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Reliability Improvement Program for District Cooling Plant

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Abstract

This research addresses the critical challenge of the absence of an appropriate asset management system for district cooling applications. The primary objective is to design and implement a suitable and robust reliability improvement program specifically tailored to district cooling applications, ensuring it strikes the right balance between costs, risks, and asset availability. This research was conducted through two planned intervention cycles at a district cooling plant in Malaysia. Based on the findings of the gaps assessment, the first intervention cycle encompasses a series of strategic measures aimed at restructuring maintenance practices. These measures include redefining strategic reliability KPIs, refining key definitions for appropriate application, and redesigning preventive maintenance to incorporate condition-based maintenance (CBM) strategies. Building upon the successes of the first cycle, the second intervention cycle focuses on further refining the maintenance processes. This involves increasing stakeholder engagement frequency to enhance skills and reduce resistance to change. It also includes prioritizing impactful preventive maintenance activities according to available resources through Quarterly Maintenance Plan Review. Additionally, the implementation adheres to the Plan-Do-Check-Act (PDCA) framework to ensure continuous improvement in maintenance management. The interventions have resulted in tangible improvements in reliability, reduced equipment downtime, and enhanced accountability throughout the plant. The holistic approach adopted in this program emphasizes the importance of integrating various strategies and continuous improvement models to optimize operational performance. By successfully achieving the set targets, this reliability improvement program has demonstrated its effectiveness in elevating the performance and reliability of district cooling plants. The findings from this research provide valuable insights and practical recommendations for enhancing reliability and maintenance management in similar industrial settings.

Keywords: Improvement Program, District Cooling Plant

Introduction

A district cooling system (DCS) is one of the cooling energy supply systems that is actively introduced and developed in urban areas in a structured way for the purpose of saving energy, optimizing space utilization, minimizing air pollution, and reducing the impact of natural disasters. DCS can be considered as a centralized air-conditioning system that supplies chilled water through distributed piping to customers' heat exchangers before it is channeled to building air-handling units (AHUs) or fan coil units (FCUs).

The chilled water energy is measured in refrigerant tonnage (RT), and the common supply and return temperatures are 6.5 and 13.5 degrees Celsius, respectively. The energy sources of DCS can vary, which normally come from domestic electricity suppliers or natural gas. The DCS configuration is designed differently in order to optimize operating costs, depending on the utility tariff in each individual country. In Malaysia, there are two DCS configurations, namely the Fully Electric Plant and the Co-Generation Plant, which use different types of equipment to produce the chilled water. The typical main asset types of district cooling applications are electrical chillers, direct-fired chillers, steam absorption chillers, chilled water pumps, condenser water pumps, and cooling towers, and some setups include boilers and gas turbines.

The district cooling system is typically designed to be able to supply the demand with the addition of standby units. In Malaysia, the months of April and May typically experience the highest monthly average temperatures, while December and January have the lowest monthly average temperatures. This variability indicates that the number of standby units may fluctuate depending on external factors or seasonality effects.

Problem Diagnosis

The district cooling plants operated by Company X have experienced a decline in equipment availability, showing a downward trend since 2017. This trend is attributed to an increase in unplanned shutdowns, which pose a risk of higher maintenance and repair costs for Company X.The target asset availability for the entire Company X group is set at 96%, yet Company X has achieved only 76.4% as of May 2022, marking its lowest performance. This downward trend has persisted since the plants were commissioned in 2017. To diagnose the problem, qualitative interviews were conducted with four respondents from the maintenance department. Additionally, a detailed root cause assessment was performed using Fault Tree Analysis, with the findings depicted in the following figure.

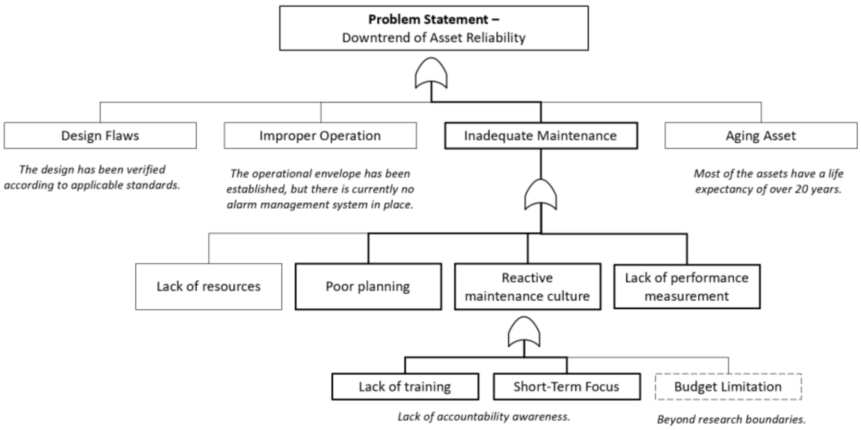

Figure 1-3: The root cause analysis of the problem statement

Based on the initial assessment, the primary causes of frequent unplanned breakdowns include a lack of performance management metrics, poor planning, and a reactive maintenance culture stemming from insufficient awareness.

Research Questions

A research question is a specific concern or area to be focused on and explored in this assessment. As a result, three Action Research Questions (ARQs) have been derived from the main issue description:

RQ1: What are the current gaps in the asset management system within X Company's maintenance department, and what is the current application of continuous improvement?

RQ2: What are the leading indicators for maintenance activities that contribute to availability improvement?

RQ3: What high-impact activities are capable of improving the availability target in a short period?

Research Objectives

The key objectives of the research are as follows:

Objective 1: To identify and analyze the specific gaps present in X Company's asset management system and the current application of continuous improvement.

Objective 2: To explore and determine the leading indicators associated with maintenance activities that positively impact availability improvement.

Objective 3: To evaluate high-impact activities capable of enhancing the availability target within a short timeframe.

Significance of the Research

The significance of this research lies in several key aspects:

i. Transitioning from a reactive maintenance approach to a proactive stance is imperative. This study offers fresh perspectives to both maintenance and management teams by identifying gaps and advocating for a structured methodology in maintenance planning and execution.

ii. Efficient allocation of resources to high-impact activities is essential given the constraints of manpower, tools, and parts. Prioritizing tasks toward activities that yield significant value is crucial.

iii. Enhancing organizational profitability is the ultimate goal. By optimizing spending, particularly on repair costs, this endeavor seeks to minimize unplanned activities, thereby directly impacting the company's expenditure and mitigating unnecessary losses.

