NOTES AND INSIGHTS

Maintaining preventive maintenance and maintenance prevention: analysing the dynamic implications of Total Productive Maintenance

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Abstract

In this paper, the dynamic implications of Total Productive Maintenance are analysed. After discussing why the successful implementation of this concept might fail, interrelations between the pillars of Total Productive Maintenance are identified. The focus of the research conducted is the analysis of fundamental structures and the identification of a strategy for the implementation of Total Productive Maintenance. This strategy has to consider the interplay of the different pillars of this maintenance approach. A system dynamics model gives valuable hints for a successful implementation taking the different influences of Maintenance Prevention and Preventive Maintenance on the Overall Equipment Effectiveness as the central performance measure of a maintenance system into account. The article contributes to a better understanding of the dynamic behaviour of Total Productive Maintenance. Copyright © 2006 John Wiley & Sons, Ltd.

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Introduction

In today's dynamic environment, a reliable production system must be seen as a critical factor for competitiveness; thus maintenance has become a strategic issue for manufacturers (Brah and Chong, 2004). Total Productive Maintenance (Nakajima, 1988, 1989) has commonly been accepted as the most promising concept for improving maintenance in order to succeed in a demanding market arena. Surprisingly, despite the large amount of literature in this field, there is a lack of work analysing the dynamic behaviour of Total Productive Maintenance. In particular, a misunderstanding of dynamic behaviour is why many concepts in operations management often cannot fulfil their potential (Sterman *et al.*, 1997). In this paper, reasons for the failure of Total Productive Maintenance will be presented with respect to its dynamic implications, which are derived from a system dynamics model as proposed by Jambekar (2000).

The overall goal of Total Productive Maintenance is to raise the overall equipment effectiveness (OEE; Shirose, 1989). The OEE is calculated by multiplying the availability of the equipment, the performance efficiency of the process and the rate of quality products (Dal *et al.*, 2000; Ljungberg, 1998). This measure can be used as an indicator for the dependability of the production system. In this paper we mainly focus on the availability of the equipment.

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Nowadays, five pillars have evolved as a standard of Total Productive Maintenance, i.e., the "elimination of the six big losses" (Nakajima, 1988; Shirose and Goto, 1989), a "scheduled maintenance program" (Miyoshi, 1989), an "autonomous maintenance program" (Goto, 1989a), "training of machine operators" (Aso, 1989), and "maintenance prevention" (Goto, 1989b). The basis of Total Productive Maintenance is the 5S-Program. The 5S-Program supports the pillars of Total Productive Maintenance, because a tidy and clean working environment fosters the "Parlor Factory" (Nakajima, 1988). The implementation of these pillars is challenging because of their interdependencies.

After discussing the basic structure of the maintenance problem, which can be interpreted as the archetype "shifting the burden" (Senge, 1990), a system dynamics model of this archetype will serve as a foundation for further analysis. The changes brought about by implementing Total Productive Maintenance will be incorporated into a more comprehensive system dynamics model. Simulation runs show the effects of the different pillars of Total Productive Maintenance and their interplay. Based on the model, important implications for a successful implementation of Total Productive Maintenance can be derived.

The pitfall of maintenance

A main problem that can be observed in many manufacturing companies is an approach commonly referred to as breakdown maintenance. In terms of breakdown maintenance, actions for maintaining equipment are not undertaken before a machine breaks down (Nakajima, 1988). Such a reactive "fire-fighting strategy" leads to many unexpected machine breakdowns (Jambekar, 2000) with the consequence of decreasing equipment availability. In a dynamic and competitive environment, breakdown maintenance must be regarded as anachronistic because the overall performance will suffer in terms of cost, quality, time, and flexibility (Thun, 2004).

A major breakthrough for managing maintenance is preventive maintenance (Nakajima, 1988). This approach aims at preventing machine breakdowns in advance by the use of a scheduled maintenance program. This approach, however, is accompanied by a more complex maintenance system because many different facets of maintenance interact with each other. The core problem is that the "logic" of breakdown maintenance might still mitigate the positive effect of preventive maintenance. Owing to machine breakdowns, the maintenance department is busy most of the time repairing machines. Accordingly, the maintenance department does not have enough time to do maintenance tasks on a regular basis, nor does it have the time to improve the maintenance system. A consequence is that preventive maintenance tasks are neglected, leading to a situation with many machine breakdowns (Carroll *et al.*, 1998).

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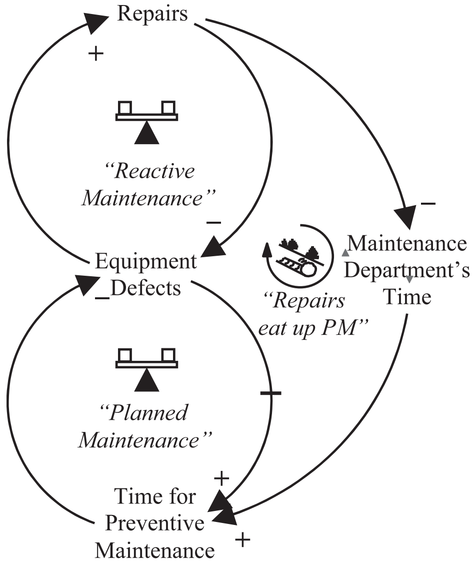
Fig. 1. The archetype "shifting the burden" in a maintenance system



