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Analyzing the effects of implementation of Total Productive Maintenance (TPM) in the manufacturing companies: a system dynamics approach

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Abstract. In today's highly competitive business environment, manufacturers have to offer a great variety of products on a high quality level, in the least amount of time for an acceptable price. Therefore machine maintenance and in general, implementing an appropriate maintenance strategy has become increasingly important for manufacturing companies to accomplish these requirements. Total productive maintenance (TPM) has become one of the most popular maintenance strategies to ensure high machine reliability. In this paper and through system dynamics concepts, effects of implementation of TPM on machine reliability, process quality and net throughput has been analyzed. Results obtained show the effectiveness and usefulness of TPM in reducing breakdown maintenance (BM) tasks as well as enhancing machine reliability, process quality and product's throughput.

Keywords: machine reliability, system dynamics, Total Productive Maintenance (TPM)

1 Introduction

In order to be successful in today's world-class manufacturing environment companies have to fulfill several requirements. Maintaining a reliable manufacturing process is a key success factor to satisfy these requirements which can be achieved through implementing a proper maintenance strategy.

Any operation or process done on machine or its parts to enhance the efficiency of machine before or after the breakdown is called maintenance. In the recently released European Standards regarding maintenance[22], maintenance is defined as "the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function". A manufacturing business is said to be prosperous over the years, when it runs non-interrupted and always maintains a stable and high productive production flow. Plant can achieve productivity up to a satisfactory level by proper maintenance work[4]. An efficient maintenance strategy not only reduces the probability of breakage of machine elements or shutdown of machines which hinders the production's schedule, but also such a strategy enhances the efficiency and life-span of machines, process quality and labor force productivity[18].

Total Productive Maintenance (TPM) has widely been accepted as an effective strategy for improving maintenance in the manufacturing companies. Especially in the last decades because of a growing competitive environment the importance of TPM has increased[23]. Therefore in this paper by getting help from system dynamics which is a part of system thinking concept the effects of implementing TPM on machine breakdowns, machine reliability, process quality, machine and labor force utilization for production in manufacturing companies is investigated.

The remainder of the paper is organized as follows. In the next section we will take a deeper look at maintenance and briefly describe some of the modern and sophisticated approaches as well as some primitive ones

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for maintaining machines. In section 3 introduction to system dynamics is given. Section 4 examines the proposed system dynamics model for analyzing effects of implementation of TPM in manufacturing companies. Finally, in section 5 conclusions are given.

2 Maintenance and its strategies

There are plenty of maintenance management approaches and strategies. However, here we name some of these strategies which are more commonplace.

2.1 Breakdown Maintenance (BM)

Preventive Maintenance (PM) first developed at General Electric[23]. PM is undertaken in advance of the interruption of production and major breakdown and strives to keep production flow continuously running. It is defined as the planned maintenance of plants and equipment in order to prevent or minimize breakdowns and depreciation rates. It is the procedure adopted in most of the companies to maintain desirable and reliable operating conditions of equipment and machinery.

2.2 Condition-Based Maintenance (CBM)

One drawback of PM policy is that some components may be over maintained, i.e. replaced prematurely. However, if the condition of the item can be monitored continuously or even frequently, PM actions will be implemented only when failure is judged that is about to happen. This is the basic concept of CBM. Performance-parameter analysis, vibration monitoring, oil analysis, etc. are some condition monitoring techniques that are involved in CBM. Each of these methods discloses a specific type of fault. For example, vibration-monitoring can be employed to detect wear, imbalance, misalignment, loosened assembles or turbulence in plant with rotational or reciprocating parts[6]. A survey of the recent CBM models can be found in Tsang [25].

2.3 Reliability-Centered Maintenance (RCM)

There are various formal definitions of RCM. Some of which are as the following: Moubray[14] has defined RCM as "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context". According to Agrawal et. al[1] RCM is "A process used to determine what must be done to ensure that any physical asset continues to fulfill its intended functions in its present operating context". Rausand[16] gives the following definition "RCM is a system consideration of system functions, the way functions can fail, and a priority based consideration of safety and economics that identifies applicable and effective PM tasks". What RCM is maintaining is the system function. It may well be required to redesign or modify a physical asset to maintain its system function in the case of a change in its operating context.

