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Maintenance for Energy efficiency: A Review

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Abstract. Energy efficiency program is used to reduce energy cost that leads to a reduction in production or overhead cost. Energy saving can be obtained by application of energy-efficient technologies, operational improvement, and effective maintenance. However, maintenance and energy efficiency is usually researched separately. The purpose of this paper is to investigate the role of maintenance in energy saving and available maintenance approaches for energy consumption reduction. Various literatures and publication on the research areas were reviewed and summarized to show the importance on maintenance and approached commonly used for energy efficiency.

1. Introduction

Energy is one the vital factors in our world, not only for the industrial sector but also to commercial and residential sectors. Our world has been heavily depending on energy for a long time, especially fossil fuel. As the fossil fuel production and reserves deplete, energy consumption increases. Consequently, fuel price direction is always going up in the long term. On the other hand, renewable energy is still trying hard to fill the hole left by fossil fuel. Therefore, energy management has shown up to be a partial solution for an increase in energy price and a decrease in fossil fuel production. The objective of energy management is to manage the energy usage effectively and efficiently. Many sectors such as industry, commercial, and residential have been planning and then implementing energy efficiency and energy management program with one goal, to reduce energy cost.

The primary benefit of application of energy-efficient technologies (EET) is a reduction in energy cost [1-2]. Generally, energy efficiency is usually related to the environment. To support this, Pons pointed out that energy efficiency had a strong relationship with environmental performance [2]. But these are not the only benefits. The application of EET also contributes to an increase in productivity that may lead to lower the production cost [1]. Other research found out that energy intensity was proportional to productivity that 1% rise in productivity may lead to more than 1% increase in energy efficiency [3]. Moreover, a study conducted in China's iron and steel industries also revealed that improvement in energy efficiency also improved productivity [4]. But the benefits do not end here. EET also generates non-energy benefits that may outweigh the energy-saving benefits [5]. The non-energy benefits may include the following: reduced production costs, reduced cost of environmental compliance, reduced waste-disposal costs, better product quality, higher utilization factor, higher reliability and better worker safety [5]. The bottom line is that energy-efficient technologies generate not only energy-benefits but also non-energy benefits.

In general, there are two ways to save energy: application of energy efficient technology, and implementation of energy management practices. Energy efficiency research mainly focuses on efficient



technology application and diffusion [6]. But, this is not the only way to save energy. Energy management practices could contribute to energy saving either. Energy management practices include housekeeping, maintenance, energy monitoring, energy training, energy audit, and etc [6-7]. In addition, several researchers also stated the importance of housekeeping and maintenance in energy savings [6] [8-11]. To make an energy efficiency program much more cost-effective, one needs to combine energy efficient technology application with energy management practices [6]. An effective maintenance program will play a very important role in energy management practices.

One of energy management practices highlighted by Backlund is maintenance and monitoring [6]. Without performing maintenance and monitoring, the potential energy savings generated by energy efficient technologies will not be achieved [6]. Moreover, by implementing proper maintenance and energy monitoring continuously, one can detect inefficiencies and malfunctioning equipment [6], and then any necessary actions could be taken to restore the equipment energy performance to an acceptable level by a user. Even, Simple maintenance actions can have a dramatic effect in maintaining energy performance of an equipment [12]. In addition, energy management practices such as maintenance and energy monitoring are less capital intensive and rather requires knowledge, attention, and awareness [6]. In contrast, energy efficient technologies investment is relatively more capital intensive. Therefore, maintenance could be used as one of the cost-effective strategies in energy efficiency program.

Although many people believe that maintenance is important for sustainable of energy efficiency project, maintenance, and energy management are two topics which are often researched independently. Therefore, there is a need to combine these two fields to gain more energy efficiency potential in its application.

2. Maintenance and Energy

Knowles has tried to investigate the relationship between maintenance and energy in a refrigeration system by surveying the literature for evidence of a link because of lack of real-world data [12]. He found out that maintenance had a major role to make sure refrigeration system operates at maximum efficiency. He also stated that detailed energy monitoring was required to improve maintenance procedures. Monitoring the condition of individual main components are also needed to obtain optimal performance [12]. He also addressed that a new method of maintenance was required [12]. This approach should apply a predictive maintenance that uses inexpensive technologies such as infrared thermography, vibration sensor, and oil analyzer [12]. The justification of monitoring technology application is based on several criteria such as investment cost, and the simplicity of use [12]. Finally, he concluded that good maintenance practice could improve energy efficiency, increase the reliability of refrigeration system and reduce the leakage of greenhouse gasses [12].

Another researcher, Lewis, tried to demonstrate the interdependencies of energy and maintenance management based on three case studies in facilities in North America [13]. Based on the case studies, there was an interdependent link between energy and maintenance management, but this interdependent link was not widely applied in practice because reactive maintenance and energy management were commonly applied [13]. If the link were widely applied, both the energy and maintenance program could be more productive. Lastly, he also concluded that tools were required to assist facility managers in planning and implementing energy and maintenance management programs [13].

In addition to Knowles and Lewis's works, Al-Ghanim developed a quantitative model in the form of multiple linear regression that related energy consumption and maintenance factor (Failure rate) and production factor (Production rate) [14] in an energy-intensive plant. This model was used and tested in an aluminum profile manufacturing plant in Middle-East. He proved that there was a significant relationship between these three factors. A proper preventive maintenance program and other factors such spare parts availability, and skill of maintenance personnel would result in lower failure. When the number of failure decrease, energy consumption per unit production would decrease because of less energy consumed for fewer production startup. This method could generate significant energy savings at low cost [14]. The same result also obtained by Nofirman, who performed a case study analysis in chiller system [15]. The condenser cleaning scheduled was optimized based on an increase in energy

consumption and condenser cleaning cost. By finding an optimal interval for condenser cleaning, there would be large energy savings potential [15]. The potential savings were obtained at low cost [15].

