	2.00%	0.5
41	Motor 6kV Stress Cone	Motor MC-1001	1,200	5	0.10%	10
42	Motor 6kV bearing	Motor MC-1001	3,000	5	0.13%	8

#	Name	In module	Price (USD)	Lead time (days)	Probability used per year	Time between usages (yr)
43	Motor 6kV Terminal Board	Motor MC-1001	900	1	0.20%	5
44	Motor CT	Motor MC-1001	450	1	0.20%	5
45	screw compressor Mechanical Seal Assembly	screw compressor C-1001	2,500	5	0.20%	5
46	O-ring kit	screw compressor C-1001	250	3	0.20%	5
47	screw compressor Thrust Bearings	screw compressor C-1001	3,500	5	0.10%	10
48	screw compressor Radial Bearings	screw compressor C-1001	2,800	5	0.10%	10
49	Slide Valve Repair Kit	screw compressor C-1001	2,000	5	0.10%	10
50	Solenoid Valves	screw compressor C-1001	400	3	0.10%	10
51	rotor	screw compressor C-1001	25,000	1	0.20%	5
52	Vibration Probes	screw compressor C-1001	500	1	0.33%	3
53	sensors	screw compressor C-1001	300	1	0.33%	3
54	O-ring kit	screw compressor C-1001	250	3	1.00%	1
55	level transmitter	Level control loop 1000 in E-1000	2,200	1	0.10%	10
56	AI/AO card	Level control loop 1000 in E-1000	1,500	1	0.05%	20
57	LCV repair kit	Level control loop 1000 in E-1000	800	5	0.10%	10
58	level transmitter	Level control loop 1000 in E-1000	2,200	1	0.33%	3
59	AI/AO card	Level control loop 1000 in E-1000	1,500	1	0.33%	3
60	LCV repair kit	Level control loop 1000 in E-1000	800	5	0.33%	3

#	Name	In module	Price (USD)	Lead time (days)	Probability used per year	Time between usages (yr)
61	pressure transmitter	Pressure control loop 1000 in E-1000	1,200	1	0.10%	10
62	AI/AO card	Pressure control loop 1000 in E-1000	1,500	1	0.05%	20
63	PCV repair kit	Pressure control loop 1000 in E-1000	800	5	0.10%	10
64	pressure transmitter	Pressure control loop 1000 in E-1000	1,200	1	0.33%	3
65	AI/AO card	Pressure control loop 1000 in E-1000	1,500	1	0.33%	3
66	PCV repair kit	Pressure control loop 1000 in E-1000	800	5	0.33%	3
67	Flange	RW cooler E-1000	150	5	0.04%	25
68	tube	RW cooler E-1000	10,000	30	0.04%	25

2. Estimated cost of upgrade equipment

We assume that higher equipment or component reliability corresponds to higher procurement costs. Consequently, improving system availability requires greater investment. We account these typically one-time costs in CAPEX.

Module	Element	Upgraded cost, USD
Screw compressor	rotor	6,000
	bearing	500
	slide valve	1,000
	vibration sensors	500
	upgrade all	8,000
Oil pump P-1001A/B	shaft seal	600
	coupling	300
	bearing	400
	upgrade all	1,300

3. Estimated manpower to improve efficiency of cooler maintenance.

To reduce the MTTR, we assume that manpower is the critical factor for improving efficiency. The baseline human resource allocation involves two mechanical engineers working for 24 hours to repair the cooler, resulting in a total workload of 48 man-hours. The number of required engineers is determined by dividing the total workload by the desired MTTR. Based on an annual salary of 50,000 USD per person, the calculations are summarized in the table below. To reduce the MTTR to 12 hours, two additional engineers are required, increasing costs by 100,000 USD/yr. For an MTTR target of 8 hours, four additional persons are needed, resulting in an additional salary expense of 200,000 USD/yr.

Workload (man*hours)	Target of MTTR	Numbers of mechanical	Additional manpower	Additional salary (USD/yr)
48	24	2	-	-
48	12	4	2	100,000
48	8	6	4	200,000