2.4 Total Productive Maintenance (TPM)

TPM, which focuses on people and is an integral part of TQM, defines the organization of maintenance work by applying the following actions[26]:

- Cultivate a sense of ownership in the operator by introducing autonomous operator maintenance, whereby the operator takes responsibility for the primary care of his/her plant. The tasks involved include routine inspection, lubrication, adjustments, minor repairs, as well as the cleanliness and tidiness of his/her workspace.
- Optimize the operator's skills and knowledge of his/her plant in order to maximize operating effectiveness. The operator is thus mobilized to detect any early signs of deterioration, wear, maladjustment, oil leaks, or loose parts. He/she should regard it as his/her duty to propose improvement suggestions to eliminate losses due to a sub-optimal or breakdown performance of the plant.

- Use cross-functional teams consisting of operators, maintainers, engineers and managers to improve personnel and equipment performance.
- Establish a schedule of clean-up and PM to extend the plant's life-span and maximize its uptime.

Top management should demonstrate their commitment to TPM by devoting sufficient time and allocating adequate resources to create and sustain any necessary cultural changes and to provide training for employees to achieve autonomous maintenance.

The overall goal of TPM is to raise the overall equipment effectiveness[17].

3 System Dynamics (SD)

System Dynamics is a computer-aided approach for analyzing and solving complex problems with a focus on policy analysis and design. The methodology, first developed by Forrester[8] and refined over the last decades, was initially applied in industrial and business systems management. The approach uses a perspective based on information feedback and delays to understand the dynamic behavior of complex physical, biological, and social systems.

System Dynamics has been applied to a wide range of problem domains. It includes work in corporate planning and policy design[8, 12], economic behavior[21], public management and policy[11], biological and medical modeling[10], energy and the environment[7], theory development in the natural and social sciences[5], dynamic decision making[19], complex non-linear dynamics[13], software engineering[9], and supply chain management[2, 3, 24].

SD and its principles of feedback and secondary effects has also helped many managers to think through how a strategy might or might not work, and what kind of consequences- intended or unintended-emerge. Much of the art of SD modeling is about discovering and representing the feedback processes, which-along with stock and flow structures, time delays, and nonlinearities- determine the dynamics of a system[20]. The understanding of these processes is then used to draw causal loop diagrams (CLDs). CLD is a powerful graphic tool to see the relationships among a system's parts and their interactions with each other.

SD is also a method to enhance learning in complex systems[20]. Attempting to draw CLDs is a useful process for gaining a better understanding of a system's mechanisms and feedback links. Going through a learning process will help us to modify our decision rules and our mental models of the real world. As we get updated in a learning process, we will be able to set dynamic improving goals (moving targets) for the system under study. This will enable us to improve system performance.

4 System dynamics model for maintenance systems

Nowadays, cost, quality, and time must be seen as main competitive success factors, which have to be considered simultaneously. TQM, TPM, and other improvement philosophies and techniques offer powerful concepts and tools for enhancing effectiveness and productivity in manufacturing companies.

In this section a systemic view to maintenance, especially TPM, through establishing a system dynamics model is taken. This model considers the relationships between training of employees, throughput pressure, machine breakdowns, machine reliability and process quality. The model uses the causal loop diagram and flow diagram to depict processes, concepts and interdependencies used in the field of system dynamics. The model is capable of explaining the dynamics of improvement efforts and employees' training and thus making the underlying problem visible for everybody's examination.

Before constructing the system dynamics model for TPM we will examine the most elementary approach for maintaining equipments through system dynamics terms and concepts and see why this strategy is not acceptable in today's competitive world.

4.1 System dynamics view to breakdown maintenance

The discussion of the history of maintenance has shown that a fire-fighting maintenance strategy in terms of reactive maintenance leads to unexpected machine breakdowns. Furthermore, the maintenance department is busy most of the time repairing machines. It does not have the time to do maintenance tasks on a regular basis nor does it have the time to improve the maintenance system within the production process. This leads to the fact that preventive maintenance tasks are neglected, resulting in more machine breakdowns. Machine breakdowns exhaust the maintenance department's capacity to maintain or improve the production system on a regular basis. In the long run, according to Fig. 1, there will be a situation with many unexpected machine breakdowns and an overloaded maintenance department.