Literature Review And Action Research Planning

Underpinning Theory and Models

There are various ideas and models available for understanding total strategic planning in the maintenance department, aimed at improving reliability. The ultimate objective of any model is to optimize total ownership costs to enhance company profitability. To begin, it is beneficial to understand the standards and guidelines widely used in the global industry.

ISO55000 - Asset Management Guidelines

According to ISO55000, Asset Management can be defined as the coordinated activities of an organisation to realise value from assets, where the Asset is an item, thing or entity that has potential or actual value to an organisation (management, 2014). ISO55000 Asset Management is focusing on how to use assets to deliver value and achieve the organisation's business objectives. On top of that, it is included approaches to an organisational transformation in term of culture and determination. Asset Management standard can be applied to all types of organisation or industries which cover form government sector, private sectors or any non-profitable sectors. There are growing evidences from around the globe that effective asset management can improve organisation's reputation and its ability to improve plant availability and reliability, operate safely, meet local regulatory and statutory obligations and significantly reduce the asset life cycle cost (Management, 2015) There are four (4) fundamentals in ISO55000 Asset Management system which are value, alignment, leadership, and assurance (Standard I. , Asset Management - Overview, principles and terminology, 2015).

Value

The first step in setting up the asset management system, any organisation shall identify the value. Any individual assets shall have the actual or potential value to an organisation and its value shall contribute towards to ultimate organisation value through value chain.

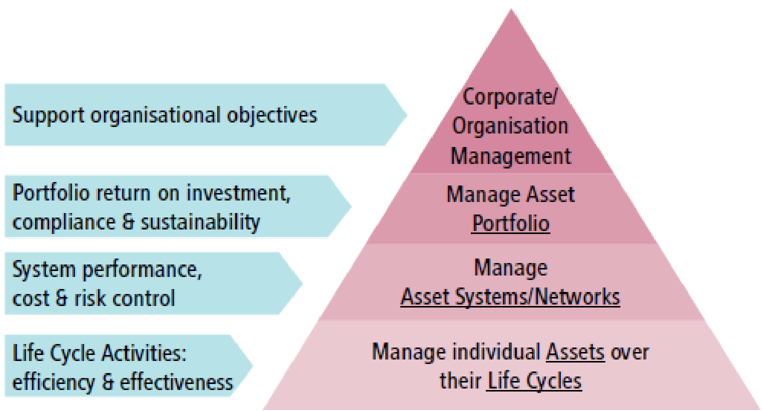

Figure 2-1: The value chain of individual asset value in organisation

A value chain describes on how defined set of activities combine within an organisation to create value (Management, 2015).

i. *Alignment*

The practical asset management exercise shall have good connectivity in between organisational strategic plan and the asset management activities executed by tactical and operation level at the field staff. The connectivity of various level from the top to bottom is called Alignment. This principle shall drive everybody in the organisation to understand their roles and responsibilities in achieving organisation success.

ii. *Leadership*

Leadership is the art of motivating a group of people to act toward achieving a common vision, mission, or goals (Ward, 2020). The key agenda that involve leadership element are Culture change, Set direction and priority, Ensure the practices are cross boundaries and disciplines.

iii. *Assurance*

Assurance is the combination exercise of monitoring and auditing to ensure the maintenance planning to be executed accordingly. The good asset management exercise requires the close loop process that require continuous improvement.

Total Productive Maintenance (TPM)

Total productive maintenance is a unique Japanese philosophy introduced by Nippon Denso Co, Ltd of Japan, a supplier for Toyota Motor Company in 1971. The TPM main objectives are to optimise equipment effectiveness, eliminates breakdowns and promote autonomous maintenance (Khamba, 2008). The TPM initially to support the manufacturing industry that rapidly growth in Japan where at that time Just-In-Time (JIT) and Total Quality Management were most popular approach for maintenance team. There are a few key pillars in performing the TPM process which can be categorised into 8 categories as following figure:

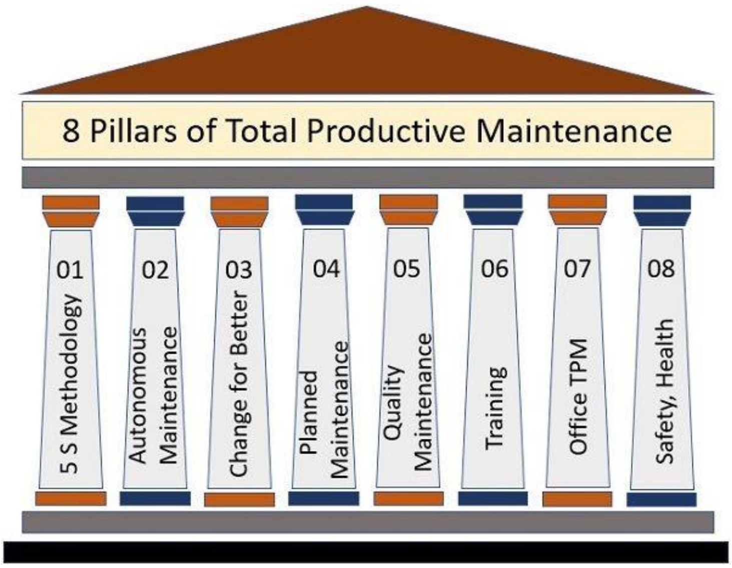

Figure 2-2: Eight pillars approach for TPM implementation.

