

System Dynamic Modeling of Plant Maintenance Strategy in Thailand

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Abstract

Although management often views maintenance work as only an expense, a proper maintenance strategy can reduce overall plant operation cost, boosting productivity and increasing plant uptime. This research studied the plant maintenance strategy and condition monitoring technology used in Thailand compared with typical and benchmarking plants in United States.

Structured interviews with respondents working in power generation, petrochemical, refinery and gas separation plants in Thailand were compared with the practice of typical and benchmarking plants in the United States, in addition to related information on condition monitoring technology. The study employed a system dynamics approach to model a generic plant maintenance system with collected data from interviews guiding appropriate inputs to the model. Plant uptime and maintenance cost were used as the relevant outputs.

The results suggest that industrial plants in Thailand should reduce preventive maintenance levels and increase predictive maintenance level to better meet the benchmark and increase plant uptime and reduce maintenance cost. The simulation model can be a starting point for particular plants to study optimal plant maintenance behavior and can be combined with actual plant data to further refine the model.

Keywords: condition monitoring technology, plant maintenance strategy, maintenance management, system dynamic

Introduction

Although management often views maintenance work as only an expense, proper maintenance can reduce overall plant operation cost, boosting productivity (Jabar, 2003) and increasing plant uptime. There are four maintenance practices, which are commonly used in industrial plants as it can be briefly defined as following.

- **Reactive maintenance:** A machine or equipment is run until failure (a breakdown), then corrective action is taken in an urgent and emergency situation. As a result, the

maintenance work can cause unplanned shutdown, lost production and expensive repair.

- **Preventive maintenance:** Performed on periodic or constant time interval work schedule, it is normally recommended in the equipment's manual by the manufacturer or is required by some regulatory standard. This can be including annual overhaul, quarterly change lubrication, or parts replacement. Though planned, this can result in higher maintenance cost due to unnecessary maintenance work and lost production due to frequent shutdowns.
- **Predictive maintenance:** Using this approach, the maintenance work is performed based on the machine or equipment's condition, assessed and predicted through use of condition monitoring systems. Some examples include vibration monitoring, oil analysis, thermography, ultrasonic, and motor current analysis.
- **Proactive maintenance:** This practice focuses on eliminating the root cause of the maintenance requirement or seeks to extend machine or equipment life. Root cause failure analysis can lead to change and improvement required in design, operation, and maintenance practices.

Studies done by Moore, 1992, 1997, and 2000 in the United States, and De Jong, 1997 in Australia concluded that optimal industrial plant operation requires reactive and preventive maintenance to be reduced, while predictive and proactive maintenance should be increased.

In this study, the maintenance practices in Thailand were compared with those of typical and benchmarking plants in United States. Various combinations of condition monitoring technologies were also studied, as these are major factors in predictive maintenance work. However, as per benchmark data, it is questionable whether different mix of technologies can affect plant operation performance in term of uptime and maintenance cost. The resistance to change in maintenance strategy from reactive to proactive also needs to be considered, as resistance to change may also be a factor in implementation.

Maintenance work has many aspects of a complex system, as it requires interaction between many parties, events, and system variables in plant operation. As a result, computer simulation and modeling are ideal for studying system behavior, its change and effects, and for determining optimal policy for a respective system. For this reason, system dynamics is adopted in this research to model and simulate the maintenance system. The focus in this research is as follows:

- Maintenance practices in manufacturing plants
- Condition monitoring technology used in manufacturing plants
- Existing plant maintenance strategy
- Change resistance of maintenance strategy
- Effects of change in maintenance strategy to plant uptime and maintenance cost

The results of the study are beneficial for plant maintenance personnel seeking to adopt the proper maintenance strategy for sustainable plant operation performance. Study results may be

helpful as a reference to get management support to improve plant maintenance strategy and invest in condition monitoring technology or other plant asset management systems.

Plant Maintenance Survey

An initial data collection stage was conducted to identify the plant maintenance strategies presently in use in power generation, petrochemical, refinery, and gas separation plants in Thailand. A questionnaire was employed, divided into four main sections:

- **Demographic data:** The research focused on respondents who work for maintenance, operating and engineering department with positions ranging from engineer up to manager. Departments were interviewed since maintenance work is sometime carried out by other departments depending on the plant maintenance strategy used e.g. operators who get trained by maintenance personnel may be able to carry out some simple maintenance work.
- **Maintenance practices:** This section identified the percentage of time routinely allocated by plant personnel to each of the four maintenance practices previously described.
- **Condition monitoring technology:** There are many condition monitoring technologies available such as vibration analysis, oil analysis, thermography, ultrasonic, performance monitoring, motor current analysis. The percentage of time routinely spent by plant personnel using each technology was identified.
- **Change resistance identification:** This section investigated whether resistance to change in plant maintenance strategy or other problem existed in the plant. These included insufficient budgetary support and insufficient training and knowledge to carry out maintenance tasks. The survey questions were presented as Likert scales, starting with “strongly disagree” to “strongly agree”.

An e-mail questionnaire was supplemented with follow up calls and in person, face-to-face structured interviews. This facilitated response, since questions were highly technical, requiring detailed explanations and clarifications. The collected data was then statistically analyzed and used in the system dynamics model construction and simulation.