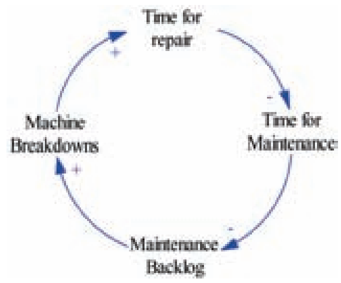

Fig. 1. Dynamics of break down maintenance

In order to investigate the effects of breakdown maintenance (BM) on Quality, production pressure and labor and machine productivity, consider the causal diagram presented in Fig. 2. A key concern for any plant manager is the adequacy of net throughput. When the manufacturing process generates unacceptable throughput, the consequence is an increase in throughput pressure. From past experience the response is to work harder to meet the demand. Working harder involves utilizing existing equipment capacity and labor force more intensively; that can include reworking defective throughput. The unacceptable throughput may include lower than expected gross throughput due to manufacturing equipment speed or power losses that can also bring about throughput pressure. The net result is increased gross throughput requirements, which demands more labor force efforts as well as equipment capacity. When equipment capacity is adequate, by increasing worker efforts, using overtime or adding workers through reassignment, the gross throughput is increased to alleviate throughput pressure. But on the other hand, more utilization of equipments gradually reduces machine reliability and therefore increase machine breakdown rate which consequently increases BM rate. More breakdowns will reduce the available time for production and therefore reduces the net throughput. As the machine reliability falls, on the other hand, process quality will be dropped and therefore acceptable throughput will be dropped which accordingly will reduce the net throughput and therefore to aggravate the problem.

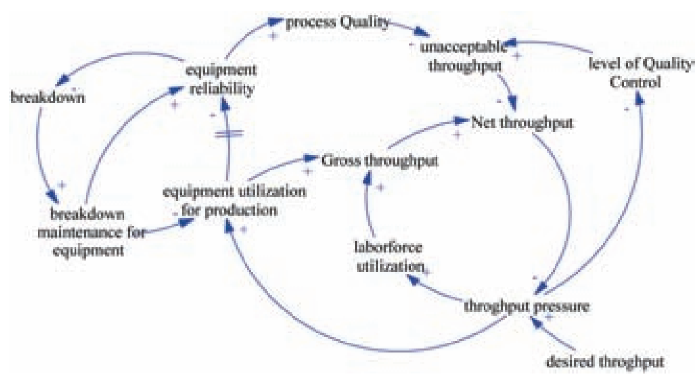

Fig. 2. Relationship between breakdown maintenance and throughput

4.2 System dynamics view to TPM

Due to the introduction of autonomous maintenance into TPM simple maintenance tasks like lubrication are assigned to machine operators themselves. Therefore maintenance department's workload will be decreased and as a result the vicious circle of BM, Fig. 1, will be broken through. A main consequence is that the maintenance department is not overloaded with reactive activities but can carry out PM tasks and will have more time to cooperate with other departments to design machines for better maintenance and maintenance-free machines. Although the maintenance tasks transferred to operators should be easy, there will be still a lack of knowledge concerning the know how to fulfill these tasks. So the machine operators must be trained. The training must be carried out by the maintenance department to guarantee a sufficient maintenance level of the machine operators. It has to be considered that operator's learning is time consuming, thus the existing lack of knowledge will be reduced gradually and not immediately. But, in the long run, the learning process leads to the fact that operators achieve a higher understanding of the functioning of their machines. Accordingly, they can give insights about their day to day work for the improvement of maintenance activities, i.e. contributing to a better design for maintainability. As the maintenance department's efforts for accomplishing maintenance tasks decreases, more simple maintenance tasks can be assigned to machine operators and as a result machine operators will become more and more familiar with their machines. This, in turn, will suggest more and more ideas for improving their machines' maintainability which as a result tend to reduce equipment defects, and the cycle goes on. Fig. 9 shows the complete flow diagram for Total Productive Maintenance (TPM) in which relationships of throughput pressure, operators' training, machine reliability, and process quality have be been shown as a whole.