The foundation of successful TPM process is the 5S exercise which are Sort, Set in Order, Shine, Standardize and Sustain. Each individual pillar is described in following table:

Table 2-1
The key elements of TPM foundation

No	Pillar Element	Description
1	Autonomous Maintenance	A set of maintenance activities to be done by operation department such as cleaning, lubricating, tightening, inspection, and minor adjustment.
2	Focused Improvement	A systematic approach to identify and eliminate or improve unplanned shutdown such as FMEA analysis or Overall Equipment Effectiveness (OEE) improvement.
3	Planned Maintenance	Planned Maintenance activities such as PM, PdM and TBM by establishing necessary Planned Maintenance Checklist
4	Quality Maintenance	Achieving Zero defect, tracking and addressing equipment problem and root cause. Set procedures and standard for 3M (machine / man / material)
5	Education and Training	Periodic skill assessment and identify the gaps to measure the improvement. Training shall be provided to align the skill set with organisational direction.
6	Safety, Health and Environment	Zero accident target and safe working environment which also may include mental healthiness.
7	Office TPM	Improve synergy between various business function. Minimise hassle procedures and focus on addressing cost related issues.
8	Development management	Provide necessary reward and initiative for the continuous improvement.

IEEE 762-2006

IEEE 762 offers a methodology for interpreting performance data from diverse electric generating unit systems, aiming to facilitate comparisons among them. It standardizes terminology and indexes for reporting reliability, availability, and productivity measures of electric generating units. The standard's purpose is to assist the electric power industry in reporting and evaluating the reliability, availability, and productivity of electric generating units, while acknowledging the industry's requirements, including marketplace competition.

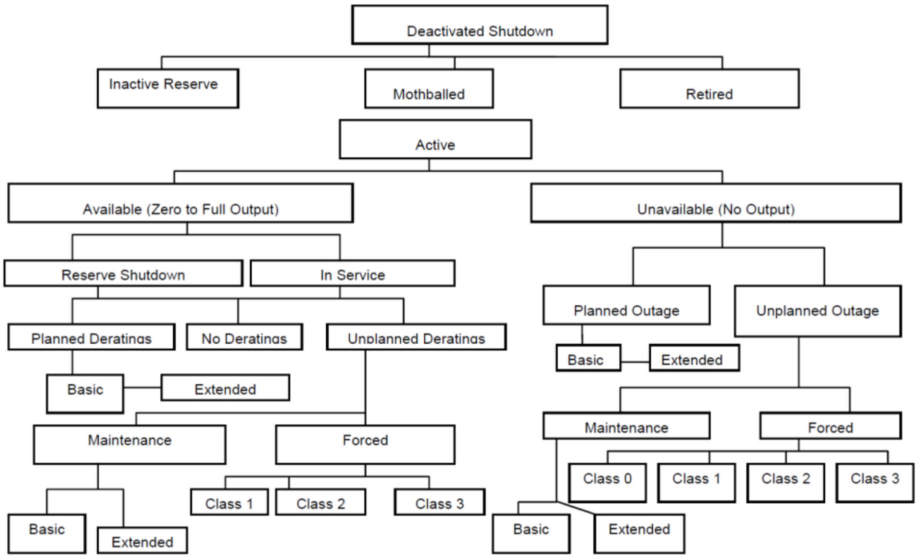

Figure 2-3: Relation between unit states as per IEEE762

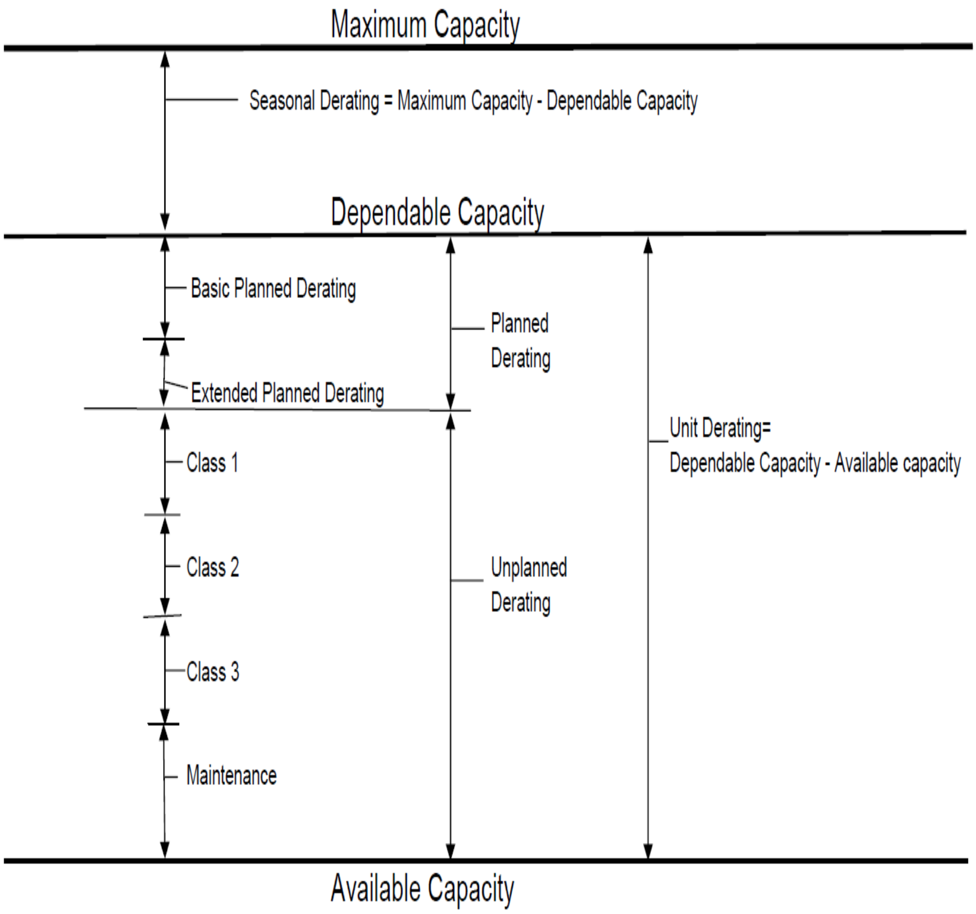

Figure 2-4: Unit capacity levels as per IEEE762

Methodology

Research Philosophy

The researcher adopts a pragmatic research philosophy, which combines aspects of both positivism and interpretivism. Pragmatist researchers believe in tailoring the research approach to fit the specific research problem and question. They employ a mixed methods approach, integrating quantitative and qualitative methods to provide a comprehensive understanding of the topic. Emphasizing practicality, relevance, and real-world applicability, pragmatism aims to identify causal relationships through deductive reasoning and quantitative data analysis.