Data Analysis Results

Survey data was collected from 24 respondents, working in 16 plants; 8 power plants, 4 petrochemical plants, and 4 oil & gas industrial plants. Forty-one percent of respondents was from power plants, 38% petrochemical and oil & gas industry for 21% of total respondents. Since the petrochemical and oil & gas industries are very similar, the researcher combined these two groups together for analysis. The respondents came mainly from maintenance department (92%), with the balance coming from operation and engineering. (See Figure 1)

Plant types	Power Plant	Petrochemical	Oil & Gas	Total
No. of Respondent	10	9	5	24
No. of Plant	8	4	4	16
Percentage	41%	38%	21%	100%

Table 1: Demographic data summary

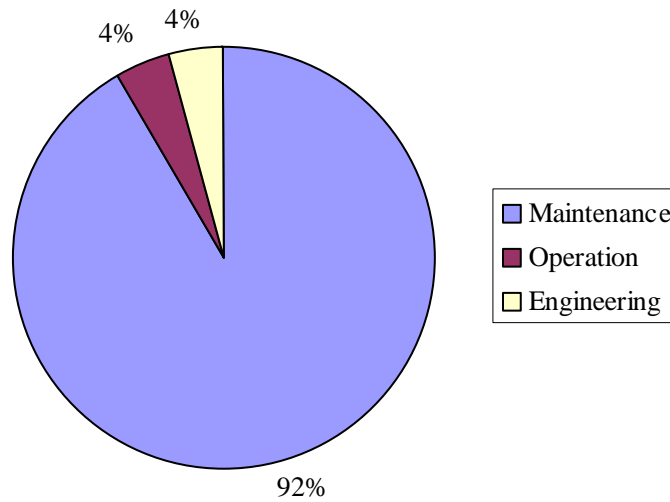


Figure 1: Work functions

The position of respondents is important, given that the research focused on maintenance strategy, typically the responsibility of higher-level staff. Therefore, the target respondent was from engineer up to maintenance or plant manager. Approximately half of respondents were engineers, with 38% manager and 13% supervisors. (See Figure 2)

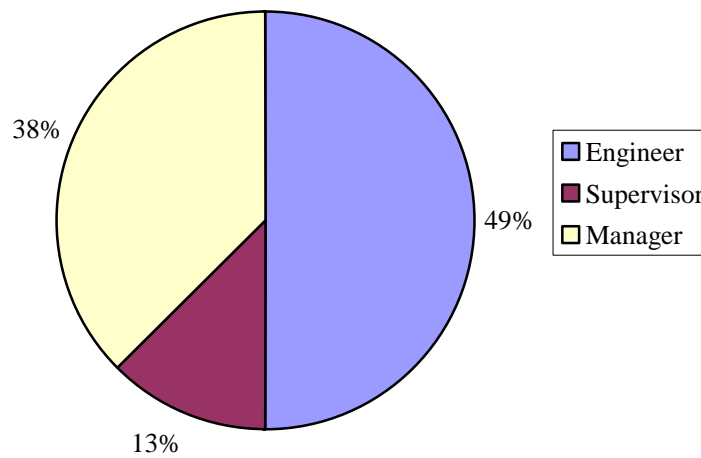


Figure 2: Position range

Figure 3 suggests that the surveyed plants in Thailand relied mainly upon preventive maintenance, as high as 50% of total maintenance work. Preventive maintenance requires unnecessary maintenance work and increased cost. Predictive maintenance practice accounted for 21% when maintenance work is based on equipment condition and monitoring technology is required. Data measured from different technology can be reduced and analyzed for equipment condition assessment. It is then used for maintenance planning such as spare parts, workforce, budget, etc. The production lost can be minimized since necessary work can be planned and carried out at the minimum operation pressure. Reactive maintenance practice is 15%. It does not require any maintenance work unless equipment breaks down, then corrective maintenance is required. This caused high maintenance cost due to consequence and collateral damages. Proactive maintenance practice is 14% when maintenance work is based on the results of root cause analysis and then it can be eliminated or minimized to prevent the same problem to reoccur. The frequent equipment failure can be prioritized according to work order records of actual plant data and then conduct root cause failure analysis for further maintenance prevention e.g. prevent water enter to oil storage tank, rotor shop balancing, machine alignment, etc.