This problem of the maintenance department equals the archetype "shifting the burden" described by Senge (1990): This archetype consists of two balancing and one reinforcing loop, which move a system in an unintended direction (Figure 1). In such a situation, a symptom of a problem is observed. In terms of maintenance, the symptom is the high number of machine breakdowns on the shop floor. For this problem, two different approaches might serve as a solution: the symptomatic solution and the fundamental solution. Both approaches can cope with the symptoms of the problems, with the difference that the fundamental solution takes more time to show an effect because of an associated delay. Here, the symptomatic solution equals the instant reactive repair of machines. The fundamental solution is similar to preventive maintenance with its proactive but time-consuming activities. Apparently, the symptomatic solution with the instantaneous effect seems to be the more favourable approach. Often, this leads to neglect of the fundamental solution. In the context of maintenance, the symptomatic solution and the fundamental solution are connected. Both approaches compete for the maintenance department's time. As a result, the symptomatic solution will inhibit the application of the fundamental solution because preventive maintenance activities will not be accomplished because of repairs. This unintended side effect will abandon the advantage and implementation of preventive maintenance in the long run. The default to implement the fundamental solution guarantees that the problem symptom will return and worsen the situation. Machine breakdowns will "eat up" the maintenance department's capacity in terms of time repairing machines instead of maintaining or improving the maintenance

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system. Figure 1 depicts the archetype “shifting the burden” in the context of maintenance.

This is the problematic but typical behaviour of a production system with an overloaded maintenance department, preventive maintenance barely being done, and no maintenance improvements because Total Productive Maintenance has not been implemented correctly. The described situation can be analysed using a system dynamics model (Forrester, 1961; Sterman, 2000). In a first step the initial model will be described. This model is the basis for the second step: the analysis of Total Productive Maintenance using a comprehensive system dynamics model.

In the model depicted in Figure 2, the level of *equipment defects* is increased by the rate of *defect creation*. Following Sterman, equipment fails when a sufficient number of latent defects accumulate. Latent defects are any problem that might ultimately cause a failure (Sterman, 2000). The level of *equipment defects* is decreased either by the rate of *defect elimination through repairs* or by the rate of *defect prevention through PM*. Each rate is influenced by a balancing loop; i.e., the higher the level *equipment defects* on the one hand, the higher the variable *breakdown rate* will be leading to more *reactive maintenance RM* and, accordingly, to more *defect elimination through repairs*; on the other hand, the higher the *takedown time* the more *preventive maintenance PM* is done, resulting in a higher rate of *defect prevention through PM*. Additionally, *preventive maintenance PM* is influenced by the variable *mechanics available for PM*, which depends on *reactive maintenance RM*, leading to the side effect *repairs eat up PM*, as described in Figure 1. The auxiliary variable *OEE*, main measurement variable of the model, is decreased by the *breakdown rate* and the *takedown time*; i.e., the time for necessary repairs and the time the machines are taken down for accomplishing preventive maintenance tasks are subtracted from the time representing the maximal availability of 100%. Figure 2 depicts the basic structure of the maintenance model with the corresponding stock/flow diagram, as described in a similar way by Sterman (2000).

A simulation of the model confirms the results of the archetype “shifting the burden”: as shown in Figure 3 the side effect inhibits the maintenance system in working efficiently. The maintenance department cannot do preventive maintenance properly, because the mechanics are busy doing reactive maintenance. Accordingly, the ratio between preventive maintenance and reactive maintenance goes down. Furthermore, the number of equipment defects will increase and the overall equipment effectiveness will decrease in contrast to a situation without the side effect.

As a consequence, the overall equipment effectiveness will go down because of more equipment defects. In the long run, the loop “repairs eat up preventive maintenance” results in a situation with many unexpected machine breakdowns and many repairs (Thun, 2004). The question of how the negative effect of the described archetype can be mitigated will be answered in the following.

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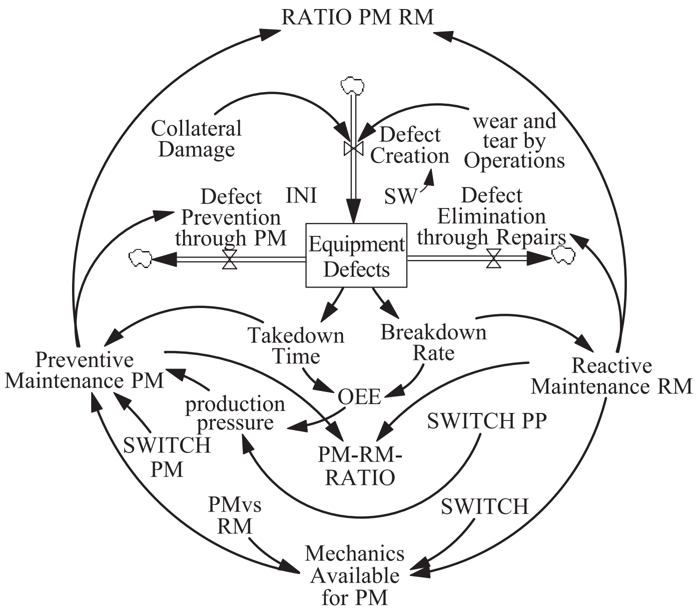
Fig. 2. The basic maintenance model



The dynamic implications of Total Productive Maintenance

The implementation of Total Productive Maintenance implies several changes. One aspect is a change in responsibilities. As stated before, due to the implementation of autonomous maintenance simple maintenance tasks are assigned to machine operators. People should get rid of attitudes like "I operate—you fix." This leads to the fact that the maintenance department is relieved. Thereby the "vicious circle" can be broken through. A main consequence is that the maintenance department is not overloaded with fire-fighting activities but can act on preventive maintenance and necessary improvements.