Research Design

Research design shall explain the outlines the specific steps, methods, and procedures that will be employed to address the research objectives or research questions.

Research Instrument and Measures

Questionnaire Design

In this exercise, initial interviews have been conducted with relevant personnel, including the maintenance manager and discipline engineers. These interviews are part of a preparatory approach to identify the problem statement and potential root causes. As a result, a root cause problem has been identified, with a major contributing factor being the absence of performance management metrics, poor planning, and a reactive maintenance culture, as explained in Chapter 1. The interviews will be conducted in separate sessions to enhance data reliability and achieve higher data validity. All interview sessions will be transcribed into interview transcripts for further analysis and evaluation. Thematic analysis has been used on the transcripts for data categorization.

Data Collection Procedure

Concurrent with the interview sessions, a quantitative observation was also conducted to assess the current state of the maintenance system, particularly focusing on reliability achievements such as Reliability Percentage, Mean Time Between Overhaul (MTBO), Mean Time Between Critical Failures (MTBCF), and Mean Time to Repair (MTTR). The sources of observation were drawn from various areas, including Management Systems & Procedures, the Centralized Maintenance Management System (CMMS), Maintenance Contract Agreements, Monthly Reports, Historian Data, and Maintenance Reports..

Data Analysis and Discussion

Data Analysis

The Interview Thematic

The interview was conducted in an earlier stage in order to identify the root cause of the problem statement. The interview involved four (4) respondents which are Maintenance Manager, a Mechanical Engineer, Electrical Engineer, and Instruments Engineer. The first session is to identify the problem statement as well as to be part of problem diagnosis. As the result, upon the thematic assessment on interview transcript, the finding of first interview is summarized in following table.

Table
The thematic assessment on the respondent answers.

No	Question	Maintenance Manager	Mechanical Engineer	Electrical Engineer	Instruments Engineer	Theme
1	How do you design the PM program and its interval?	Act & Regulation, OEM Manual, Industrial Best Practice	Act & Regulation, OEM Manual, Industrial Best Practice	Act & Regulation, OEM Manual, Industrial Best Practice	Act & Regulation, OEM Manual, Industrial Best Practice	Planning
2	Who is responsible to develop Annual Maintenace Plan (AMP)?	Discipline Engineer	Discipline Engineer	Discipline Engineer	Discipline Engineer	Planning
3	Do the AMP is integrated and uploaded in the CMMS?	No	No	No	No	Planning
4	Do you report the WO Maintenance Compliance for each individual activities?	Schedule only (Not tracker)	Schedule only (Not tracker)	Schedule only (Not tracker)	Schedule only (Not tracker)	Execution
5	If yes, what is the completion target of planned vs actual?	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Performance Metrics
6	Do the planner	No	No	No	No	Planning

No	Question	Maintenance Manager	Mechanical Engineer	Electrical Engineer	Instruments Engineer	Theme
	report the Schedule Compliance?					
7	Do you include CBM Program in your PM?	Oil Analysis Only	Oil Analysis Only	No	No	Performance Metrics
8	Do you have standardized PM checklist to be filled up by Field Staff?	Yes	Yes	Yes	Yes	Execution
9	Do you have tuning activities in your PM program?	Yes at SME Level	Yes at SME Level	Yes at SME Level	Yes at SME Level	Continous Improvement
10	If yes, how frequent do you do the tuning process?	Annual Tuning	Annual Tuning	Annual Tuning	Annual Tuning	Continous Improvement
11	Do you have backlog management system?	No	No	No	No	Performance Metrics
12	Do you think Corrective Maintenance is Dynamic	Yes	Yes	Yes	Yes	Planning

From the first interview engagement, it was concluded that the key takeaways to be assessed in detail were the absence of performance management metrics, poor planning, and a reactive maintenance culture.

The Achievement & Indicators
Below are the table of current achievement and the measurement mechanisms.

Table 4-1
The Current Achievement of Company X

No	Metric	Company X Achievement (June 2022)	Target
1	Availability	76.40%	94%
2	Reliability	87.37%	96%

The Availability and Reliability are measured by using following formulas:

Availability (%) = 1 – (Plan Shutdown Hours + Unplanned Shutdown Hours) / (No of equipment x Hours in a Month) x 100%

Reliability (%) = 1 – (Unplanned Shutdown Hours) / (No of equipment x Hours in a Month) x 100%

The planned definition includes any activities outlined in the Annual Maintenance Plan (AMP) and subsequently approved by management. The AMP should undergo review and approval by management at least one month before the upcoming year.

CMMS Data Analysis By Coding & Failure Pareto Result
Further analysis of failure descriptions is conducted to categorize failure classifications. The failure codes are plotted on a Pareto Chart to apply the 20:80 rule.

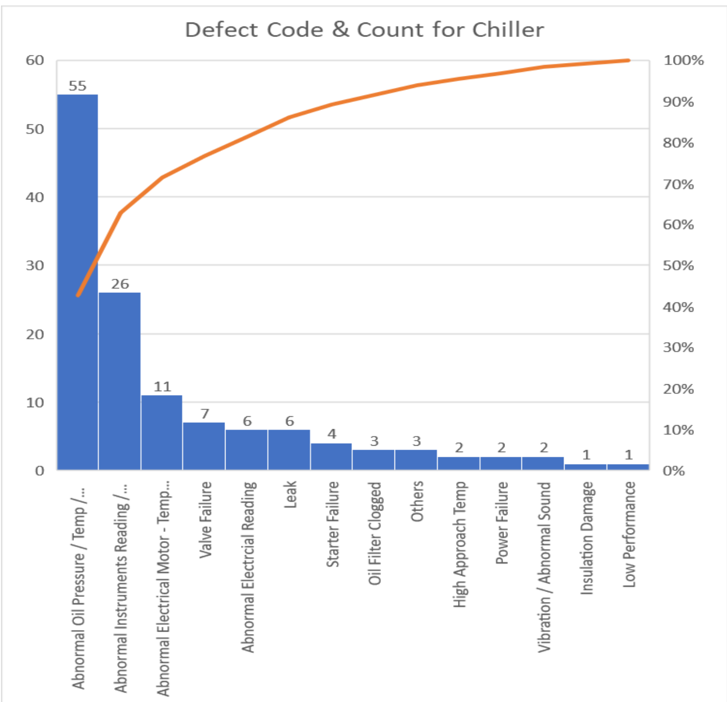

Figure 4-1A: The defect category count for the chiller

The highest defect that led to chiller failure was abnormal oil pressure and temperature, followed by abnormal instrument readings. They contributed 55 times or 43.31% and 26 times or 20.47%, respectively.
The failure descriptions of the cooling tower were coded into seven (7) categories as shown in the following chart.