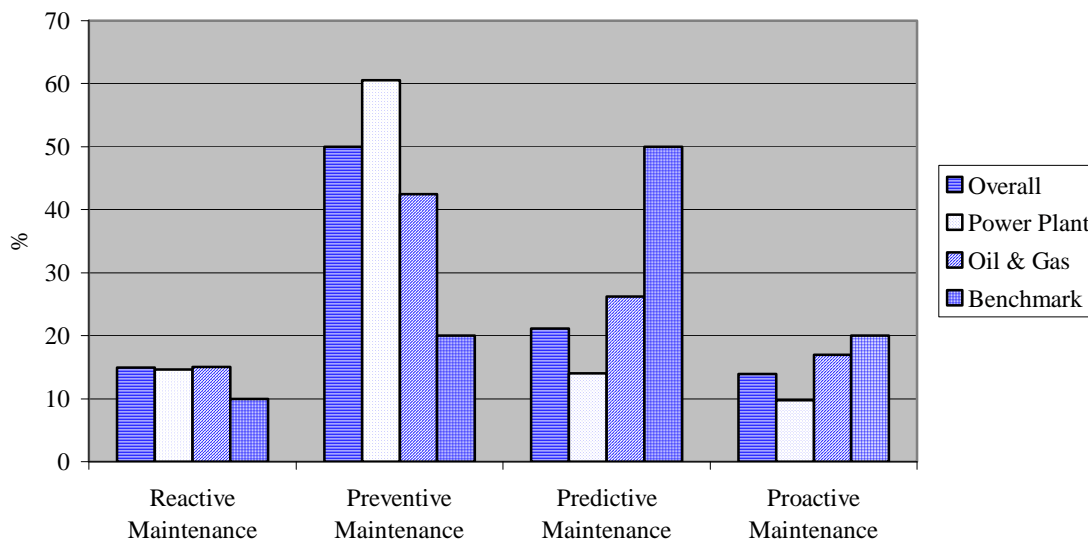


Figure 3: Perception of plant maintenance practices in comparison with benchmark

In comparison to the United States benchmarking plants, preventive maintenance in Thailand is higher than in the United States, where the focus is on predictive maintenance (50%) and preventive maintenance is reduced to a maximum level of 20%. It was also noticed that power plants in Thailand carry out preventive maintenance more than 60% (42% for oil & gas plants). Industrial plants in Thailand are subjected to decreased preventive maintenance and increased predictive maintenance in order to reach benchmarking levels. However, a positive observation is that reactive maintenance is 12-14%, which is close to 10% of benchmarking level.

The best estimated percentage of condition monitoring technology deployed is given as per respondents' awareness and their knowledge and available information in plants. All of industrial

plants in Thailand are mainly focused on vibration analysis (as high as 34% on average) and oil analysis and performance monitoring (14% each). Thermography is 12% as for equipment temperature and its profiles measurement and monitoring. There is 5% accounted for other technologies beyond the scope of the present research. This portion is accounted for water quality monitoring and analysis in power plants and some operating process variables in petrochemical and refinery plants such as pressure, flow, gas compositions, gas molecular weight, etc.

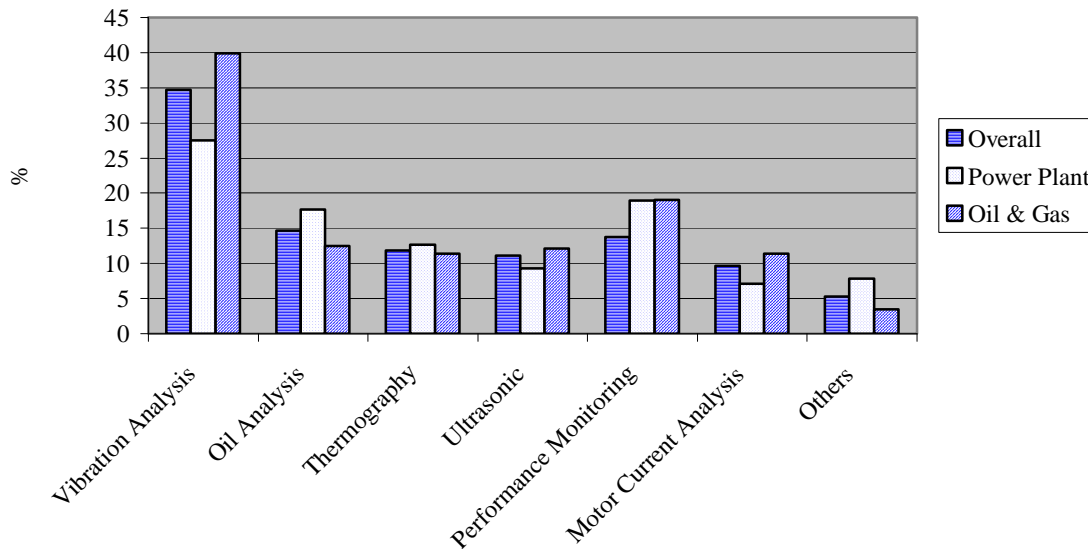


Figure 4: Overview of condition monitoring technology

Figure 4 highlights the comparison between power generation and oil & gas plants. It showed that vibration analysis is carried out more in oil & gas plants as it is up to 40% while oil analysis is used more in power generation plants. Other technologies were approximately the same between these two industries. The researcher focused on only plant uptime and maintenance cost in term of percentage of replacement asset value (%RAV) as operation performance indicators since all data was taken from continuously operating plants; therefore, plant uptime is highly important to prevent lost production or penalty payment.

The average plant uptime of all plants is 90.69% and maintenance cost is 17.22% RAV. However, it is noticed that mean value deviates very much from median value; therefore, suggesting a non-normal distribution. The raw data was reviewed and found that plant uptime varies from 50 to 100% while maintenance cost was from 1 to 70 % RAV due to wide range of industrial plants data was covered in this research. There was also no actual calculation and record of this value in some plant. It was found that most of plants in Thailand don't use RAV unit for their maintenance cost record rather it is calculated or recorded in absolute cost.