The transfer of the simple maintenance tasks has two implications. On the one hand, machine operators must be trained in order to learn how to fulfil the assigned maintenance tasks as stated before (Aso, 1989). The training must be carried out by the maintenance department to guarantee a sufficient maintenance level of the machine operators. Thereby, it has to be considered that learning processes cannot be done overnight. They are time consuming; thus the existing lack of knowledge will be reduced gradually and not immediately, leading to a behaviour that can be described by an S-curve. Accordingly, the effect of autonomous maintenance on the maintenance department's time is characterized by a delay. But, in the long run, the operators' potential will be realized and a higher understanding of the functioning of the machines will be achieved.

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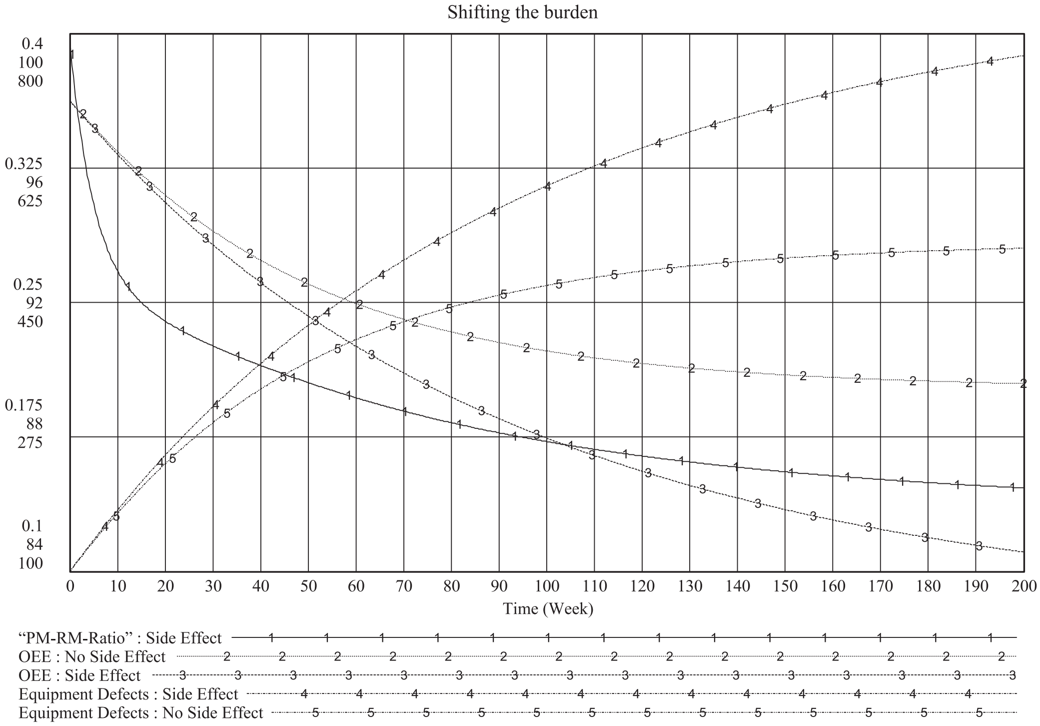

Fig. 3. Simulation runs of the basic maintenance model

On the other hand, the maintenance tasks might hinder people on the shop floor to fulfil their day-to-day workload because the sum of the additional workload by maintenance and the regular workload is too big. This aspect might lead to the fact that maintenance will not be done properly. Additionally, production pressure initiated by the management is problematic. The problem works analogously to the "production pressure chokes off PM" cycle described by Maier (2000). Production pressure can inhibit the take-down of a machine for preventive maintenance which is described by the loop "too busy for PM". The willingness to perform improvements in terms of maintenance would decrease. This situation is described by a similar structure discussed by Repenning and Sterman (2001). Here, patience and confidence regarding autonomous maintenance and training must be seen as the remedy against refusal and overstrain.

The implementation of Total Productive Maintenance goes along with several other implications. One important point is that the maintenance department has more capacity to fulfil preventive maintenance tasks; thus the maintenance schedule is done properly. By assigning simple maintenance tasks to machine operators the vicious circle will be broken, as stated before.

If the maintenance department has the time to do preventive maintenance activities on a regular basis, machine breakdowns will decline. This sets free further time capacity of the maintenance department. Accordingly, it can work together with engineers elaborating valuable results with regard to maintainability and maintenance-free machines, which is indicated by *maintenance prevention*. In the long run, an improvement of machine maintainability will decrease the need for maintenance tasks.

The described changes due to the implementation of Total Productive Maintenance might result in a counterintuitive and a counterproductive behaviour of the underlying system. This dynamic behaviour can lead to a misunderstanding of the system; thus wrong decisions in terms of maintenance might be the consequence (Mashayekhi, 1996; Crespo-Márquez and Usano, 1994). Despite the great potential of improvement programs for operations management, like the one described in this paper, most attempts to use them have ended in failure, which is described by the "improvement paradox" (Keating *et al.*, 1999; Sterman *et al.*, 1997). Therefore, a comprehensive system dynamics model showing the dynamic behaviour of Total Productive Maintenance will be useful.