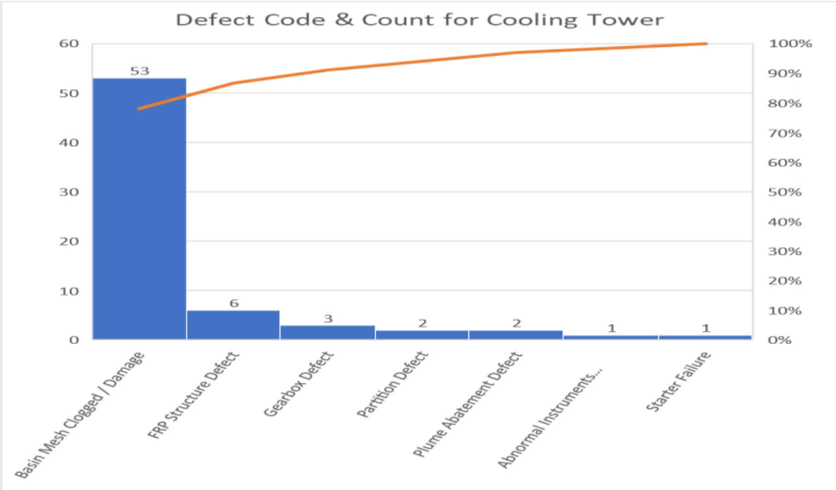

Figure 4-1B: The defect category count for the cooling tower

The highest failure code for the cooling tower was due to clogged and damaged basin mesh, contributing to 55 failures or 80.88% of the total failures. Currently, the maintenance approach for addressing basin mesh defects is reactive, where cleaning is only required when conditions warrant it. Preventive maintenance activities to be included for the cooling tower should encompass basin cleaning activities.

For the pump, the same approach was taken for defect categorization and Pareto assessment, with the results presented in the chart below.

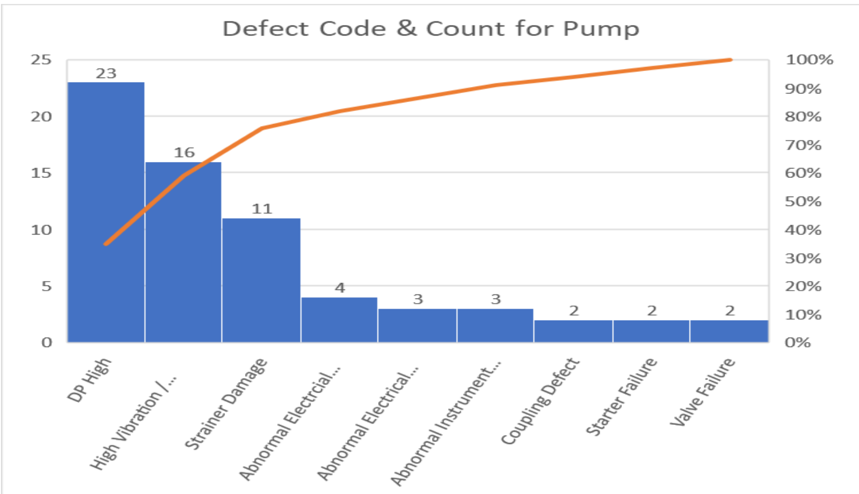

Figure 4-1C: The defect category count for the pump

The defect code of the pump reveals that the primary cause of unplanned breakdowns was the high strainer differential pressure (DP) and high vibration. High DP contributed the highest factor with 23 occurrences, accounting for 34.85% of unplanned breakdowns, followed by high vibration with 16 occurrences, constituting 24.24% of total failures. From observations, it was noted that high DP is closely related to the cooling tower basin mesh being clogged, indicating a strong dependence on basin cleanliness levels.

Cycle 1 Intervention

After identifying the current state and the key pain points of Company X, the following interventions were implemented:

Redefine the definition of planned maintenance and increase the AMP review frequency from annually to quarterly. This ensures that proper planning and scheduling can be done accordingly to reduce unplanned downtime.

Empower the existing team to perform internal CBM activities, especially vibration analysis, as most failure codes are detectable by CBM programs. This intervention comes at zero cost to the organization.

Restructure the targets by incorporating new leading indicators for maintenance, which include PM Compliance, PM Backlog, CM Compliance, CM Backlog, CBM Compliance, and CBM Backlog. Additionally, the CM priority is being revised to be dynamic in response to seasonal effects.

Redefined Key Definition and Measurement Mechanism through Asset Management System (AMS)

The district cooling system should emphasize maintaining a dynamic balance between cost, risk, and targeted availability and reliability, incorporating the influence of seasonality effects. This balance can be achieved through various driving factors, including:

i. Dynamic Availability Target
ii. Priority-Driven Maintainability
iii. Redefined Key Definition

It has been observed that the current key definition is too stringent, making the target very difficult to achieve. Sometimes, adhering strictly to higher-level industry standards can backfire. Therefore, it is necessary to revise the key definition to better suit district cooling applications. The updated key definitions are as follow:

Table 4-2A
Revised key definitions for district cooling applications.