3. Maintenance for Energy Efficiency

Energy efficiency program is important to reduce energy consumption and cost. Energy efficiency improvement can be achieved by application of energy efficiency technologies [2], operational or production improvement [16], and proper housekeeping and maintenance practices [11] (Figure 1). Application of energy efficiency technology can range from application of energy-efficient motor, application of variable speed drives (VSD), application of waste heat recovery technologies and etc. Energy consumption reduction also can be achieved by operational or production improvement [16] in many ways, such operational or production improvement, economic scheduling of equipment, economic scheduling of chiller plants and etc. Our focus is on reducing energy consumption through proper maintenance strategies (Figure 2). Maintenance strategies for energy efficiency can be classified into housekeeping, preventive maintenance, predictive maintenance (PdM), and condition-based maintenance (CBM), and advanced condition monitoring (Fault detection and diagnosis and etc) (Figure 2). Potential reduction of energy consumption through maintenance strategies is discussed in the next several sections.

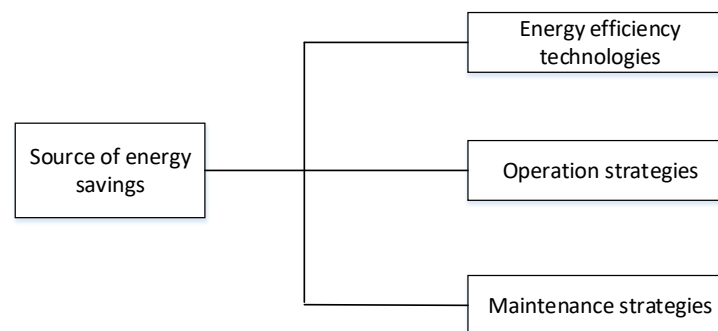


Figure 1. Sources of energy saving opportunities

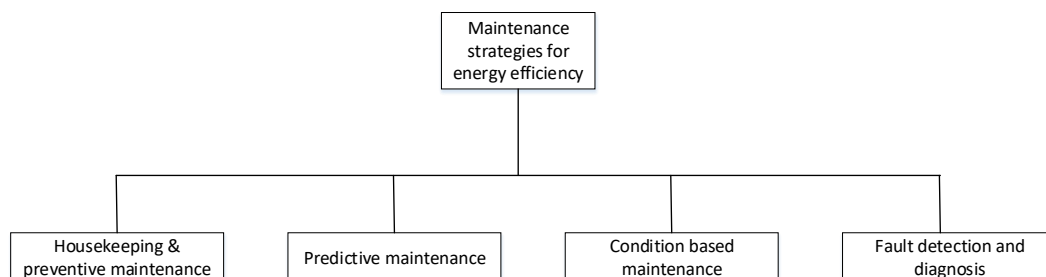


Figure 2. Maintenance strategies for energy efficiency

3.1. Housekeeping and Maintenance

Housekeeping is usually concerned with aesthetic, organizational aspects, and safety hazards [17]. However, there is no single accepted definition for housekeeping. The example of housekeeping for safety consideration is such as identification of spills, leaks, damaged equipment, faulty and etc. A steam leak does not have an impact on safety only but also on energy consumption. Preventing or repairing steam leak would minimize the negative impact both on safety and energy consumption. Nowadays, the effective energy management program incorporates housekeeping into the program. In energy efficiency perspective, housekeeping are things related to energy loss identification by walking through or performing a visual inspection on a facility [18]. In practice, implementation of housekeeping cannot be separated from maintenance.

Housekeeping and maintenance are recognized as energy saving practices that can be implemented at no or low cost [11]. Identification of (potential) energy loss is usually part of an energy audit. The basic level of energy audit is walk-through energy audit. During the walk-through audit, an auditor always performs a visual inspection to identify (potential) wasted energy in a facility [18]. Some energy audits finds energy savings potential through housekeeping and maintenance in areas of steam distribution system, compressed air distribution system, electric motor and etc [10-11] [43] .

3.1.1. Housekeeping and Maintenance in Industrial Facilities A walk-through energy audit on steam distribution found improper insulation, poor insulation, worn-out insulation, and no insulation on some part of steam distribution [10] [19]. The estimate of energy loss was equal to 250 MWh annually [10]. A large part of steam distribution was not properly installed which lead to steam leakage and energy loss [19]. Repairing steam leak has payback period within 4 months [11]. Corroded pipes and valves were also discovered because of improper maintenance [19]. In addition, inspection of steam traps was also potential for energy savings. During an energy audit, most of the steam traps are in bad condition, some of them did not function properly, some of them were damaged, and few of them did not function at all [10-11] [19]. Checking and maintaining steam traps regularly has payback period within 5 months [11]. Based on the result, it seems that a good housekeeping and maintenance to prevent energy loss in steam distribution system was ignored.

Lighting energy audit is performed to evaluate the lighting system in a facility while production running. During an energy audit, it was found that windows and roof-light were difficult to access and rarely cleaned, and the workers were not satisfied with the lighting level [10]. To solve this issue, regularly scheduled maintenance was proposed. Providing adequate lighting level can increase productivity. Lumen level of lighting system degrades over time by 30-50% [18]. Additional lumen degradation may be caused by accumulated dirt on the lighting equipment. It is believed that there is a relationship between lighting level and productivity. The worker might prefer higher lighting level than the minimum required by standard [20]. One study showed that a proper lighting level might increase worker productivity up to 7.7% [20]. Another study demonstrated that changed the light level from 30 fc to 50 fc might increase the productivity by 8% [21]. In contrast, reducing lighting level from 100 fc to 50 fc may decrease productivity up to 28% [18]. Therefore, a good maintenance program to maintain the lighting level is necessary

Electric motor energy consumption is responsible for 30-80% of total industrial consumption around the world [22]. Life cycle cost (LCC) of electric motors indicate that 92% of the cost spent on energy consumption, 5% on capital, and the rest 3% on maintenance [23]. To lower motor LCC, one needs to reduce its energy consumption. One energy audit found out that the motors were 25 years old, rewound several times, and fortunately well-maintained [10]. However, when rewinding the motor, the cost of rewinding and reduction in motor efficiency should be taken into consideration. First, the cost of motor rewinding is between 17.5% (for large motor) and 88% (for small motor) of the initial cost of high efficient- motor [22]. For a small motor, replacing the motor with a high-efficient motor may be the best option. In contrast, rewinding larges motor may be more cost-effective. Second, the motor rewinding may reduce its efficiency in the range of 1-2% [22]. Rewound the motor several times may further reduce motor efficiency.