4.2.1 System dynamics equations for TPM

System dynamics equations and relationships between different variables in Fig. 9 are defined in Appendix A.

4.2.2 Running the simulation model

By running the flow diagram of Fig. 9 in Vensim® PLE environment following results are obtained. Here we just depict the graphical behavior of the most important variables and exclude others.

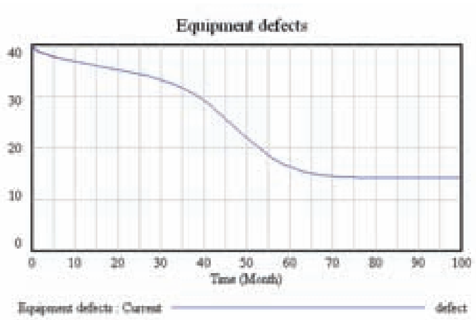

Fig. 3. Equipment defects

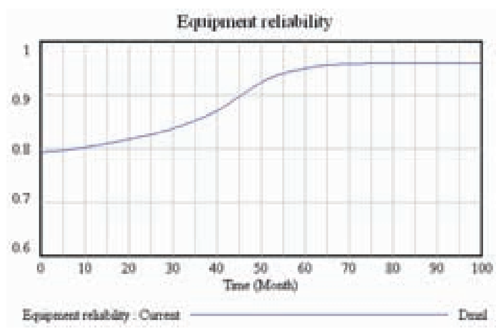

Fig. 4. Equipment reliability

From Fig. 3 we can see that by implementing TPM, Equipments defects gradually declines from the initial 40 defects per month to about 14 defects per month and after month 70 remains at a steady state. In addition, according to Fig. 4 equipment's reliability gradually increases from about 0.8 at month 0 to about 0.98 at month 70. These improvements are mainly due to an increase in employees' training hours, and on the other hand an increase in PM efforts done by maintenance department which are depicted in Figs. 6 and 7 respectively. These two factors cause breakdown rate, Fig. 5, to drop from 2 unexpected breakdowns per month to about 0.4 unexpected breakdowns per month.

According to Fig. 6 we can see that due to applying TPM, employees' training hours has increased from about 5 hours per month to about 17 hours per month which is a critical factor to improve autonomous maintenance, a crucial aspect in TPM, and therefore decreasing equipment's defects.

Finally, according to Fig. 8, by implementing TPM, process quality has been enhanced which as a result caused the net throughput to be increased. As we can see, net throughput has gradually got closer and closer to

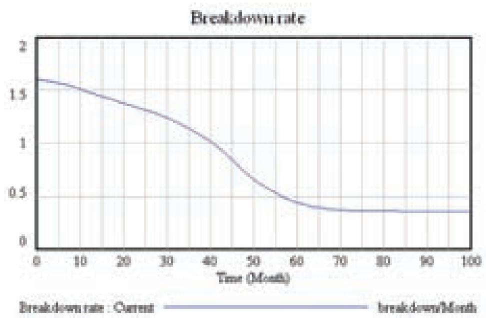

Fig. 5. Breakdown rate

Fig. 6. Training employee

the desire throughput. In addition the gap between gross and net throughput steadily decreased which means reduction in unacceptable throughput.