Analysing the dynamics of Total Productive Maintenance

The basic model will be extended by the changes through the implementation of Total Productive Maintenance. Firstly, autonomous maintenance is incorporated into the model. This is done by a structure considering the necessity for training of machine operators in order to realize their potential competence for autonomous maintenance. Training is performed by the maintenance department; thus the maintenance department's time will decrease in the short run. But due to autonomous maintenance the maintenance department's time will increase in the long run.

The underlying structure follows the idea of the Bass model (Bass, 1969; Sterman, 2000, p. 324): analogous to the diffusion model of Bass, the potential competence of operators will be realized by a maintenance-oriented training leading to a higher degree of autonomous maintenance, whereby the training progress itself depends on both variables. Secondly, maintenance prevention is built into the model by a similar structure. The realization of the potential of maintenance prevention takes time for the maintenance department but in the long run maintenance prevention will decrease the creation of defects. Again, the structure of the Bass model builds the foundation of this approach: the potential for maintenance prevention will be successively realized by maintenance prevention, leading to a higher level of maintenance-free operation.

Both structures are connected by the variable *time for improvements*, which depends on the variable *time of maintenance department*. The latter is one of the core variables of the model. The variable time of the maintenance

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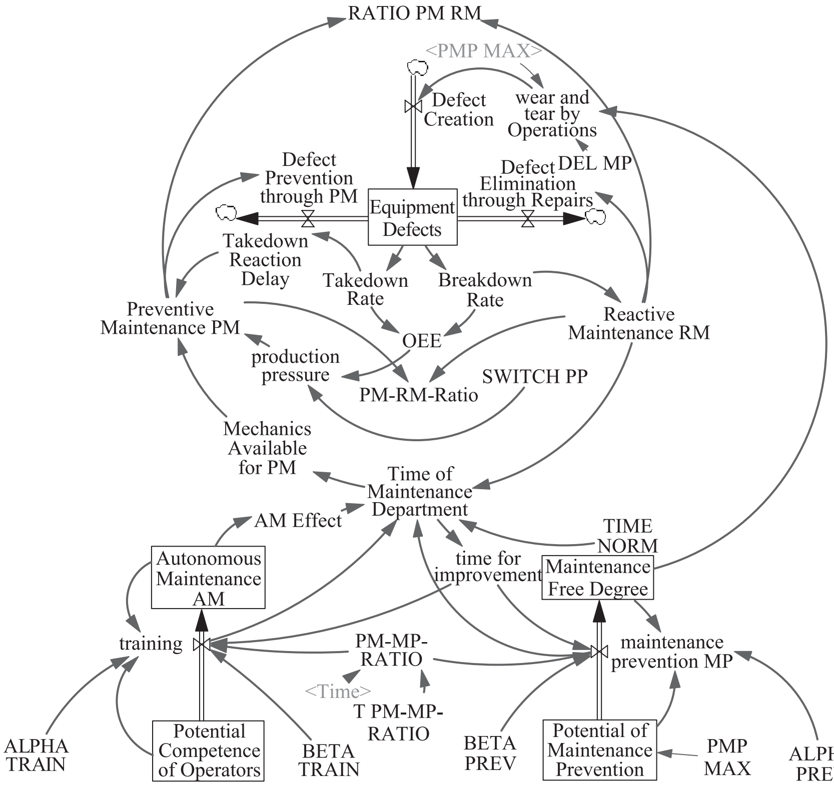

Fig. 4. The Total Productive Maintenance model

department is increased by *autonomous maintenance*, as mentioned before, but decreased by the time needed for *training* and *maintenance prevention MP* on the one hand and *reactive maintenance RM* on the other. Figure 4 gives an overview of the model, including the changes brought about by the implementation of Total Productive Maintenance (note that, for the sake of clarity, only the key variables are shown).

A simulation analysis shows that the particular approaches of Total Productive Maintenance have a different impact on the behavior of the system. Based on the simulation of the maintenance model, critical aspects can be identified (the following scenarios can be reproduced by setting the particular switch either to 0 or to 1). In a test simulation run, the system is run with 100% maintenance-free machines—there is no necessity for simple maintenance tasks; i.e., “miracle machines” are assumed. The overall equipment effectiveness reaches its equilibrium at the maximum level after some periods shown by the simulation run “MM”. An interpretation of this utopian scenario is that the production system can absorb any possible defect or the maintenance systems prevent the defects from occurring.

In a second run, the unrealistic assumption of “miracle machines” is given up. In this simulation the system is run with reactive maintenance only. In such a system with realistic machines, defects will occur and maintenance tasks have to be fulfilled. This leads to the effect that machine breakdowns will happen, leading to necessary repairs. The overall equipment effectiveness (OEE) reaches its equilibrium after some periods on a low level shown by the simulation run “RM” in Figure 5.

In a third run, preventive maintenance is added. In a system with preventive maintenance, the overall equipment effectiveness will reach equilibrium on a higher level (simulation run “PM”). But because of the limited capacity of the maintenance department preventive maintenance cannot be done appropriately, which will lead to the critical situation described by the archetype “shifting the burden” and the basic maintenance model: the time used for repairs prevents the maintenance department from doing maintenance tasks, resulting in further unexpected machine breakdowns. Accordingly, autonomous maintenance and training will be introduced. The simulation run “PM&AM” shows that the maintenance system will show a real improvement after some periods.