Term	Description / Definition
AV	Probability of an item to be in a state to perform a required function under given conditions at a given instant of time.
AV in %	Availability is a measure of the readiness of a system or equipment to perform its intended function at any given point in time.
AV Ratio	The ratio of available trains to the required number of trains.
Look Ahead Availability	Measure plant readiness for upcoming load.
RE	Probability of an item to perform a required function under given conditions for a given time interval.
RE in %	Reliability measures the ability of a system or equipment to perform its intended function under specified operating conditions without experiencing critical failures and includes the timely restoration of functionality when **unplanned** disruptions occur.
Planned Outage	Planned Outage refers to planned maintenance or shutdown activities that can be planned in advance without disrupting the normal plant operation and it is registered in Annual Maintenance Planned.
Unplanned Outage	Unplanned refers to any unintended or immediate shutdown that results in capacity reduction and it is not registered in Annual Maintenance Plan. The unplanned outage can be divided into three categories: Tripping, Stoppage, Extended Outage. All unplanned is categorized as OOS.
Tripping	Unscheduled downtime events by instrumentation / protection system during start-up or operation.
Stoppage	Human intervention unplanned outage requires immediate removal from the available state.
Extended Outage	The extended outage state is the extension of the planned outage that surpass LACD.
Active Asset	Active asset refers to an asset that is actively utilized, or deployed to generate value, contribute to operations.
In-Service Asset	Refer to asset that is currently being used for operations.
Standby Asset	Refer to asset that is available and ready for use when needed, but it's not actively in use at the moment.
Available with Remark	Refer to an asset that is operatable but requires attention or improvement to enhance its condition or performance
Healthy Standby	Standby mode of an asset that is comply with the established and allowable duration
Moderate Standby	Standby mode exceeding the predetermined or permissible shutdown duration for three consecutive months (3) or less.

Term	Description / Definition
Prolonged Standby	Standby mode exceeding the predetermined or permissible shutdown duration for four (4) consecutive months or more.
Inactive Asset	The Inactive Asset state is where a unit is unavailable for service for an extended period of time for reasons **not related** to the equipment.
Retired Asset	Referred to as a state of an asset unit is available but not in service due to it no longer being in use.
Mothballed Asset	The mothballed state is where a unit is unavailable for service but can be brought back into service with appropriate amount of notification, in less than 6 month.
Reserve	The reserve state is where a unit is unavailable for service but can be brought back into service in a relatively short period of time, within 30 days.
Failure	Termination of the ability of an item to perform a required function.
Critical Failure	Failure resulting in the immediate inability to perform its required function, leading to being out of service for more than 72 hours.
Non-Critical Failure	Failure of an equipment which does not cause immediate cessation of the ability to perform its required function.
Overhaul	An overhaul involves major maintenance activities of mechanical rotating equipment that include disassembling, inspecting, repairing, and restoring equipment to a state of zero running hours.
MTBO	Metric used to measure the average time that passes between consecutive overhauls.
MTBF	Average time elapsed between any failures
MTB(C)F	Average time elapsed between Critical Failures
MTTR	The average time required to repair out-of-service equipment to restore its intended function in delivering.
Failure Mode	Observed manner of failure.
Failure Mechanism	Physical, chemical or other process which has led to a failure.
Maintainability	Refers to the difficulty level of repairing and restoring an asset to perform its required function.
OOS	Refers to the status of an asset that is complete unavailable due to failure.
PM WO Compliance	Measures the degree of any PM and PDM tasks are executed within a predefined Compliance Window, in accordance with the Work Completed status date.

Term	Description / Definition
CBM WO Compliance	Measures the degree of any CBM tasks are executed within a predefined Compliance Window, in accordance with the Work Completed status date.
CM WO Compliance	Measures the degree of any CM and BD tasks are executed within a predefined Last Acceptable Completion Date (LACD), in accordance with the Work Completed status date.
PM WO Backlog	Any PM and PDM that have not been changed to Completed status within compliance window.
CM WO Backlog	Any CM and BD that have not been changed to Completed status within predefined LACD.
CBM WO Backlog	Any PDM under CBM that have not been changed to Completed status within compliance window.

It is also introduced the concept of asset states to be applied to the district cooling system. The states of assets are illustrated in the following figure.

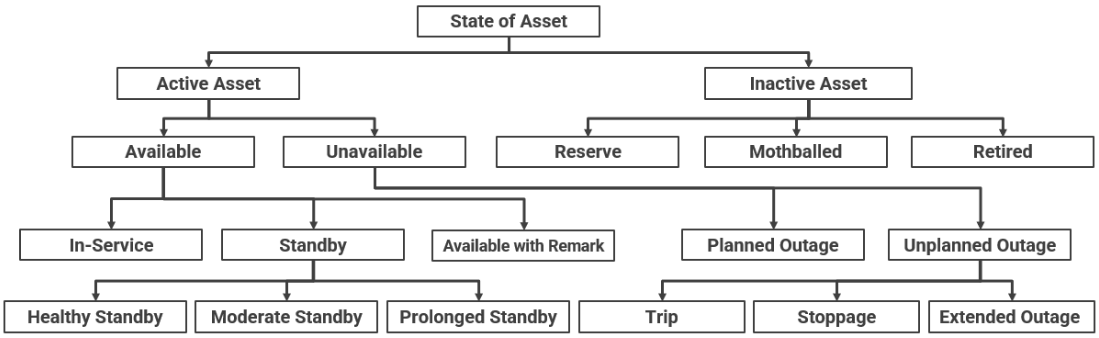

Figure 4-2B: State of asset for district cooling system

The formula for AVRE measurement remains unchanged, but the annual maintenance plan is now reviewed quarterly to ensure proper planning and scheduling of work. Company X management has agreed to this dynamic review of the AMP to prevent unplanned and unexpected downtime.

Upskilling Internal Staff for CBM

The CBM program is crucial for early detection of failure symptoms, as it can capture nearly 50% of failure mechanisms before they occur. However, individuals responsible for designing and implementing the program must be competent and experienced in equipment configuration, data acquisition, and result interpretation. In this case, the researchers possess the necessary skill set, recognized by multiple international organizations in vibration analysis, oil analysis, thermography inspection, and ultrasound inspection. To begin, the internal team has been empowered to perform data acquisition for vibration analysis. Initially, the vibration analysis program is designed to be in quarterly basis for the main assets.