In addition to the application of energy-efficiency technology to motors, there are other opportunities to save energy by implementing a good housekeeping and maintenance program. Firstly, turning off the motor when it is not needed. Zohir recommended to switch-off the 20 motors when they were not needed in a factory in Egypt [11]. It could save energy by 84,000 MWh annually without additional investment cost [11]. Secondly, further savings could be achieved by performing proper cleaning on the motor [22]. The failure modes of motor failure consist of overloading (25%), contamination and dirt (43%), single phasing (10%), broken insulation (12%), deterioration (5%), and other (5%) [24]. Any dirt covers the motor surface and parts may lead to insulation damaged, contamination of lubricant (a damaged to bearing), and higher motor temperature by blocking the motor cooling process. Thirdly, to perform proper lubrication on the motor. Fourthly, to make sure proper installation and alignment of the motor [22]. All of these factors, if they are not done properly, may cause motor failure or at least a performance deterioration. Proper maintenance program may prevent or reduce the consequences of motor failure.

Compressed air system (CAS) is widely used in industrial or manufacturing process because it is easy to use and has low investment cost. But it is also one of the most expensive utilities in an industrial facility. The largest part of CAS life cycle cost goes to energy cost (78%) and then followed by capital and maintenance cost (16% and 6%) [25]. The CAS consist of the supply-side and demand-side system. It is believed that 50-70% of energy saving potential may come from the demand side and the rest saving potential may come from the supply-side [26]. The greatest energy loss of compressed air system comes from air leaks. Air leaks in compressed air system have no use and waste 20-50% of a compressor output [25] [27-28].

Air leaks also contribute to operating losses, reduced reliability, lowered production, and increased maintenance requirement and cost [25]. The best way to detect leaks is to use an ultrasonic leak detector. By knowing the size and the location of the leaks, immediate action to seal the leaks can be performed to mitigate further energy losses. Preventing and repairing the leaks are very cost-effective. Several studies has revealed that it had a payback period of less than one year [27]. Consequently, reduced air leaks can increase production and decrease operating and maintenance cost [27]. However, total prevention of air leaks is impractical, but 15% leakage rate is acceptable [28]. In addition to reducing leaks, housekeeping and maintenance can have a positive impact on energy efficiency on compressed air system by minimizing or eliminating inappropriate use of compressed air, switching-off air-using equipment when not in used, changing air filter regularly, and keeping the compressor and intercooling surface clean [27] [29].

The operation and maintenance (O&M) personnel also play a very important role in energy management practice. Incapability of O&M personnel in maintaining and operating the equipment could prevent or at least lower the projected energy savings. Shirley has demonstrated the importance of energy management practices related to O&M [30]. One study showed that 80% of energy savings could be caused by energy management practices of O&M personnel [30], what's more, many energy audits focus on technical and economic analysis and usually does not consider the operation and maintenance factors. These factors included evaluation of past maintenance practices, maintenance cost, preventive maintenance techniques and tools, staff skills and attitudes [31]. Therefore, for a successful energy efficiency programs, operation and maintenance factors should be addressed accordingly.

3.2. Condition Based Maintenance (CBM) For Energy Efficiency

Less than a decade ago, the term of factories 4.0, also known as smart factory, has been introduced. The concept of a smart factory is the future of manufacturing. It also indicates that the era of 4th industrial revolution has just begun. The factories 4.0 concept combines the automation and data exchange in manufacturing technologies. It includes the application of internet of things (IoT), cloud computing, cyber-physical system (CPSs), big data analysis (BDA), and information and communication technology (ICT) [32]. These key technologies enable intelligent manufacturing. The emerge of the new manufacturing technology also affects the energy management and maintenance strategy and practice. It leads to an advanced application of condition monitoring technology. It may enables maintenance

strategy to shift from traditional preventive and predictive maintenance to condition-based maintenance [33-34].

The application of IOT in energy management might enable manufacturing to measure and record energy consumption at near real-time at the component, sub-system, equipment, production line, and plant level [35-37]. By monitoring energy consumption in near real time and with the supporting tool for visualization of energy consumption pattern and profile, one might be able to notice any abnormal behavior in increased energy consumption. The increased energy consumption profile may indicate fault or malfunction of the equipment [38-39]. With the help of data and decision analysis for maintenance, immediate and proper maintenance actions can be performed to tackle the problem [35&38]. Monitoring energy consumption also enables maintenance personnel to detect the source of failure (At what machine and its location) and diagnose the type of failure [36]. To enable maintenance personnel to detect and diagnose faults correctly, the measurement of other parameters may be required. The parameters need to be measured divided into two categories but not limited to equipment and work environment parameter [34]. The equipment parameter consists of speed, displacement, position, vibration, flow, temperature, voltage, power and etc. On the other hand the. The work environmental parameter comprises of noise, temperature, humidity, electromagnetic radiation and etc [34].

3.2.1. Application of CBM in Industrial Manufacturing

Endo conducted field experiments of energy monitoring for maintenance of two press machine, a molding machine and four compressors in a discrete manufacturing plant [40-41]. The monitoring collected two kinds of data for two press machines, and a molding machine. Firstly, a behavior data (Equipment behavior data) in the form of the waveform of energy. Secondly, a target data in the form of energy [40]. In addition, it was important to define the operational condition of equipment: Normal energy and wasted energy. The normal energy represented the energy consumption during the production of a normal product (Non-defected product) on the designed tact time. The wasted energy is classified into stopped condition (Anomaly stop, and tooling change), performance decrement condition (Idling and tact delay), and defective condition [40].

With the help of visualization tool, the operator could decide the proper action to restore the performance when the abnormal behavior of energy consumption happens for each operational condition type. In this case, they did two improvement action to reduce energy consumption. First improvement action was to reduce the tact delay by maintaining the components of the molding machine and a press machine and replacing a mold in the molding machine. Second improvement action was to reduce energy consumption by turning off the press machine when it was not needed and replacing a mold in a molding machine. The energy saving obtained from the improvement was around 10% [40].

The same procedure was applied to compressor system. Endo defined compressed air flow and waveform of energy as behavior data and energy as target data. The wasted energy occurred during stop condition. To improve the energy consumption, several improvement actions were performed based on the visualization of behavior and energy data pattern, and operational condition of equipment. First, lowering the set pressure of the compressor system. Second, improving pipes around the dicing machine. The result of the improvement was 7% energy savings in term of kWh consumption and 20% energy savings in term of specific energy consumption (kWh/m³) [41]. The improvement result for machine tools and compressors was not only in term of reduced energy consumption but also an increase in productivity [40-41].