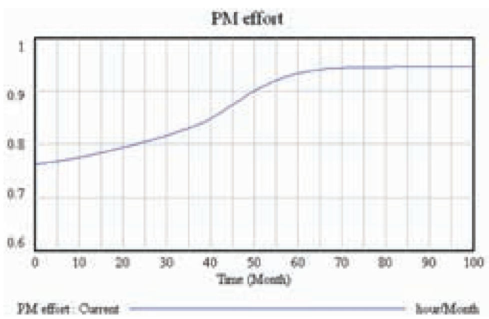

Fig. 7. PM effort

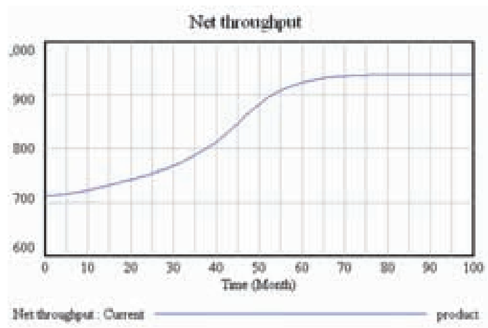

Fig. 8. Net throughput

5 Conclusion

Today, manufacturers have to offer a great variety of products on a high quality level, in the least amount of time for an acceptable price. Therefore, in order to be successful in today's world-class manufacturing environment companies have to fulfill these requirements effectively. Maintaining a reliable manufacturing process is a key success factor in doing so, which can be achieved through implementing a proper maintenance strategy. Because maintaining an efficient and effective maintenance strategy is crucial to keep high-level process quality, achieve high machine and labor force efficiency, and reach time competence.

Among various maintenance strategies Total Productive Maintenance (TPM) has widely been accepted as an effective strategy for improving maintenance in the manufacturing companies. Therefore, in this paper by using "system dynamics" which is a branch of "system thinking" effects of implementation of TPM on machine reliability, process quality and net throughput was analyzed. Results obtained showed the effectiveness and usefulness of TPM in reducing breakdown down maintenance (BM) tasks as well as enhancing machine reliability, process quality and product's net throughput. Simulation results using Vensim ® PLE environment are depicted in Figs. 3 ∼ 8.

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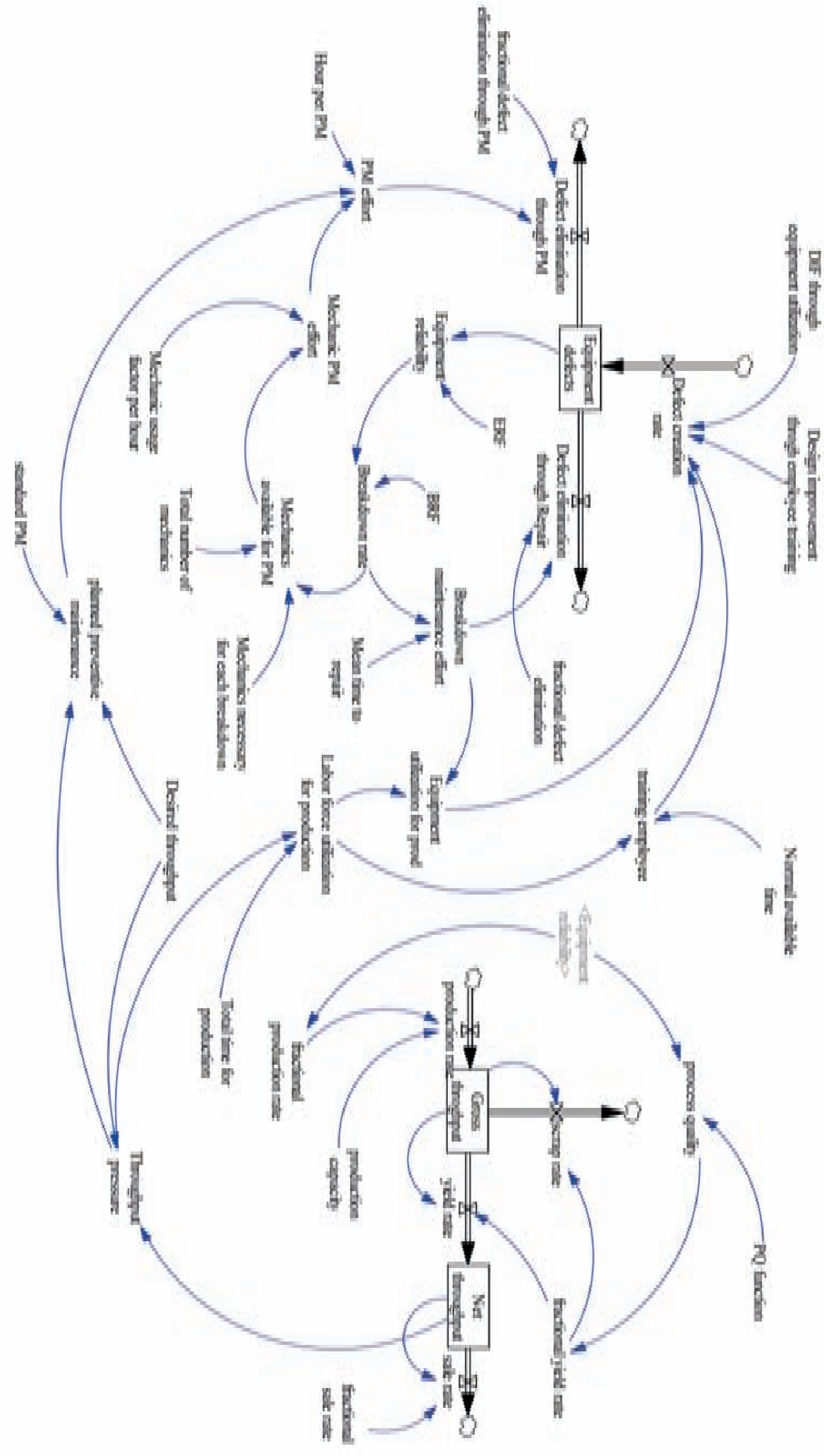