Yearly maintenance budget (in million Baht) and training budget for plant maintenance personnel per head (in Baht) was also collected. The budget can be varied depending on such as plant size, process type, financial condition, and management team vision. It was found that

yearly maintenance budget vary from 3 to 1,800 million Baht (50 million USD) and training budget vary from 0 to 500,000 Baht (14,285 USD) per year. There was some power plant data given that no training budget for maintenance personnel, therefore, they perceived as insufficient training. The management team concentrates in short-term operation rather than long-term for continuous improvement and learning organization.

Focused Areas	Response				
	Mean	Median	Agree (%)	Strongly Agree (%)	Total Agree (%)
Management Support	4.29	4.00	62.5	33.3	95.83
Sufficient Training	3.83	4.00	54.2	20.8	75.00
Importance of CM	4.41	4.50	41.7	50.0	91.67
Importance of CMMS	4.50	5.00	41.7	54.2	95.83
Integrated Policy	4.45	5.00	37.5	54.2	91.67
Sufficient Knowledge	3.91	4.00	62.5	16.7	79.16
Policy Improvement	4.00	4.00	62.5	20.8	83.33
<p><i>Note: Ranging scale coding: 1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree or Disagree, 4 = Agree, 5 = Strongly Agree</i></p> <p><i>CM: Condition Monitoring</i> <i>CMMS: Computerized Maintenance Management System</i></p>					

Table 2: Change resistance factors summary

A set of questions was designed to identify whether resistance to change in plant maintenance strategy was a hidden problem encountered in various plants. The majority of respondents agreed or strongly agreed at least 75% in frequency in all questions; therefore, there appears to be very low resistance to change.

However, there were lower percentages on agree and strongly agree responses in the areas of “Sufficient Training”, “Sufficient Knowledge”, and “Policy Improvement”. These might be considered hidden problems regarding to training and knowledge required by maintenance personnel, as well as minor resistance to change when the perception is that they are in position and no improvement required.

System Dynamics Model Development

A system dynamics model was developed using the defects management process first invented by Ledet and team in 1991 (Sterman, 2000) and later converted to The Manufacturing Game (Ledet and Mark, 1994) for maintenance management simulation. In the models, defects in equipments can be eliminated by either repair and planned maintenance, which is accounted for preventive and predictive maintenance. Sources of defect could be generated from wear and tear in operation, equipment/part effects, and collateral damage of consequence or secondary failure caused by run-to-failure or breakdown. With the model, different policy mixes can be simulated and the plant uptime can be improved, generating more revenue. The core model was studied and expanded by Thun in 2006 for studying and analyzing total productive maintenance (TPM)

implementation and maintenance prevention impacts. TPM generally promotes cross function responsibility in maintenance work and training investment. The delay in action of plant maintenance personnel was introduced into model. The operation performance indicator focused is overall equipment effectiveness (OEE). Maintenance cost was not concerned in (Thun, 2006).