Restructure the targets by incorporating new leading indicators

Since the company is only measuring lagging indicators without structured leading indicators, a comprehensive set of leading indicators for maintenance is measured as follows incorporated with clear guidelines of Reliability Performance Metric

Table 4-2D

The current state of Company X

No	Metric	Company X Achievement (June 2022)	Brilliant at Basic	Effective Performance	Top Tier
	Lagging				
1	Availability (AV)	76.40%	90%	92%	94%
2	Reliability (RE)	87.37%	92%	94%	96%
3	MTB(C)F - Chiller	251	400 days	450 days	493 days
4	MTB(C)F - CT	169	200 days	224 days	249 days
5	MTB(C)F - Pumps	1485	1,200 days	1,336 days	1,484 days
6	MTTR - Chiller	41	18 days	17 days	15 days
7	MTTR - CT	6	11 days	10 days	9 days
8	MTTR - Pump	15	18 days	17 days	15 days
	Leading				
9	PM Compliance	Not Applicable	85%	90%	95%
10	CM Compliance	Not Applicable	85%	90%	95%
11	CBM Compliance	Not Applicable	85%	90%	95%
12	CM Backlog	Not Applicable	20% Backlog	10% Backlog	0% Backlog
13	PM Backlog	Not Applicable	20% Backlog	10% Backlog	0% Backlog

Intervention Cycle 2

The intervention program of cycle 1 has been rolled out and executed since July, with results improvement measured on a monthly basis. In the early stages of the intervention, several leading indicators were introduced as part of the improvement actions. While the results have gradually improved, they still fell below the targeted availability. Interventions Cycle 2 essentially build on the leading indicators from Cycle 1. The Intervention Cycle 2 can be simplified as follows:

i. Incorporating reliability programs which are ECA and FMEA as part of the leading maintenance program
ii. Enhancing reliability performance metrics
iii. Accelerating results through frequent engagement and designing life dashboards for management.

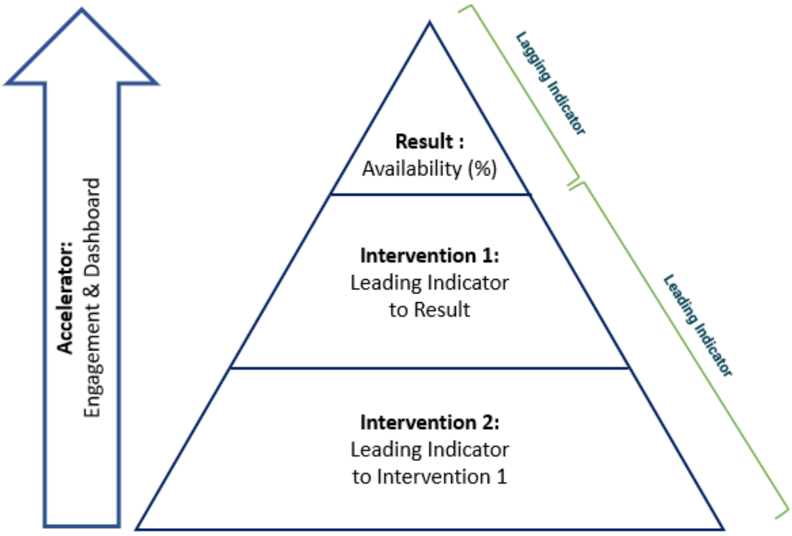

Figure 4-2E: The overall concept of intervention approaches.

Findings

The reliability performance matrix was introduced during the first cycle of intervention to identify current gaps and measure performance. It was further enhanced for Cycle 2 by introducing several leading factors aimed at accelerating impact. Below are the achievements as of May 2023.

Table 4-2F

Reliabiity performance matrix achievement by end of May 2023

No	Metric	Company X Achievement (June 2022)	End of Intervention 1 (Nov 2022)	End of Intervention 2 (May 2022)	Brilliant at Basic
	Lagging				
1	Availability (AV)	76.40%	78.10%	84.70%	90%
2	Reliability (RE)	87.37%			92%
3	MTB(C)F - Chiller	251	277	298	400 days
4	MTB(C)F - CT	169	198	202	200 days
5	MTB(C)F - Pumps	1485	1498	1520	1,200 days
6	MTTR - Chiller	41	27	19	18 days
7	MTTR - CT	6	6	6	11 days
8	MTTR - Pump	15	15	15	18 days
	Leading – Tier 1				
9	PM Compliance	Not Applicable	85.0%	86.7%	85%
10	CM Compliance	Not Applicable	43.5%	29.1%	85%

11	CBM Compliance	Not Applicable	85.0%	86.7%	85%
12	CM Backlog	Not Applicable	20%	19%	20% Backlog
13	PM Backlog	Not Applicable	98.2%	98.7%	20% Backlog
	Leading – Tier 2				
14	Percentage of ECA completion against asset register (%)	Not Applicable	Not Applicable	67.9%	80%
15	FMEA completion for C1 & C2 incorporated with Maintenance Strategy establishment.	Not Applicable	Not Applicable	58%	80%
16	Compliance to the actionable items (%)	Not Applicable	Not Applicable	85.7%	85%

Discussion
The objective of the study is to enhance the asset's availability percentage by improving its reliability and maintainability. The targeted availability for this exercise is set at 82.3%, representing a 30% increase compared to the base target prior to the introduction of the intervention program.

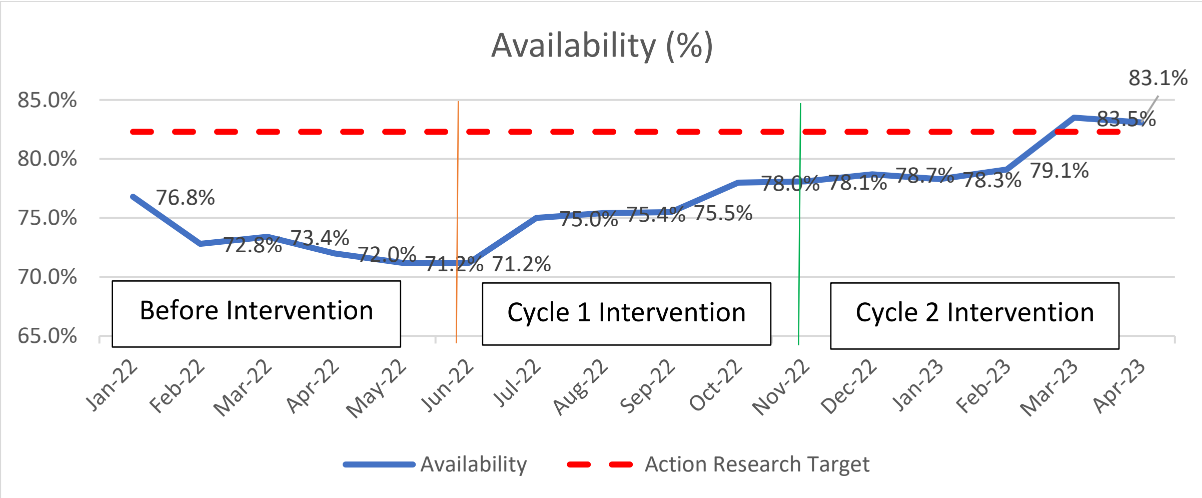

Figure 4-5: The overview of the Availability result from the before and after intervention program