Motor one of the largest energy-consuming equipment in industries [22]. Most of the energy efficiency programs for the motor is a replacement with more efficient more [22][42]. Second is by using variable speed drive whenever possible [42-43]. However, the motor efficiency deteriorates overtime and wastes energy. To overcome this issue, Singh proposed a methodology for motor efficiency motoring and maintenance optimization with cost-benefit analysis [44]. Simulation was performed for three type of efficiency drop curves: Linear, exponential, and quadratic curves [44]. On the other hand, traditional condition monitoring usually defines the critical limit, when a parameter reaches the limit, it is time to perform maintenance. Unfortunately, it is not always economically to

perform maintenance since it does not consider the wasted energy during the performance degradation since most motor faults lead to efficiency degradation. Consequently, the need for condition monitoring such as vibration, oil, current, and thermography analysis can be minimized. In addition, by performing correct maintenance based on efficiency monitoring, the wasted energy can be minimized [44]. Therefore, performing efficiency monitoring based maintenance can reduce wasted energy and maintenance cost.

3.2.2. Maintenance Policies with Energy Efficiency Consideration

Maintenance policy definition is "... set of rules describing the triggering mechanism for the different maintenance action. It is a question of what triggers maintenance action ?..." [45]. Nowadays, maintenance policy in literature is more related to maintenance optimization model. Maintenance policies are classified into corrective maintenance, preventive maintenance, predictive maintenance, autonomous maintenance, and design out maintenance [46]. Unfortunately, there are only few maintenance policies with energy saving consideration available in the literature [47-48]. Combination of condition monitoring and maintenance policies create a condition-based maintenance (CBM). Some of available energy-oriented maintenance policies is discussed in the next few paragraphs.

First, Hoang introduced energy efficiency indicator (EEI) and mathematical formulation for calculating the proposed EEI at component and system level [49]. He also proposed a concept of remaining efficiency-efficient lifetime (REEL). REEL provided the information regarding efficient lifetime before the efficiency degrades below an allowable level at component or system level. REEL may be a useful tool to assist maintenance decision. The proposed concept was tested on a fan blower system. Hoang also tested the proposed EEI based-CBM model on TELMA platform software to predict the EEI and REEL at both component and system level. The results showed that the proposed model could predict the EEI and REEL when the motor experienced efficiency degradation on their two main components; accumulator and motor drive [50]. Then He compared the proposed EEI based-CBM model with conventional CBM Model (Based on deterioration level). The result demonstrated that EEI based-CBM could surpass conventional CBM in term of cost and implementation [51].

Second, Xu proposed a periodic maintenance model that considered productivity and energy efficiency. In a special case, this model could lead to maximum average productivity and average efficiency. But it is likely that in most cases, there must be a trade-off between average productivity and efficiency [52]. Furthermore, Yildirim proposed a combined model for production and maintenance problem with minimal repair and energy consumption consideration to minimize the total cost [53]. In addition, a study by Yan showed that there was a relationship between energy consumption and reliability of a machine tool. Yan also proposed a methodology to assess the impact of maintenance on energy consumption. The result demonstrated that as the reliability decreases, energy consumption increases dramatically [54].

Next, Zou proposed an opportunity window model to optimize energy saving by turning off a certain machine and performing preventive maintenance at the same time without sacrificing the production output [47]. The trade-off between energy saving and production output may occur. Finally, Xia developed an energy-oriented opportunistic maintenance [48]. The concept is different from traditional opportunistic maintenance that only considers maintenance cost and equipment downtime [55]. The proposed methodology used energy saving window (ESW) policy to reduce energy consumption, downtime, and simplify scheduling for a batch production line in series [48].

3.3. Faults detection and diagnosis, and thermoeconomic diagnosis

Fault detection and diagnosis (FDD) and thermoeconomic diagnosis are one of advanced condition monitoring methods for an energy system. An energy system usually consists of several subsystems or components that work in series. One fault or malfunction on a component may affect the performance of the next component and so on. Therefore, fault or malfunction diagnosis for this type of system is relatively difficult to detect what component causes faults since a fault in one component may affect

many other component performance and the entire system. Several chiller FDDs and thermoeconomic diagnosis are briefly explained in the next two paragraphs.

Chiller faults detection and diagnosis (FDD) is used to detect a fault on the system and then diagnose the cause of the fault. Therefore, necessary maintenance actions can be performed to restore the performance. Chiller FDD is one type of condition monitoring (CM) techniques. In general, the chiller FDD is classified into quantitative-model based, qualitative-model based, and process history based [56]. There are eight common faults occur on the chiller system [57]: reduced condenser water flow, reduced evaporator water flow, refrigerant leak, refrigerant overcharge, excess oil, condenser fouling, non-condensables in the refrigerant, and defective expansion valve. Each of the common faults contributes to reduced chiller performance, in other words, it increases chiller energy consumption. The examples of chiller FDD method are ruled-based diagnostician [58], simple thermodynamic model [59], thermoeconomic monitoring [60], and etc. However, the integration of the chiller FDD into current maintenance program has never been available in the literature yet.

A thermoeconomic diagnosis was first theoretically developed by Valero [61]. Thermoeconomic analysis can be applied to the design, operational, and maintenance stage of an energy systems [62]. It is as important as energy analysis. Thermoeconomic diagnosis can detect a malfunction of an equipment and then quantify the wasted energy because of the malfunction, and therefore proper maintenance action can be taken on the right equipment and with the right maintenance solution [62-65]. By considering maintenance cost and wasted energy cost, an optimal maintenance result can be obtained. In addition, the effect of maintenance on an equipment of an energy system can be validated by thermoeconomic diagnosis [62]. Some case studies applied thermoeconomic diagnosis on refrigeration system [66], steam power plant [62], combined cycle power plant [67], gas turbine system [68], desalination plant [69] and etc. However, it seems that the application of thermoeconomic diagnosis in practices is not widely used in practice.