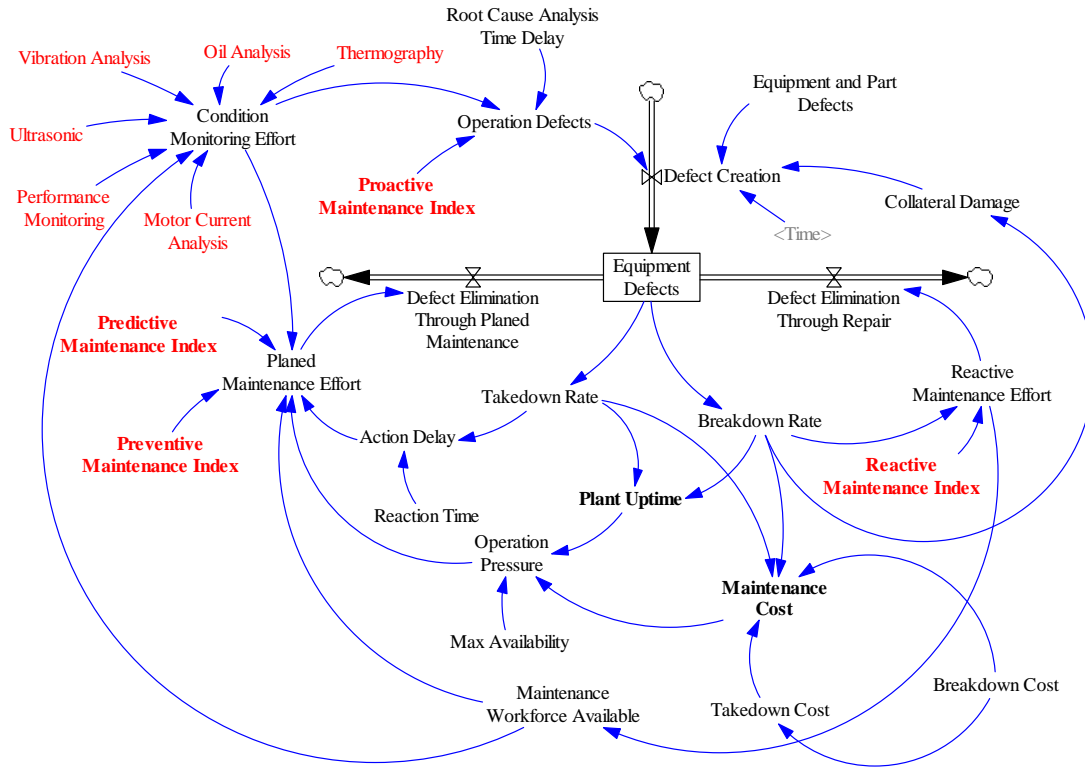


Figure 5: System dynamics model of plant maintenance system

An extension to the model was constructed by adding constant variables of maintenance practice and condition monitoring technology used in plant maintenance. The model output was expanded to include plant uptime and maintenance cost. Sources of equipment defect are from operation due to wear and tear, equipment/part defects that was modeled as random defects creation, and collateral damage of consequence failures due to equipment breakdown. Condition monitoring technologies included vibration analysis, oil analysis, thermography, ultrasonic, performance monitoring, and motor current analysis. This can impact predictive maintenance work schedule depending on equipment condition. The results can also be used for root cause failure analysis as a part of proactive maintenance in order to prevent the same problem from reoccurring. Predictive and preventive maintenances influence to planned maintenance effort with different weight factor. The researcher assumed that predictive maintenance is more effective than preventive maintenance since it can prevent catastrophic failure by early equipment defect detection and reduce unnecessary maintenance work. All condition monitoring technologies influence to condition monitoring effort with different weight factor assuming vibration analysis is more effective in detecting equipment condition over oil analysis and others technology since it can detect equipment failure in early state. Reactive maintenance normally

consumes more maintenance workforce while the remaining is being used by planned maintenance and condition monitoring task. The interaction model diagram is shown in Figure 5.

Simulation Results

A system dynamics model was developed for generic plant maintenance system in Thailand. Maintenance practice and condition monitoring technology were inputs of the model; plant uptime and maintenance cost were outputs. The simulation varied various combinations of maintenance practice consisting of reactive, preventive, predictive, and proactive maintenance, to analyze their influence on plant uptime and maintenance cost. In addition, the combination of condition monitoring technology such as vibration analysis, oil analysis, thermography, ultrasonic, performance monitoring, motor current analysis, etc. was also varied into the model to study its impact on system behavior.

Simulation Data Set	US Typical	Power Plant	Power Plant + CM	Oil & Gas	Oil & Gas + CM	US Benchmark*
Plant maintenance practice						
Reactive maintenance	0.52	0.14	0.14	0.15	0.15	0.10
Preventive maintenance	0.25	0.60	0.60	0.42	0.42	0.20
Predictive maintenance	0.15	0.14	0.14	0.26	0.26	0.50
Proactive maintenance	0.08	0.09	0.09	0.16	0.16	0.20
Condition monitoring technology						
Vibration analysis	0.05	0.05	0.34	0.05	0.34	0.05
Oil analysis	0.05	0.05	0.14	0.05	0.14	0.05
Thermography	0.05	0.05	0.12	0.05	0.12	0.05
Ultrasonic	0.05	0.05	0.11	0.05	0.11	0.05
Performance monitoring	0.05	0.05	0.14	0.05	0.14	0.05
Motor current analysis	0.05	0.05	0.10	0.05	0.10	0.05

Table 3: Input data sets summary

**Note that condition monitoring technology data is not available for benchmark so that the simulation result is considered only maintenance practices.*

While practices for the benchmarking and typical plants in United States were gathered from literature-reviewed results, the survey data was used to simulate maintenance policy used in Thailand for power generation and oil & gas plants.. To see the maintenance system behavior, the simulation study was conducted using four simulations:

- **Simulation #1 (“US Typical”):** Typical plants in United States carry out mainly reactive maintenance with minimum condition monitoring technology applied: 52% Reactive, 25% Preventive, 15% Predictive, 8% Proactive. Condition monitoring is used only 5% of each technology.

Plant maintenance personnel are focusing on repair work of reactive maintenance in “fire fighting” mode. Repair work can lead to consequence failures, therefore, increased equipment defects. Most of the maintenance resources are used for repair work; therefore, insufficient workforce is available for planned maintenance and condition monitoring efforts. After long time operation, most of defects are eliminated and more time remains for workforces to do planned maintenance and condition monitoring work. Under these conditions, equipment defects seem to be stable, though there is some additional defects introduced into equipment by depreciation when the plant and equipment becomes older than an assumed ten years. Plant uptime is slowly decreasing while maintenance cost is increasing.