In a further step maintenance prevention is done exclusively. In order to show the isolated effect of maintenance prevention training, preventive maintenance and autonomous maintenance are excluded from the simulation again. The simulation run “MP” indicates that maintenance prevention takes time to fulfil its potential. But in the long run the improvements will increase the overall equipment effectiveness because fewer maintenance tasks have to be done.

Finally, all approaches of Total Productive Maintenance are simulated simultaneously. The simulation run “TPM” in Figure 5 shows that the system achieves the highest overall equipment effectiveness in the long run compared with the other approaches. The maintenance system attains the best results (except for the situation with “miracle machines”). The machines are able to prevent or absorb most of the possible or occurring defects. Figure 5 depicts the behaviour of the overall equipment effectiveness for different approaches.

The simulation runs “PM&AM” and “TPM” show that the overall equipment effectiveness will be lower than the run “PM” for some periods before the system will be improved, because autonomous maintenance and training take time and resources from the maintenance department. This situation can be characterized by the “worse before better” effect. The “worse before better” effect indicates that the performance of a system might first suffer before the improvement activities advance the system. A reason for this effect is that the system must be adapted to the necessary changes; i.e., autonomous maintenance must first be implemented and machine operators must be trained. Particularly the loop “too busy for PM” can play a counterproductive role, reinforcing the “worse before better” effect. An important implication is that the activities for maintenance improvement have to be continued, even if the situation worsens in the beginning. The impact of the “worse before better” effect is illustrated in Figure 6.

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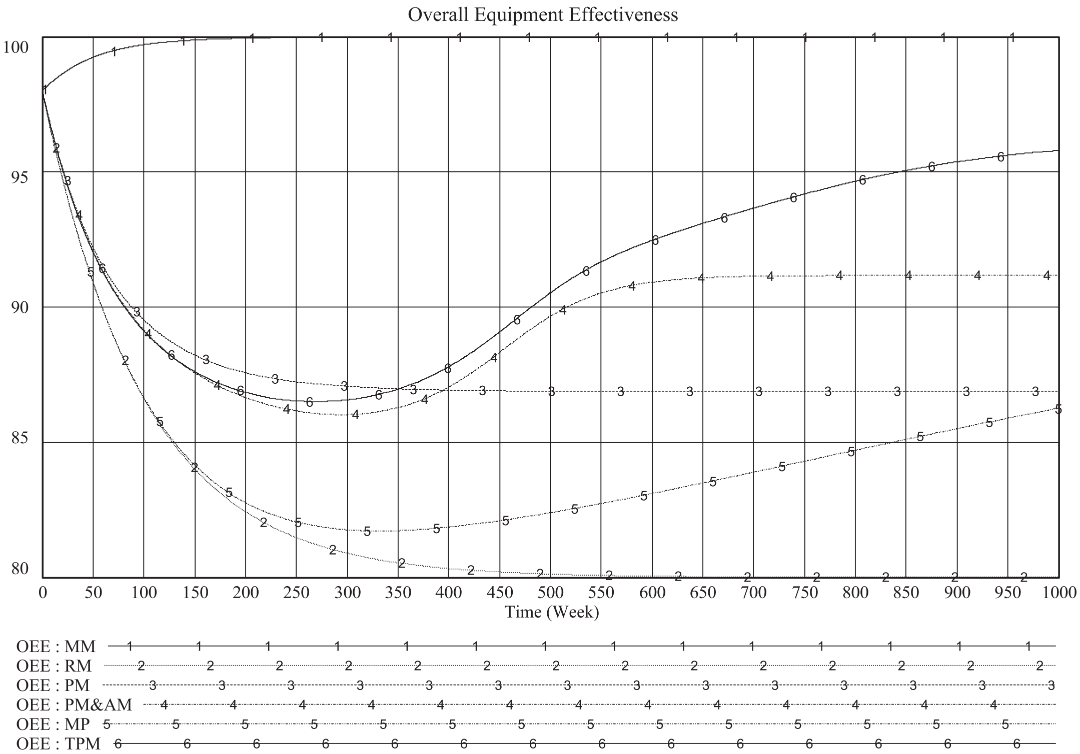

Fig. 5. Simulation runs of Total Productive Maintenance

Conclusively, for a successful implementation of Total Productive Maintenance it seems to be useful to understand the functioning and interaction of the different facets of Total Productive Maintenance, so that the concept can fulfil its whole potential.

An interesting question is the timing of Total Productive Maintenance. Although there is no doubt about the importance of maintenance prevention and preventive maintenance, as the analysis has shown, the problem of balancing both approaches must be discussed. In order to analyse the timing of Total Productive Maintenance different simulation runs are performed, as depicted in Figure 7.