4. Maintenance concept: RCM, TPM, and ECM

A maintenance concept is defined as the set of various maintenance strategies (Corrective, predictive, CBM, etc) and the general structure in which these strategies are selected and implemented [29&70]. The maintenance concept forms the framework from which maintenance strategies are developed [70]. The well-known maintenance concepts are reliability centered maintenance (RCM) and total productive maintenance (TPM) (Figure 3). RCM was born in airlines industries, on the other hand, TPM was born in manufacturing industries. The RCM is an asset-centered methodology, on the other hand, TPM is a people-centered methodology [71]. However there could be a relationship between TPM and RCM [72]: RCM could enhance TPM implementation, and vice versa. These two approaches are widely used in industrial and manufacturing plants around the world. However, there is another maintenance concept developed for energy efficiency called energy centered maintenance [ECM]. These maintenance concepts will be briefly reviewed in the next several paragraphs.

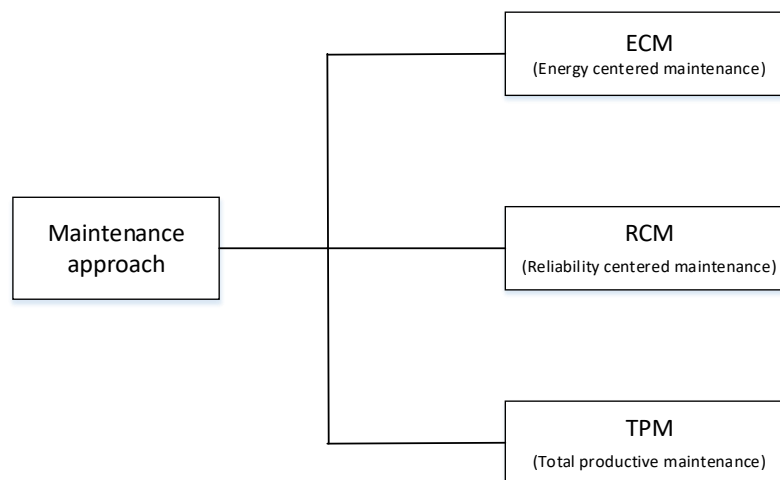


Figure 3. Potential maintenance approaches for energy efficiency consideration

First is reliability-centered maintenance (RCM). RCM is a process used to determine the maintenance requirements of any physical assets in its operating context [73]. The primary objective of RCM is to maintain system function, not on the system hardware [74]. The RCM was born for the first time in the airline's industry. RCM can be applied to the component, sub-system, and system level. Since then, the RCM has been applied to many different industries such as marine industry [75], US Navy ships [76], steel industry [77], electric distribution systems [78], automotive industry [79], refining industry [80], real estate industry [81], process industry [82], airline industries [83], power plant [84], and etc. Moreover, RCM can also be applied for specific consideration such as safety [85] and reliability [86]. The RCM could also be adapted and modified for specific needs such as maintenance design for a paint-spraying robot [87]. Unfortunately, it seems that specific application of RCM for energy efficiency consideration has never been done.

Next is total productive maintenance (TPM). TPM according to Nakajima [88] is ...” *productive maintenance carried out by all employees through small group activities....*”. TPM also has a goal to maximize equipment effectiveness. To improve equipment effectiveness, TPM starts by identifying the six losses with respect to equipment [88]. The overall equipment effectiveness (OEE) is used a key performance indicator in TPM implementation. However, in recent development and implementation of TPM, there are 16 losses types that fall into four categories: losses that impede overall equipment efficiency, equipment loading time, worker efficiency, and efficient use of resources [89]. The last category includes yield loss, consumable loss, and energy loss. Implementation of TPM in a manufacturing company in Japan could reduce energy consumption by 30% [88]. A case study of TPM in a steel manufacturing plant showed that TPM implementation could reduce the energy cost between 8% and 27% [90].

A greater savings might be achieved by more focusing on the maintenance with energy consideration. Unfortunately, there are only few researches focusing on the application of TPM with energy consideration. Al-Homoud introduced the concept of total productive energy management (TPEM) [91]. TPEM approach combined the principle of total quality management (TQM) and total productive maintenance (TPM) to reduce energy consumption. The objective of TPEM is to motivate all members involves in the operation and maintenance of a facility to take part in energy conservation activities. He also emphasized that energy savings through operation and maintenance practices could be successfully achieved and more feasible to implement than those achieved through major retrofits [92].

To improve TPM process, Barletta proposed an Energy Overall Equipment Effectiveness (Energy OEE) as key performance indicator (KPI) for a discrete manufacturing firms [93]. Energy OEE was

used to assess the impacts of energy consumption losses instead of time losses. The application of Energy OEE was tested in a virtual manufacturing facility modeled by discrete event simulation (DES) on a CNC machine [92]. The result demonstrated that the use of Energy OEE along with DES might improve both energy efficiency (Reduced energy consumption) and productivity (Reduced defective parts) [92]. The introduction of Energy OEE on TPM process could improve energy efficiency factor in manufacturing industries.

The last one is energy centered maintenance (ECM). Howell introduced ECM concept to increase energy efficiency of a facility through maintenance [93]. ECM is a maintenance concept focusing on energy consumption reduction. Energy consumption excesses or energy waste are used as the primary criterion in determining the specific maintenance or repair needs [93]. ECM consists of six steps: First step is equipment identification that energy related. Second is data collection and equipment baseline prediction. Third is development of ECM inspection plan. Fourth is equipment performance monitoring and then comparing with the baseline. Any deviation with baseline needs root cause analysis for improvement. Next is the selection of maintenance action to restore equipment efficiency. The last step is the improvement of maintenance plans. A case study of ECM application in a facility claimed that ECM could help reducing energy consumption by as much as 30% [93]. It seems that ECM can be a prospective maintenance concept focusing on energy consumption reduction.

5. Discussion

The heart of maintenance for energy efficiency is predictive maintenance. The first strategy of maintenance for energy efficiency is housekeeping. Housekeeping identifies a potential energy loss by performing a visual inspection of an industrial facility. In several circumstances, the use of a predictive technology such as ultrasonic leak detector, light meter and other may be required during the housekeeping activity. From an economic point of view, housekeeping is usually cost-effective for energy management program since it can be done at no or low cost. In addition, more saving can be obtained from non-energy benefits such as an increase in productivity.