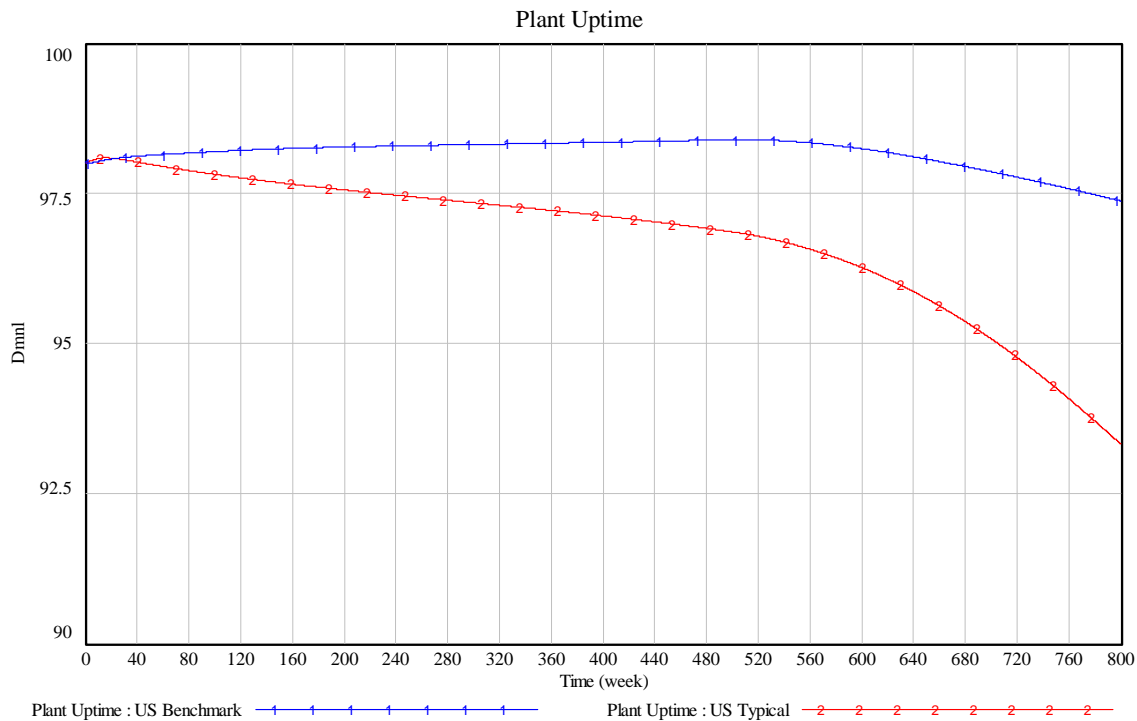


Figure 6: Plant uptime versus time in comparison between typical and benchmarking plants in United States

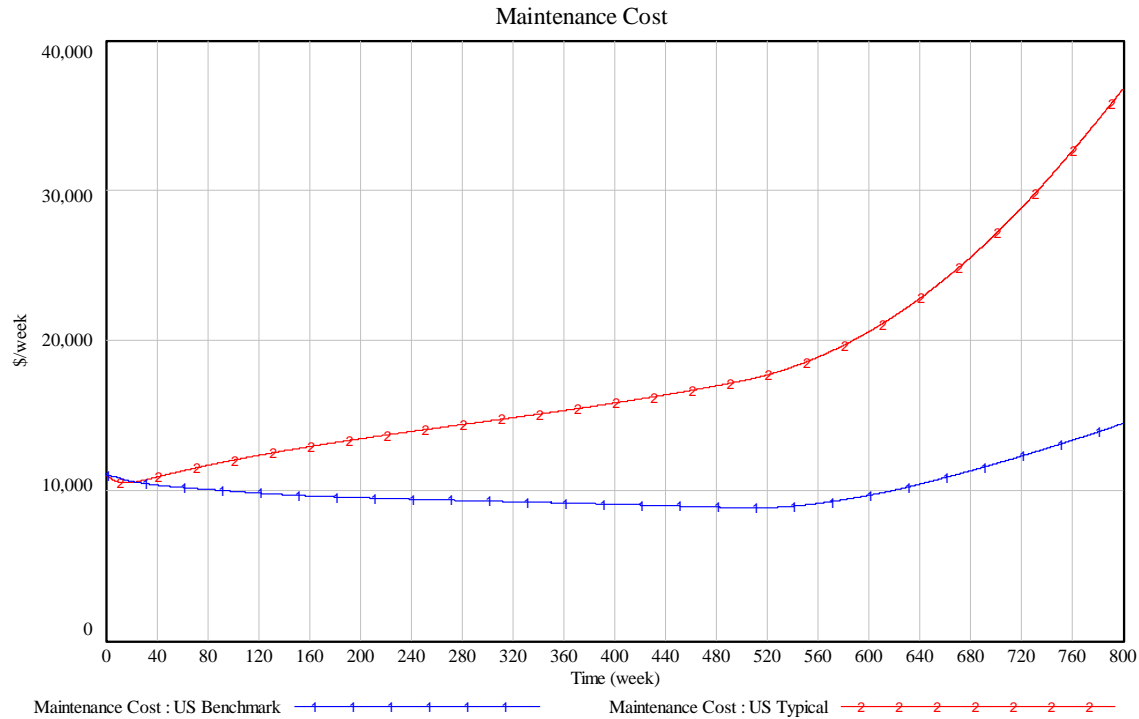


Figure 7: Maintenance cost versus time in comparison between typical and benchmarking plants in the United States

- Simulation #2 (Thailand: “Power Plant”, “Power Plant + CM”):** Power generation plants in Thailand: 14% Reactive, 60% preventive, 14% Predictive, 9% Proactive. Condition monitoring is minimum as 5% of each technology. The comparison is studied with and without condition monitoring technologies applied as 34% Vibration analysis, 14% Oil analysis, 12% Thermography, 11% Ultrasonic, 14% Performance monitoring, 10% Motor current analysis.