The tier 2 leading indicator was introduced to enhance the impact of the first cycle intervention, which should consequently affect the Availability result. The maintenance team managed to achieve an Availability of 85.7%, slightly higher than the AR target set at 82.3%. However, it still fell below the organizational target of at least 90%. Nevertheless, examining the healthy trend indicates convincing progress if the team maintains momentum. This indicator demonstrates that the team is embracing the intervention program and recognizing progress in the results.

Conclusion

Introduction

Both cycles of action research have met all the three (3) of research objectives as follows:

i. Research Objective 1. To identify and analyze the specific gaps present in the District Cooling asset management system and the current continuous improvement application.
In this action research, the researcher has established several elements in the asset management system, incorporating the Plan-Do-Check-Act improvement model. The key elements in this exercise include sub-programs which redefine key definitions and upskill for CBM.

ii. Research Objective 2: To explore and determine the leading indicators associated with maintenance activities that have a positive impact on improving Availability.
Availability improvement is the ultimate indicator for assessing the successful rate of the intervention program. However, relying solely on availability as a lagging indicator may hinder proactive actions to improve results. In conjunction with the earlier introduced Planned Maintenance System, the researcher also introduced new leading Key Performance Indicators (KPIs), namely Reliability Performance Triangle incorporated with Reliability Performance Matrix. The availability improvements can be seen consistent with the leadings indicators improvements that had been discussed earlier.

iii. Research Objectve 3: To evaluate the high-impact activities that have the potential to enhance the Availability target within a short timeframe.
The higher-impact activities were identified through CMMS assessment and Pareto analysis. Further assessment was conducted and refined using the ECA (Equipment Criticality Analysis) and RCM (Reliability Centered Maintenance) approaches. As a result, the availability successfully achieved the desired target within the research duration, with an actual achievement exceeding 82.3%.

Research Impact to Practice

Through a comprehensive analysis of industry standards, best practices, and case studies, this research paper presents key findings related to the reliability improvement program for district cooling systems. Firstly, identifying gaps and current processes is crucial to understand the current states and practices. Restructuring targets and objectives and identifying leading indicators is crucial for teams to adopt the right approach. This should be done concurrently with redefining definitions that suit district cooling applications for striking a balance between risk, cost, and targeted availability. Additionally, incorporating the PDCA model, engagement, and dashboard accelerate results. Lastly, optimizing maintenance strategies through condition-based maintenance (CBM) and predictive maintenance techniques allows for more efficient allocation of resources and reduces unnecessary downtime and costs.

Research Limitations and Delimitations

Limitations of the reliability improvement program research at Company X may include the following:

i. Time Constraints. Conducting an extensive study on the reliability improvement program may require significant time and resources. Depending on the scope of the research, limitations in time and budget constraints may restrict the breadth and depth of the analysis, resulting in a more focused or limited examination of certain aspects of the program.

ii. External Factors. External factors beyond the scope of the research, such as changes in regulations, technological advancements, or environmental conditions, can influence the performance and reliability of the systems. These factors may not be fully accounted for in the research study, potentially affecting the generalizability and applicability of the findings.
iii. Implementation Challenges. While the research may provide valuable recommendations for improving reliability, the actual implementation of the program faced various challenges. These challenges include resistance to change, resource constraints, lack of expertise or knowledge, or conflicting priorities within organizations. The research study may not fully address or anticipate these implementation challenges.
iv. Long-term Evaluation. The research study have limited ability to assess the long-term effectiveness of the reliability improvement program. Evaluating the program's impact over an extended period requires continuous monitoring and data collection, which may extend beyond the timeframe of the research study.

Research Future Recommendations

Future recommendations for reliability improvement program research in the context of district cooling systems could include the following:
i. Cost-Benefit Analysis. Perform cost-benefit analyses to evaluate the economic impact of reliability improvement programs. Assess the return on investment (ROI) of implementing various strategies and quantify the potential savings in terms of reduced downtime, maintenance costs, and improved system performance.
ii. Human Factors Consideration. Investigate the impact of human factors, including training, awareness, and organizational culture, on the success of reliability improvement programs. Examine how organizations can foster a culture of reliability, encourage proactive maintenance practices, and involve stakeholders at all levels in the implementation and continuous improvement of reliability improvement initiatives.
iii. Data Standardization and Sharing. Encourage standardization of data collection methods and parameters to facilitate data sharing and comparability across different research studies. This can enable researchers to collaborate, combine data sets, and conduct more robust analyses to draw broader conclusions about the effectiveness of reliability improvement programs.

Conclusions

In conclusion, the reliability improvement program for district cooling systems is essential for ensuring the smooth and efficient operation of these critical systems. The findings of this research highlight the importance of a proactive and systematic approach to enhance the reliability in Company X. By implementing preventive measures, conducting regular inspections, and optimizing maintenance strategies, organizations can minimize unexpected failures, reduce downtime, and extend the lifespan of equipment. This program emphasizes the significance of considering critical components, failure modes, and employing advanced diagnostic tools to detect and address potential issues before they escalate. The successful implementation of the reliability improvement program requires collaboration among maintenance teams, management team as well as university supervisor. With a focus on continuous improvement, organizations can create a more reliable and resilient system that contributes to enhanced occupant comfort, energy efficiency, and overall operational effectiveness.

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