The second maintenance strategy is condition-based maintenance (CBM). CBM techniques are performed by monitoring energy in real time with the help of IoT technologies. It may need many sensors to monitor many key parameters of in-service equipment. The key performance indicator of a fault is the increase in energy consumption. Any abnormal profile of energy consumption indicates that a fault on an equipment has occurred. Since many equipment faults lead to performance degradation, the need for other predictive maintenance tasks such as vibration analysis, oil analysis, and thermography analysis can be minimized. Therefore, CBM application may generate two main benefits; lower energy and maintenance cost. Since the CBM may require many measurement instruments and supporting system, the investment cost tends to be higher. Unfortunately, the cost-effectiveness of CBM application is rarely discussed in the literature. In addition, there may be a need for a methodology to assess the economics of CBM application in practice.

The third strategy is advanced condition monitoring for an energy system such as FDD and thermoeconomic diagnosis. The investment cost for the application of advanced condition monitoring might be low since it usually only needs existing measurement instruments. But it may need a human resource with high knowledge and skills to develop the system and interpret the result of condition monitoring into maintenance action. The human factor may cause the application of these methods is not widely applied in practice. In addition, the Integration of FDD and thermoeconomic diagnosis into current maintenance program have never been available in the literature yet.

The application of these maintenance strategies can be optimized by applying maintenance concepts such as RCM and TPM. The use of maintenance concept may help to select the appropriate maintenance strategy and to implement the proactive task effectively and efficiently. Unfortunately, the application of RCM and TPM with energy efficiency consideration is rarely available in the literature. In addition, a novel maintenance framework may be needed to integrate available maintenance concepts and strategies to achieve more energy-saving potential cost-effectively.

6. Conclusion

Proper maintenance is essential to reduce energy losses. Energy saving through maintenance can be obtained by housekeeping and simple maintenance, condition based maintenance and advanced condition monitoring. Proper housekeeping and simple maintenance can reduce energy losses at low cost and relatively cost-effective (Shorter payback period). Application of condition-based maintenance also can generate energy savings. But the economic analysis of CBM implementation for energy efficiency may be required to justify the cost-effectiveness of CBM application.

The trend of maintenance strategy for energy efficiency is condition-based maintenance. First is by combining energy monitoring with IoT technologies. Second is by introducing an energy-related performance indicator for condition-based maintenance. Next is the use of advanced condition monitoring method such as fault detection and diagnosis (FDD), and thermoeconomic diagnosis. However, maintenance for energy efficiency cannot be separated from operational improvement. During an inspection or condition monitoring, energy can be saved by both proper maintenance and operational improvement.

There are some maintenance concepts available in the literature, the well-known concepts are RCM and TPM. Both RCM and TPM have been widely used in many applications. Unfortunately, RCM and TPM applications are not fully explored and utilized for energy reduction consideration. In addition, a new maintenance framework may be required to integrate available maintenance concepts and strategies to achieve more energy-saving potential.

References

- [1] Worrell E, Laitner J A, Ruth M and Finman H 2003 Productivity benefits of industrial energy efficiency measures *Energy* 28 p 1081–98
- [2] Pons M, Bikfalvi A, Llach J and Palcic I 2013 Exploring the impact of energy efficiency technologies on manufacturing firm performance *J. Clean. Prod.* 28 p 289–96
- [3] Boyd G A and Pang J X 2000 Estimating the linkage between energy efficiency and productivity *Energy Policy* 28 p 289–96
- [4] Zhang J and Wang G 2008 Energy saving technologies and productive efficiency in the Chinese iron and steel sector *Energy* 33 p 525–37
- [5] Pye M and McKane A 2000 Making a stronger case for industrial energy efficiency by quantifying non-energy benefits *Resources, Conservation and Recycling* 28 p 171–183
- [6] Backlund S, Thollander P, Palm J and Ottosson M 2012 Extending the energy efficiency gap *Energy Policy* 51 p 392–96
- [7] Jovanović B and Filipović J 2016 ISO 50001 standard-based energy management maturity model - Proposal and validation in industry *J. Clean. Prod.* 112 Part 4 p 2744–55
- [8] Abdelaziz E A, Saidur R and Mekhilef S 2011 A review on energy saving strategies in industrial sector *Renew. Sustain. Energy Rev.* 15 p 150–68
- [9] Kannan R and Boie W 2003 Energy management practices in SME - Case study of a bakery in Germany *Energy Convers. Manag.* 44 p 945–59
- [10] Gordić D, Babić M, Jovičić N, Šušteršič V, Končalović D and Jelić D 2010 Development of energy management system - Case study of Serbian car manufacturer *Energy Convers. Manag.* 51 p 2783–90
- [11] Zohir A E 2010 Energy efficiency improvement by housekeeping measures. Thermal Issues in Emerging Technologies, ThETA 3, Cairo, Egypt, Dec 19–22 nd
- [12] Knowles M and Baglee D 2012 The role of maintenance in energy saving in commercial refrigeration *J. Qual. Maint. Eng.* 18 No. 3 p. 282–94
- [13] Lewis A, Elmualim A and Riley D 2011 Linking energy and maintenance management for sustainability through three American case studies *Facilities*. 29 Issue: 5/6, p.243–254
- [14] Al-Ghanim A 2003 A statistical approach linking energy management to maintenance and production factors *J. Qual. Maint. Eng.* 9 Issue: 1 p.25–37