Plant uptime is initially increasing while maintenance cost is decreasing but this starts to slowly change in an opposite direction when plant and equipment get old due to depreciation. If plant maintenance personnel spend more time on condition monitoring work, this can reduce maintenance cost and increase plant uptime. Condition monitoring technology can make plant uptime and maintenance cost converse the goal faster and is stable at better level over period of time.

- Simulation #3 (Thailand: “Oil & Gas”, “Oil & Gas + CM”):** Oil & gas plants in Thailand: 15% Reactive, 42% Preventive, 26% Predictive, 16% Proactive. The comparison study is conducted at with and without condition monitoring technologies applied as 34% Vibration analysis, 14% Oil analysis, 12% Thermography, 11% Ultrasonic, 14% Performance monitoring, 10% Motor current analysis.

Plant uptime of oil and gas plants is slightly lower than power plants in Thailand, since reactive maintenance is slightly higher. Maintenance cost is slightly higher than power plants. However,

these two operation indicators are not significantly different when condition monitoring technology is introduced to the plants as it converges to the goal faster and stable at better level than without condition monitoring technology applied.

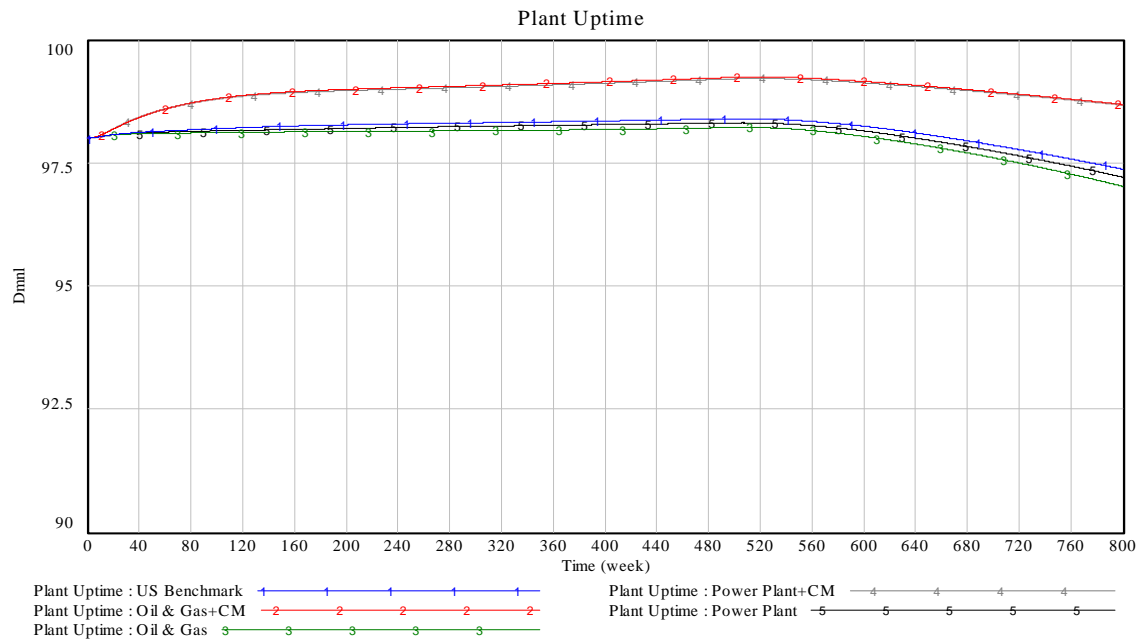


Figure 8: Comparison of plant uptime of typical plants in Thailand with and without condition monitoring technology applied to benchmarking plant in the United States