The analysis shows that different maintenance strategies, i.e., the balancing of maintenance prevention and preventive maintenance, are not equally successful. There are differences in the behaviour of the overall equipment effectiveness. The simulation run "TPM" is the same as shown in Figure 5 and functions as a reference run for other simulations. In the following, two extreme maintenance strategies are tested. In the first run only maintenance prevention is done at the beginning and afterwards only preventive

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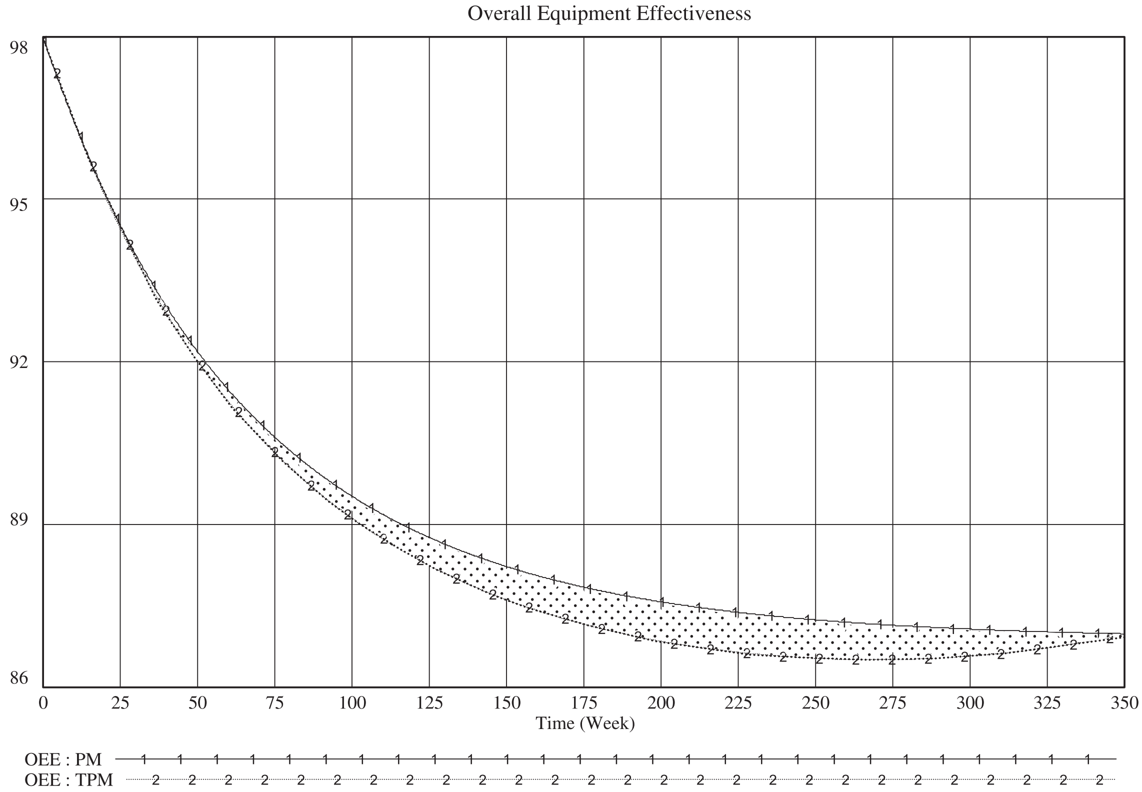

Fig. 6. The "worse before better" effect

maintenance. The simulation run "TPM ALT" shows that the reference run has a worse performance concerning the overall equipment effectiveness. In a second run, the inverse strategy is tested; i.e., first preventive maintenance is done and afterwards maintenance prevention. The simulation run "TPM OPT" shows that this strategy results in a better system behaviour than the other two runs. Conclusively, it can be stated that a switch from preventive maintenance to maintenance prevention seems to be the most promising maintenance strategy in the long run. This means that the overall maintenance system needs some time for maintenance prevention and preventive maintenance in order to gain significant improvements.

Conclusion and further research

In this paper, dynamics of an implementation of Total Productive Maintenance are discussed within the framework of a system dynamics model.

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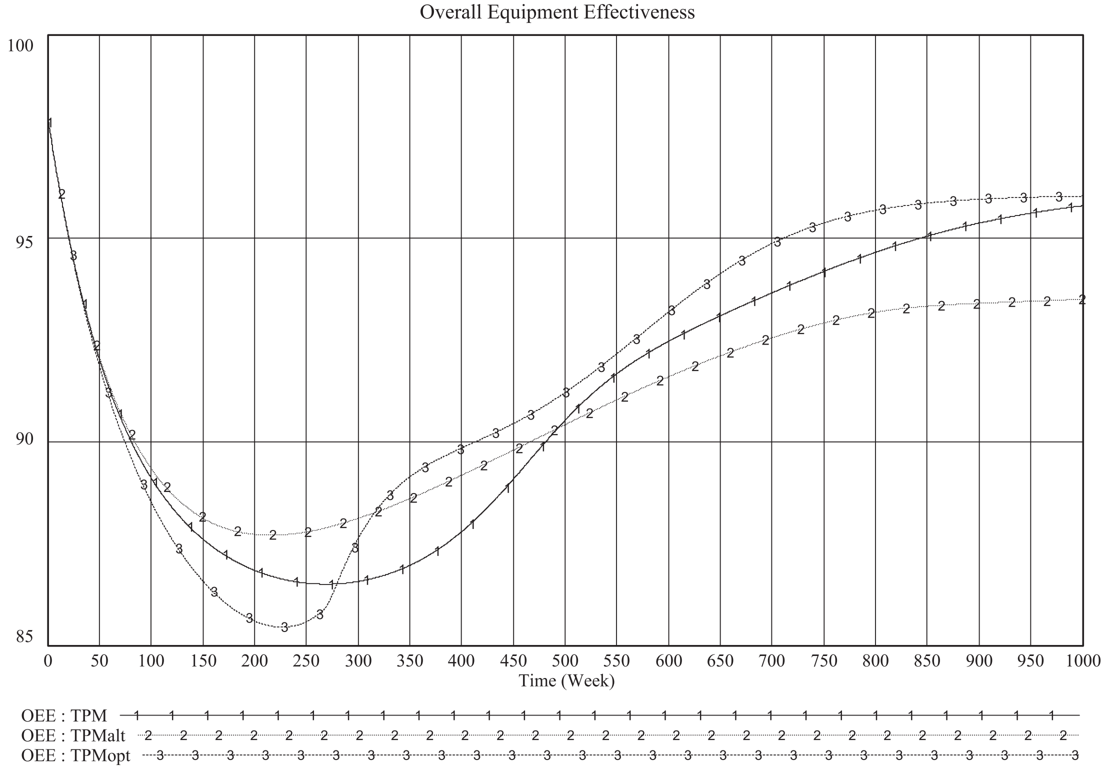