- [15] Firdaus N, Prasetyo B T and Luciana T 2016 Chiller: Performance deterioration and maintenance *Energy Eng. J. Assoc. Energy Eng.* 113
- [16] Plambeck E L 2012 Reducing greenhouse gas emissions through operations and supply chain management *Energy Econ.* 34 p S64–S74
- [17] Dufort V M and Infante-Rivard C 1998 Housekeeping and safety: An epidemiological review *Saf. Sci.* 28 p 127–38
- [18] Capehart B L, Turner W C and Kennedy W J 2006 *Guide to energy management*
- [19] Ozturk H K 2005 Energy usage and cost in textile industry: A case study for Turkey *Energy*. 30 p 2424–46
- [20] Juslén H 2007 *Lighting , Productivity and Preferred Illuminances - Field Studies in the Industrial Environment*
- [21] van Bommel W and van den Beld G 2004 Lighting for work: a review of visual and biological effects *Light. Res. Technol.* 36(4) p 255 – 69
- [22] Hasanuzzaman M, Rahim N A, Saidur R and Kazi S N 2011 Energy savings and emissions reductions for rewinding and replacement of industrial motor *Energy* 36 p 233-240
- [23] Krings A, Boglietti A, Cavagnino A and Sprague S 2017 Soft Magnetic Material Status and Trends in Electric Machines *IEEE Trans. Ind. Electron.*
- [24] McCoy GA, Litman T and Douglass JG 1003 *Energy-efficient electric motor selection handbook*
- [25] Saidur R, Rahim N A and Hasanuzzaman M 2010 A review on compressed-air energy use and energy savings *Renew. Sustain. Energy Rev.* 14 p 1135–53
- [26] Nehler T, Parra R and Thollander P 2018 Implementation of energy efficiency measures in compressed air systems: barriers, drivers and non-energy benefits *Energy Effic.* 11 p 1281 – 1302
- [27] Saidur R and Mekhilef S 2010 Energy use, energy savings and emission analysis in the Malaysian rubber producing industries *Appl. Energy* 87 p 2746–58
- [28] Dindorf R 2012 Estimating potential energy savings in compressed air systems *Procedia Engineering* 39 p 204 – 11
- [29] Alsyouf I 2007 The role of maintenance in improving companies' productivity and profitability *Int. J. Prod. Econ.* 105 p 70–78
- [30] Hansen S J 1999 Investment Grade Energy Audits *Cogeneration and Competitive Power Journal* 14 pp 63-70
- [31] Hansen S J and Brown J W. 2003 *Investment Grade Energy Audit* CRC Press
- [32] Zhong R Y, Xu X, Klotz E and Newman S T 2017 Intelligent Manufacturing in the Context of Industry 4.0: A Review *Engineering* 3 p 616–630
- [33] Shrouf F and Miragliotta G 2015 Energy management based on Internet of Things: Practices and framework for adoption in production management *J. Clean. Prod.* 100 p 1-12
- [34] Xiaoli X, Yunbo Z and Guoxin W 2011 Design of intelligent internet of things for equipment maintenance *Proceedings - 4th International Conference on Intelligent Computation Technology and Automation, ICICTA 2011*
- [35] Shrouf F, Ordieres J and Miragliotta G 2014 Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm *IEEE International Conference on Industrial Engineering and Engineering Management*
- [36] Brizzi P, Conzon D, Khaleel H, Tomasi R, Pastrone C, Spirito A M, Knechtel M, Pramudianto F and Cultrona P 2013 Bringing the Internet of Things along the manufacturing line: A case study in controlling industrial robot and monitoring energy consumption remotely *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*
- [37] Vijayaraghavan A and Dornfeld D 2010 Automated energy monitoring of machine tools *CIRP Ann. - Manuf. Technol.*
- [38] Karnouskos S, Colombo A W, Lastra J L M and Popescu C 2009 Towards the energy efficient future factory *IEEE International Conference on Industrial Informatics (INDIN)*

- [39] Vikhorev K, Greenough R and Brown N 2013 An advanced energy management framework to promote energy awareness *J. Clean. Prod.*
- [40] Endo M, Tsuruta K, Saitoh Y, Nakajima H and Hata Y 2011 Toward an optimal QCDE in manufacturing by health monitoring of equipment energy consumption *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*
- [41] Endo M, Nakajima H and Hata Y 2012 Simplified Factory Energy Management System based on operational condition estimation by sensor data *IEEE International Conference on Automation Science and Engineering*
- [42] Saidur R 2010 A review on electrical motors energy use and energy savings *Renew. Sustain. Energy Rev.* 14 p 877–98
- [43] de Almeida A T, Fonseca P and Bertoldi P 2003 Energy-efficient motor systems in the industrial and in the services sectors in the European Union: Characterisation, potentials, barriers and policies *Energy* 28 p 673–90
- [44] Singh G, Anil Kumar T C and Naikan V N A 2019 Efficiency monitoring as a strategy for cost effective maintenance of induction motors for minimizing carbon emission and energy consumption *Reliab. Eng. Syst. Saf.* 170
- [45] Pintelon L, Gelders L and Puyvelde F V 2000 *Maintenance Management* 2nd Edition (Acco)
- [46] Ding S H and Kamaruddin S 2014 Maintenance policy optimization—literature review and directions *Int. J. Adv. Manuf. Technol.* 76 p 1263 – 83
- [47] Zou J, Arinez J, Chang Q and Lei Y 2016 Opportunity Window for Energy Saving and Maintenance in Stochastic Production Systems *J. Manuf. Sci. Eng.* 138
- [48] Du S, Xia T, Xi L, Pan E and Xiao L 2018 Energy-Oriented Maintenance Decision-Making for Sustainable Manufacturing Based on Energy Saving Window *J. Manuf. Sci. Eng.* 140
- [49] Hoang A, DO P, Iung B, Levrata E and VOISIN A 2014 Prognostics and Energy Efficiency: Survey and Investigations *Annual conference of the prognostics and health management society*
- [50] Hoang A, Do P and Iung B 2015 Prognostics on energy efficiency performance for maintenance decision-making: Application to industrial platform TELMA *Proceedings of 2015 Prognostics and System Health Management Conference, PHM 2015*
- [51] Hoang A, Do P and Iung B 2016 Investigation on the use of energy efficiency for condition-based maintenance decision-making *IFAC-PapersOnLine* 49:28 p 073–078
- [52] Xu W and Cao L 2014 Energy efficiency analysis of machine tools with periodic maintenance *Int. J. Prod. Res.* 52:18 p 5273 – 85
- [53] Yildirim M B and Nezami F G 2014 Integrated maintenance and production planning with energy consumption and minimal repair *Int. J. Adv. Manuf. Technol.* 74 p 1419 – 30
- [54] Yan J and Hua D 2010 Energy consumption modeling for machine tools after preventive maintenance *IEEM2010 - IEEE International Conference on Industrial Engineering and Engineering Management*
- [55] Ab-Samat H and Kamaruddin S 2014 Opportunistic maintenance (OM) as a new advancement in maintenance approaches: A review *J. Qual. Maint. Eng.* 20 No. 2 pp. 98-121
- [56] Katipamula S and Brambley M R 2005 Review article: Methods for fault detection, diagnostics, and prognostics for building systems—A review, part I *HVAC R Res.* 11:1 p 3-25
- [57] Comstock M C, Braun J E, Groll E A and Danks R 2002 A survey of common faults for chillers *ASHRAE Transactions.* 108 p 819
- [58] Comstock M C, Braun J E and Groll E A 2002 The sensitivity of chiller performance to common faults *ASHRAE Transactions.* 7:3 p 263-79
- [59] Saththasivam J and Ng K C 2008 Predictive and diagnostic methods for centrifugal chillers *ASHRAE Transactions.* 114 p 282-87
- [60] Piacentino A and Talamo M 2013 Innovative thermoeconomic diagnosis of multiple faults in air conditioning units: Methodological improvements and increased reliability of results *Int. J. Refrig.* 36:8 p 2343-65