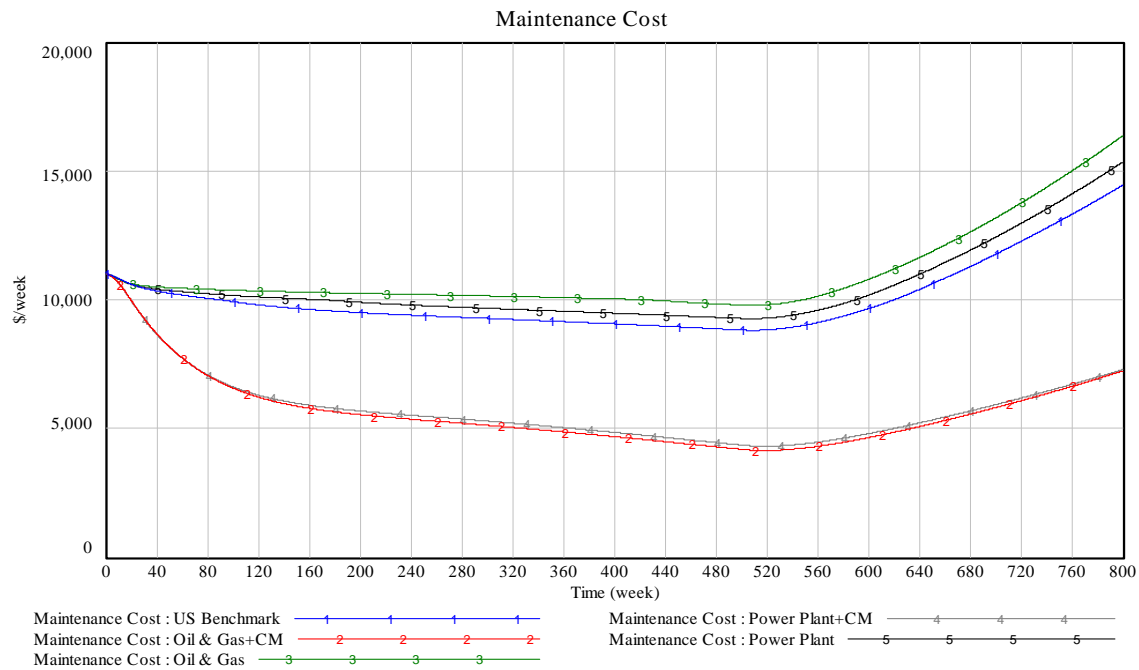


Figure 9: Comparison of maintenance cost of typical plants in Thailand with and without condition monitoring technology applied to benchmarking plant in United States

- **Simulation #4 (“US Benchmark”):** Benchmarking plants in United States: 10% Reactive, 20% Preventive, 50% Predictive, 20% Proactive. Condition monitoring technology is minimum at 5% each technology.

In comparison, typical plants in Thailand have higher maintenance cost and lower plant uptime than benchmarking plants in the United States.

Conclusions

Plant maintenance strategy in Thailand involves a low level of reactive maintenance or “fire fighting” behavior. It can generate consequence or secondary failures of associated parts and equipment. Moreover, it can cause additional cost due lost production during an unplanned shutdown. Most of plants are reducing reactive maintenance and increasing preventive, predictive and proactive maintenance since the maintenance work can be planned. However, the percentage of preventive maintenance in Thailand at 42-60% is still considered high compared with benchmarking plants in the United States (20% preventive and 50% predictive maintenance), so that it should be reduced while increasing predictive maintenance instead because of maintenance work can be managed and planned according to equipments condition. Condition monitoring technology is very helpful in this regard and major contribution factor to predictive maintenance work as a result. Reactive maintenance is 14% for plants in Thailand while it is 52% of total maintenance in typical plants in United States. This is considered a positive observation.

A system dynamics model was developed to represent generic plant maintenance system and used for simulation study of plant maintenance behaviors. Plant maintenance practices and condition monitoring technology from survey data were used as inputs to model while considering outputs in term of plant uptime and maintenance cost. The study found that changes in percentage of maintenance practice and condition monitoring technology significant impact to plant uptime and maintenance cost. Plant uptime was increased when reducing reactive maintenance and increasing planed maintenance of preventive, predictive, and proactive maintenances. On the other hand, maintenance cost was reduced. Adding more condition monitoring effort could cause plant uptime and maintenance cost converse to goal faster (maximum plant uptime, minimum maintenance cost) and stable at desired level. The system behavior is considered as goal seeking pattern.

Limitations

Some limitations of the research should be noted, which could affect model accuracy and the research process:

The model was developed for a generic plant maintenance system covering various plant types e.g. power generation, petrochemical, refinery, gas separation plants, etc. Outputs of system behaviors can represent only typical behavior and might not be accurate for all types of plant. System dynamics can only give relative magnitude and direction of system outputs as its nature and limitation.

Since data collection from the structured interviews was based on respondents' perceptions, not actual data recorded, the system behavior identified might not represent actual behavior of a particular plant, but instead generic behavior of plant maintenance system. This research covered various types of industrial plant as a starting point of applying system dynamics methodology in the field of plant maintenance in Thailand. Further modification and model development is required to use in a particular plant with actual data inputted.

Recommendations

Both benchmarking plants in the United States and the system dynamics simulations suggest that industrial plants in Thailand should reduce reactive maintenance to below 10% and preventive maintenance to 20% or less, while increasing predictive maintenance to more than 50% of total maintenance.

Such a recommendation can keep plant maintenance behavior away from "fire fighting" condition and result in increased plant uptime, and reduced maintenance cost. To perform more on predictive maintenance, condition monitoring technology is required to collect data, monitor, and analyze equipments' condition for maintenance planning and scheduling. Also, equipment condition data can be used for root cause failure analysis as a part of proactive maintenance to prevent problem from reoccurring.

In order to find optimal maintenance policy for a particular plant, system dynamics and simulation can be performed at a particular plant using actual data recorded. The concept of system thinking and modeling is a very important tool for continuous improvement in a learning organization.

Implications and Future Research

The generic system dynamics model developed here is a useful starting point for a particular plant or case study, but the model can be modified to fit the plant maintenance system in effect. Actual data recorded can be used for model construction and simulation study. The input of model can be changed from constant values to actual data, which varies over time; in such cases, a lookup function is very useful to read data into such model.

Integration and synergy strategy is considered very important for plant maintenance, since there are currently many condition monitoring technologies available. Technologies can be integrated and used together to get an optimum plant maintenance strategy. The collecting of data of condition monitoring technology in different units is recommended because more than one technology used for each particular equipment.

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