Fig. 7. Timing of Total Productive Maintenance

Gradually, the pillars of the concept are built into the model. Simulation runs show that different pillars of Total Productive Maintenance have a different impact on the behaviour of the system. By the implementation of Total Productive Maintenance the performance of the overall system depends on the chosen maintenance strategy. Based on the simulation analysis it can be stated that a switch from preventive maintenance to maintenance prevention should be considered in the maintenance strategy.

Concerning managerial implications it is important to note that Total Productive Maintenance has to be managed carefully in order to achieve the desired output. Managers must beware of the existing interdependencies within the maintenance system. Accordingly, the model can be used as a simulation tool when companies start to implement Total Productive Maintenance. Based on simulation analyses managers can learn how to deal with such a comprehensive approach like the one investigated in this paper. Furthermore, the different parties, i.e., the maintenance department, engineers and machine operators, can jointly work with the model in order to understand their particular role and their relationship to the other groups. This will

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help in accepting the necessary changes when implementing Total Productive Maintenance.

Future work will be on a deeper investigation of maintenance prevention in order to achieve more insights of this approach to increase the Overall Equipment Effectiveness. A possible model extension would consider a relationship between maintenance prevention and the potential of autonomous maintenance, because by ease of maintenance, a facet of maintenance prevention besides maintenance free design, more tasks can be assigned to the operators on the shop floor. Accordingly, the potential for ease of maintenance and the management of maintenance prevention could be further investigated.

References

Aso M. 1989. Maintenance skill training. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR.

Bass FM. 1969. A new product growth model for consumer durables. *Management Science* **15**(5): 215–227.

Brah SA, Chong W-K. 2004. Relationship between total productive maintenance and performance. *International Journal of Production Research* **42**(12): 2383–2401.

Carroll JS, Sterman JD, Marcus AA. 1998. Playing the maintenance game: how mental models drive organizational decisions. In *Debating Rationality: Nonrational Elements of Organizational Decision Making*, Stern RN, Halpern JJ (eds). Cornell University Press: Ithaca, NY; 99–121.

Crespo-Márquez A, Usano RR. 1994. Learning maintenance management through system dynamics. In *Proceedings of the 12th International Conference of the System Dynamics Society*, Wolstenholme EF (ed.), Stirling, UK; 20–27.

Dal B, Tugwell P, Greatbanks R. 2000. Overall equipment effectiveness as a measure for operational improvement. *International Journal of Operations and Production Management* **20**(12): 1488–1502.

Forrester JW. 1961. *Industrial Dynamics*. MIT Press: Cambridge, MA. (Now available from Pegasus Communications, Waltham, MA).

Goto F. 1989a. Autonomous maintenance. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR; 165–218.

——. 1989b. Maintenance Prevention. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR: 85–164.

Jambekar AB. 2000. A systems thinking perspective of maintenance, operations and process quality. *Journal of Quality in Maintenance Engineering* **6**(2): 123–132.

Keating EK, Oliva R, Repenning NP, Rockart S, Sterman JD. 1999. Overcoming the improvement paradox. *European Management Journal* **17**(2): 120–134.

Ljungberg O. 1998. Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations and Production Management* **18**(5): 495–507.

Maier FH. 2000. Feedback structures driving success and failure of preventive maintenance programs. In *Operations Management: Crossing Borders and Boundaries:*

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr

The Changing Role of Operations, Van Dierdonck R, Vereecke A (eds). Academia Press: Ghent; 376−383.

Mashayekhi AN. 1996. Oscillation in maintenance programs. In *Proceedings of the 14th International Conference of the System Dynamics Society*, Richardson GP, Sterman JD (eds), Cambridge, MA; 361–364.

Miyoshi A. 1989. Preventive maintenance. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR; 85–164.

Nakajima S. 1988. *Introduction to Total Productive Maintenance (TPM)*. Productivity Press: Portland, OR.

——. 1989. An introduction to TPM. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR.

Repenning NP, Sterman JD. 2001. Nobody ever gets credit for fixing problems that never happened: creating and sustaining process improvement. *California Management Review* **43**(4): 64–88.

Senge PM. 1990. *The Fifth Discipline: The Art and Practice of the Learning Organization*. Doubleday: New York.

Shirose K. 1989. Equipment effectiveness, chronic losses, and other TPM improvement concepts. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR; 27–84.

Shirose K, Goto F. 1989. Eliminating the six big losses. In *TPM Development Program: Implementing Total Productive Maintenance*, Nakajima S (ed.). Productivity Press: Portland, OR; 85–164.