Fig. 9. Flow diagram of TPM

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Appendix

A. system dynamics equations for TPM

Unit of measure of each variable is written in parenthesis.

- (1) Gross throughput = INTEG (production rate − scrap rate − yield rate, production rate) (product)
- (2) Net throughput = INTEG (yield rate − sale rate, yield rate) (product)
- (3) production rate = production capacity × fractional production rate (product/Month)
- (4) yield rate = fractional yield rate × Gross throughput (product/Month) Yield rate is the percent of acceptable products produced.
- (5) sale rate = Net throughput (product/Month)
- (6) scrap rate = (1 − fractional yield rate) × Gross throughput (product/Month)
- (7) fractional production rate = Equipment reliability (Dmnl)
- (8) production capacity = 1000 (product/Month) Production capacity is assumed to be constant at 1000 (products/Month)
- (9) Throughput pressure = IF THEN ELSE ((Desired throughput − Net throughput) > 0, Desired throughput − Net throughput, 0) (product)
  In the above equation if the demand can not be satisfied throughput pressure is equal to the gap between demand and net throughput. Else, there is not any throughput pressure.
- (10) Desired throughput = 1000 (product)
- (11) Total time for production:
  Graph: $[(-1000, 0) - (1000, 400)], (0, 160), (100, 165), (200, 170), (300, 175), (400, 180), (500, 185), (600, 190), (700, 195), (800, 200), (900, 205), (1000, 210)$
- (12) Equipment defects = INTEG (Defect creation rate-Defect elimination through PM-Defect elimination through Repair, 40) (defect)