- [61] Valero A, Serra L and Lozano M A 1993 *Structural Theory of Thermoconomics ASME Winter Annual Meeting Symposium on thermodynamics and the design, analysis and improvement of energy systems*.
- [62] Ray T K, Datta A, Gupta A and Ganguly R 2010 Exergy-based performance analysis for proper O&M decisions in a steam power plant *Energy Convers. Manag.* 51:6 p 1333–44
- [63] Usón S, Valero A and Correas L 2010 Energy efficiency assessment and improvement in energy intensive systems through thermoeconomic diagnosis of the operation *Appl. Energy* 87 p 1989–95
- [64] Verda V, Serra L and Valero A 2005 Thermoeconomic Diagnosis: Zooming Strategy Applied to Highly Complex Energy Systems. Part 1: Detection and Localization of Anomalies *J. Energy Resour. Technol.* 127 p 42–49
- [65] Verda V 2006 Accuracy level in thermoeconomic diagnosis of energy systems *Energy* 31 p 3248–60
- [66] D'Accadia M D and De Rossi F 1998 Thermoeconomic optimization of a refrigeration plant *Int. J. Refrig.* 39:12 p 1223–32
- [67] Zaleta-Aguilar A, Olivares-Arriaga A, Cano-Andrade S and Rodriguez-Alejandro D A 2016 β -characterization by irreversibility analysis: A thermoeconomic diagnosis method *Energy* 111 p 850–58
- [68] Orozco D J R, Venturini O J, Palacio J C E and Del Olmo O A 2016 A new methodology of thermodynamic diagnosis, using the thermoeconomic method together with an artificial neural network (ANN): A case study of an externally fired gas turbine (EFGT) *Energy* 123 p 20–35
- [69] Uche J, Serra L and Valero A 2006 Exergy Costs and Inefficiency Diagnosis of a Dual-Purpose Power and Desalination Plant *J. Energy Resour. Technol.* 128:3 p 186–93
- [70] Waeyenbergh G and Pintelon L 2002 A framework for maintenance concept development *Int. J. Prod. Econ.* 77 p 299–313
- [71] Jardine A K S and Tsang A H C 2013 *Maintenance, replacement, and reliability: Theory and applications, second edition*
- [72] Ben-Daya M 2000 You may need RCM to enhance TPM implementation *J. Qual. Maint. Eng.*
- [73] Moubray J 1997 *Reliability centered maintenance*
- [74] Rausand M 1998 Reliability centered maintenance *Reliab. Eng. Syst. Saf.* 60:2, pp 121–132
- [75] Conachey R M and Montgomery R L 2002 Application of reliability-centered maintenance techniques to the marine industry *ABS Technical Papers*
- [76] Jacobs K S 1998 Reducing maintenance workload through Reliability-Centered Maintenance (RCM) *Nav. Eng. J.* 110:4 pp 89–97
- [77] Deshpande V S and Modak J P 2002 Application of RCM to a medium scale industry *Reliab. Eng. Syst. Saf.* 77 pp 31–34
- [78] Goodfellow J W 2000 Applying reliability centered maintenance (RCM) to overhead electric utility distribution systems, *Power Engineering Society Summer Meeting IEEE*
- [79] Ramli R and Arffin M N 2012 Reliability centered maintenance in schedule improvement of automotive assembly industry *Am. J. Appl. Sci.* 9:8 p 1232–36
- [80] Deepak P and Jagathy Raj 2013 A New Model For Reliability Centered Maintenance In Petroleum Refineries *Int. J. Sci. Technol. Res.* 2:5 p 54–64
- [81] El-Haram M A and Horner M W 2002 Practical application of RCM to local authority housing: A pilot study *J. Qual. Maint. Eng.* 8 p 135–43
- [82] Afefy I H 2010 Reliability-Centered Maintenance Methodology and Application: A Case Study *Engineering* 2 p 863–73
- [83] Matteson T D 1985 Airline experience with reliability-centered maintenance. *Nuclear Engineering and Design* 89 p 385–90
- [84] Bhangu N S, Singh R and Pahuja G L 2011 *Reliability centred maintenance in a thermal power plant: a case study. Int. J. Productivity and Quality Management.* 7 p 209–28
- [85] Deshpande V S and Modak J P 2002 Application of RCM for safety considerations in a steel plant

- Reliab. Eng. Syst. Saf.* 78 p 325–34
- [86] Deshpande V S and Modak J P 2003 Maintenance strategy for tilting table of rolling mill based on reliability considerations *Reliab. Eng. Syst. Saf.* 80 p 1–18
- [87] Pintelon L, Nagarur N and Van Puyvelde F 2002 Case study: RCM – yes, no or maybe? *J. Qual. Maint. Eng.* 5 p.182-92
- [88] Nakajima S 1998 *Introduction to TPM: Total Productive Maintenance* Productivity Press
- [89] Ahuja I P S and Khamba J S 2008 Total productive maintenance: Literature review and directions *Int. J. Qual. Reliab. Manag.* 25 p 709-56
- [90] Ahuja I P S and Khamba J S 2007 An evaluation of TPM implementation initiatives in an Indian manufacturing enterprise *J. Qual. Maint. Eng.* 13 p. 338-52
- [91] Al-Homoud M S 2000 Total productive energy management *Energy Engineering*, 97 p 21-38
- [92] Barletta I, Andersson J, Johansson B, May G and Taisch M 2015 Assessing a proposal for an energy-based Overall Equipment Effectiveness indicator through Discrete Event Simulation *Proceedings - Winter Simulation Conference*
- [93] Howell M T, Alshakhshir F 2017 *Energy Centered Maintenance: A Green Maintenance System* Fairmont Press, Incorporated, CRC Press, Taylor & Francis Group