Sterman JD. 2000. *Business Dynamics: System Thinking and Modelling in a Complex World*. McGraw-Hill: Boston, MA.

Sterman JD, Kofman F, Repenning NP. 1997. Unanticipated side effects of successful quality programs: exploring a paradox of organizational improvement. *Management Science* **43**(4): 503–521.

Thun J-H. 2004. The dynamics of maintenance: a system thinking view of implementing total productive maintenance. In *Komplexität und Dynamik als Herausforderung für das Management: Festschrift zum 60. Geburtstag von Peter Milling*, Maier F (ed.). Gabler: Wiesbaden.

Model listing

(01) ALPHA PREV = 0.001
Units: 1/week
(02) ALPHA TRAIN = 0.001
Units: 1/week
(03) AM effect = SMOOTH (autonomous maintenance AM, DEL AM)
Units: defects
(04) Autonomous maintenance AM = INTEG (training, 0)
Units: defects
(05) BETA PREV = 0.01
Units: 1/(defects * week)

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(06) BETA TRAIN = 0.05
Units: 1/(defects * week)
(07) BR = 100
Units: Dmnl
(08) Breakdown rate = equipment defects/BR
Units: defects
(09) Collateral damage = 10
Units: defects/week
(10) Defect creation = (collateral damage * wear and tear by operations)
Units: defects/week
(11) Defect elimination through repairs = reactive maintenance RM
Units: defects/week
(12) Defect prevention through PM = preventive maintenance PM
Units: defects/week
(13) DEL AM = 1
Units: week
(14) DEL MP = 100
Units: week
(15) Equipment defects = INTEG (defect creation – defect prevention through PM – Defect elimination through repairs, INI)
Units: defects
(16) FINAL TIME = 1000
Units: week
(17) IMPR TIME = 1
Units: week
(18) INI = 100
Units: defects
(19) INITIAL TIME = 0
Units: week
(20) MAIN EFFORT = 100
Units: Dmnl
(21) Maintenance free degree = INTEG (maintenance prevention MP, 0)
Units: defects
(22) Maintenance prevention MP = (ALPHA PREV * potential of maintenance prevention + BETA PREV * maintenance free degree * potential of maintenance prevention) * SWITCH MP * (1 – "PM-MP-RATIO") * time for improvement
Units: defects/week
(23) MD TIME = 1
Units: week
(24) Mechanics available for PM = time of maintenance department
Units: Dmnl
(25) OEE = OEE MAX – breakdown rate – takedown rate
Units: defects

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(26) OEE MAX = 100
Units: defects
(27) "PM-MP-RATIO" = "T PM-MP-RATIO" (time)
Units: Dmnl
(28) "PM-RM-ratio" = preventive maintenance PM/(reactive maintenance RM + preventive maintenance PM)
Units: Dmnl
(29) PMP MAX = 1
Units: defects
(30) PMvsRM = 10
Units: Dmnl
(31) Potential competence of operators = INTEG (– training, 1)
Units: defects
(32) Potential of maintenance prevention = INTEG (– maintenance prevention MP, PMP MAX)
Units: defects
(33) PP = 100
Units: defects
(34) PREV TIME = 1
Units: week
(35) Preventive maintenance PM = takedown reaction delay * mechanics available for PM/production pressure * SWITCH PM/PREV TIME
Units: defects/week
(36) Production pressure = IF THEN ELSE (SWITCH PP = 1, (PP/OEE), 1)
Units: Dmnl
(37) RATIO PM RM = preventive maintenance PM/reactive maintenance RM
Units: Dmnl
(38) REACTION TIME = 10
Units: week
(39) Reactive maintenance RM = breakdown rate/REP TIME
Units: defects/week
(40) REP TIME = 1
Units: week
(41) SAVEPER = TIME STEP
Units: week
(42) SWITCH = 1
Units: Dmnl
(43) SWITCH AM = 1
Units: Dmnl
(44) SWITCH MP = 1
Units: Dmnl
(45) SWITCH PM = 1
Units: Dmnl

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(46) SWITCH PP = 1
Units: Dmnl
(47) "T PM-MP-RATIO" ([(0, 0) – (1000, 1)], (0, 0.498221), (1000, 0.498221))
Units: Dmnl
(48) Takedown rate = equipment defects/TR
Units: defects
(49) Takedown reaction delay = SMOOTH (takedown rate, REACTION TIME)
Units: defects
(50) Time for improvement = SMOOTHI (time of maintenance department, IMPR TIME, 0)
Units: Dmnl
(51) TIME NORM = 1
Units: defects/week
(52) Time of maintenance department = (TIME NORM + ((AM effect/MD TIME – TRAIN EFFORT * training) * SWITCH AM) – MAIN EFFORT * maintenance prevention MP * SWITCH MP)/(TIME NORM + (SWITCH * (reactive maintenance RM/PMvsRM)))
Units: Dmnl
(53) TIME STEP = 0.25
Units: week
(54) TR = 100
Units: Dmnl
(55) TRAIN EFFORT = 200
Units: Dmnl
(56) Training = ((potential competence of operators * ALPHA TRAIN + autonomous maintenance AM * potential competence of operators * BETA TRAIN) * SWITCH AM) * "PM-MP-RATIO" * time for improvement
Units: defects/week
(57) Wear and tear by operations = SMOOTH3 (PMP MAX/(PMP MAX + (maintenance free degree) * SWITCH MP), DEL MP)
Units: Dmnl

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