- (13) Defect elimination through PM = PM effort $\times$ fractional defect elimination through PM (defect/Month)
- (14) fractional defect elimination through PM = 8 (defect/hour) It's assumed that 8 defects will be eliminated per hours via PM.
- (15) Defect elimination through Repair = Breakdown maintenance effort $\times$ fractional defect elimination (defect/Month)
- (16) Defect creation rate = SMOOTH3 (Design improvement throgh employee training(training employee), 8) + SMOOTH (DIF through equipment utilization (Equipment utilization for prod), 5) (defect/Month)
- (17) Equipment reliability = ERF (Equipment defects)(Dmnl)
  In the above equation equipment's reliability is a function of equipments defects.
- (18) ERF : Graph :
  $[(0, 0) - (100, 1), (0, 1), (85.6269, 0.964912), (200, 0.88), (300, 0.8), (400, 0.7), (500, 0.55), (600, 0.4), (700, 0.3), (800, 0.22), (900, 0.18)], (0, 1), (11.9266, 0.969298), (21.1009, 0.929825), (30.8869, 0.859649), (38.2263, 0.789474), (46.4832, 0.697368), (54.1284, 0.570175), (59.633, 0.451754), (66.3609, 0.307018), (72.1713, 0.192982), (79.5107, 0.114035), (88.685, 0.0657895), (96.6361, 0.0438596), (100, 0.0394737), (100.917, 0.0877193)$
- (19) Breakdown rate = BRF (Equipment reliability) (breakdown/Month)
- (20) BRF: Graph:
  $[(0, 0) - (1, 50)], (0, 50), (0.0489297, 38.5965), (0.0917431, 31.5789), (0.134557, 25), (0.211009, 17.3246), (0.311927, 12.2807), (0.415902, 8.55263), (0.538226, 6.14035), (0.614679, 4.16667), (0.672783, 3.07018), (0.749235, 1.97368), (0.825688, 1.31579), (0.932722, 0.6), (1, 0)$
- (21) Breakdown maintenance effort = Breakdown rate $\times$ Mean time to repair (hour/Month)
- (22) Mean time to repair = 2 (hour/breakdown)
- (23) fractional defect elimination = 5 (defect/hour)
- (24) Mechanics available for PM = IF THEN ELSE ((Total number of mechanics $-$ Mechanics necessary for each breakdown $\times$ Breakdown rate) $< 0, 0$, (Total number of mechanics $-$ Mechanics necessary for each breakdown $\times$ Breakdown rate)) (mechanic/Month)
- (25) Mechanics necessary for each breakdown = 1.5 (mechanic/breakdown)
- (26) Total number of mechanics = 10 (mechanic/Month) Total number of maintenance staff is assumed to be 10 persons.
- (27) Mechanic PM effort = Mechanics available for PM $\times$ Mechanic usage factor per hour (hour/Month)
- (28) PM effort = MIN (Hour per PM $\times$ planned preventive maintenance, Mechanic PM effort) (hour/Month)
  In the above equation with respect to available maintenance staff required PM effort is determined.
- (29) Hour per PM = 2 (hour/PM) Required hour to perform each PM task is assumed to be 2 hours.
- (30) Mechanic usage factor per hour = 0.1 (hour/mechanic)
- (31) Equipment utilization for production = Labor force utilization for production-Breakdown maintenance effort (hour/Month)
- (32) Labor force utilization for production = Total time for production (Throughput pressure) (hour/Month)
- (33) planned preventive maintenance = $4 - 2\times$ Throughput pressure/Desired throughput (PM/Month)
- (34) training employee = IF THEN ELSE ((Normal available time $-$ Labor force utilization for production) $+20 < 0, 0$, (Normal available time $-$ Labor force utilization for production) $+20$) (hour/Month)
  Maximum available time to train machine operators in order to perform autonomous maintenance is assumed to be 20 hours per month.
- (35) Normal available time = 8×20 (hour/Month) Normal available time is 8 hours per day, 20 days per month.
- (36) Design improvement through employee training: Graph:
  $[(0, 10) - (20, 25)], (0, 21.2), (1.11927, 21.1184), (2.14067, 20.9868), (3.79205, 20.6579),$

$(5.50459, 19.7368), (7.15596, 17.9605), (8.50153, 15.7895), (9.72477, 13.75), (11.2538, 12.1053),$
$(13.4557, 11.0526), (15.841, 10.5921), (18.0428, 10.5263), (19.8165, 10.4605)$ (defect/hour)
The above graph explains the behavior of how cooperation of operators in eliminating their machines defects and offering suggestions in order to better design of equipment decreases machine defects.

- (37) DIF through equipment utilization: Graph:
$[(0, 0) - (400, 200)], (150, 0), (150, 0), (170, 1), (190, 3), (210, 5), (250, 7)$ (defect/hour)
- (38) process quality = PQ function (Equipment reliability) (Dmnl)
- (39) PQ function : Graph:
$[(0, 0) - (10, 1)], (0, 0), (0.1, 0.1), (0.2, 0.22), (0.3, 0.35), (0.4, 0.48), (0.5, 0.6), (0.6, 0.72), (0.7, 0.85),$
$(0.8, 0.9), (0.9, 0.96), (1, 0.99)$
- (40) fractional yield rate = process quality (Dmnl)
- (41) fractional sale rate = 1 (1/Month)

It's assumed that all of the products will be soled.