# DYNAMIC MODELING OF MAINTENANCE STRATEGIES

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**Abstract**

Maintenance strategy formulation is difficult because different systems, such as production control and maintenance, are integrated and highly interdependent. Thus, the system has to be studied in a systemic way. Dividing the problem into smaller sub-problems helps only in short term and may be even harmful in long term. The longer the time span the more significant are the interactions between maintenance and other parts of the organization. Considering the whole system, the problems of maintenance strategy formulation are complex. This paper presents a system dynamics simulation model for the maintenance of a generic process plant. The model was created in order to facilitate understanding the complex system and the strategy formulation. The model describes the maintenance activity and its interactions with other parts of the organization. It includes equipment degradation and different maintenance policies, maintenance workforce allocation, maintenance's effects on production process etc. With the help of the simulations and the causal diagram of system's feedback structure it is possible to find the shared view to the maintenance process and clarify maintenance's role in the organization. When the role is clear, it is easier to set goals and to plan maintenance strategy so that they serve best the needs of the company. The simulated maintenance strategies were evaluated with different performance measures i.e. financial measures, equipment related measures and process related measures. Additionally, strategies' sensitivities to different uncertainties were tested.

**Keywords: System dynamics, maintenance strategy, simulation**

## Presenting Author's Biography

Tero Jokinen works as a research scientist at VTT's (Technical Research Centre of Finland) System dynamics team. He completed recently his master's thesis which discusses dynamic modeling of maintenance strategies. His focus areas are system dynamic modeling of maintenance systems and of special product production.

 

## 1 Introduction

The fundamental purpose of maintenance is to support the corporate strategy and achieve the objectives. In the maintenance strategy formulation the whole organization has to be taken into consideration. The strategy planning is difficult because different systems such as production control, operation and maintenance systems are integrated and highly interdependent. The reductionistic problem solving approach, in which the problem is divided into smaller pieces, is known to lead to troubles, as the suboptimized strategies and policies tend to help only in short term. The longer the period of time the more significant are the interactions between different functions of the organization. This is because the effects of the policies and interventions tend to accumulate in different parts of the system. Thus, incoherent policies may cause problems in other parts of the systems. Therefore, maintenance has to be studied in a systemic way.

## 2 System Dynamics

System dynamics is an approach to solve problems concerning complex management systems and their obscure dynamic behavior. The concept was introduced by Jay Forrester in the 1950s at MIT. The idea is to apply systems and control theory to model organizations and corporate structures and study the system's behavior through simulations. At first, system dynamics was called "Industrial Dynamics" since it was aimed to industrial and corporate systems [1]. The name changed to system dynamics as the approach was applied to study problems like urban planning, economics, sociology and medicine.

The purpose of system dynamic modeling is to solve problems occurring in complex feedback processes. To be more precise, the goal is to understand dynamic complexity, that is as Senge [2] describes it, "situations where cause and effect are subtle, and where the effects over time of interventions are not obvious". The premise is that the dynamic behavior arises from system structure which consists of interacting components. The idea is to see the system as a whole in which every component affects everything through looped causal connections. The starting point for the approach is that causes for problematic behavior are assumed to be inside the system, not outside. Consequently, the approach is used to explain the essential dynamic behavior with system's internal structure and endogenous components. In practice, this means that model boundaries are broadened out so that problem can be explained without exogenous factors. Therefore, the boundaries of system dynamic models become often so broad that they cover many different disciplines. In addition to the models' breadth, they usually involve complexity and non-linearity in a way, that analytic solutions fail to apply. According to Ylén [3] this is mainly because linear approximations cannot be used.

In system dynamics the structure of the system is described with a combination of causal loop diagrams (Fig. 1) along with stock and flow diagrams (Fig. 2). These diagrams form the qualitative part of the model, in which the mathematical model (e.g. differential and algebraic equations) is hidden. The focus is on interactions and feedbacks (see Fig. 1).

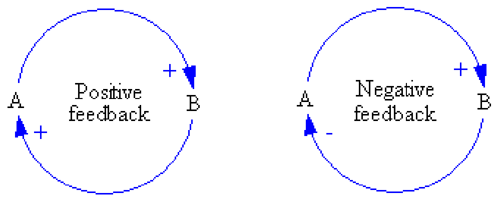


Fig. 1 Causal loop diagrams of positive and negative feedback. Plus and minus signs refer to the direction of the influence.

Stocks, also known as state variables or accumulations, represent accumulations of material, money, information etc. Flows refer to rate at which the level of the stock is changing.

The general structure of stock and flow (Fig. 2) represents the following integral equation:

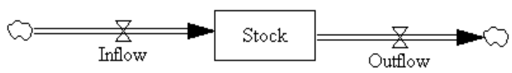


Fig. 2 Stock and flow diagram

$$S(t) = S(t_0) + \int_{t_0}^{t} [F_{in}(s) - F_{out}(s)]ds, \qquad (1)$$

where $S$ is stock level, $F_{in}$ is inflow and $F_{out}$ is outflow.

System dynamics is an approach to study dynamically complex, nonlinear, and large systems, of which people have limited understanding. It opens up a possibility to i) enrich mental models as it reveals the causal map concerning the problem, ii) to facilitate group working among the different parties, experts of different disciplines and finding a shared view and strategy for the process, iii) to simulate and test policies before put into use, and iv) to find levers for process improvement

## 3 Maintenance

### 3.1 Maintenance policies

According to the definition of PSK standard [4] maintenance is a "combination of all the 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". There are several maintenance policies presented in the literature. They are divided into two main categories by the timing of maintenance activity. Maintenance is said to be *corrective maintenance* (CM) if it is carried out after the component failure. Maintenance is *preventive* *maintenance* (PM) if it is done before the actual failure [4].

Corrective maintenance (CM) is the simplest maintenance policy considering that the decision making is based only on the fact that a component has failed. It is done by repair, replacement or by switching to a redundant component [5]. CM is also known as run-to-failure maintenance.

Despite its simplicity, CM is rarely an optimal policy due to its considerable shortcomings. First of all, production losses caused by unpredictable breakdowns, are usually significant. Moreover, delivery disturbances consequent upon forced outages can harm relations with customers. The failure of a component can cause consequential damage to other components [6, 7]. Furthermore, failures take place unpredictably, which makes it difficult to plan the use of personnel and spare parts [8]. Hence, it is often much more affordable to prevent a failure according to a plan in advance, than to repair or replace them after an unpredictable failure.

In order to tackle the problems of CM, the idea of preventive maintenance (PM) was introduced in the 1950s [9]. PM is carried out before an actual failure occurs. This policy strives to decrease the probability of failures by such actions as inspection, lubrication, parts replacement, calibration and the repair of components that are wearing out [5]. As it is done beforehand, it is possible to pre-arrange the maintenance and perform it in a way that suits best the needs of production. Moreover, PM makes it easier to anticipate the need for personnel and spare parts as well.

PM can be divided into different categories, typically by the events that trigger the maintenance action. The terminology concerning these categories varies depending on writer and application. Used terms are for example predictive-maintenance, improving maintenance, failure-finding maintenance, and opportunistic maintenance [5, 10, 11, 12]. Considering this research the following PM categories are the most essential. *Predetermined maintenance* in which maintenance schedule is set up to predefined calendar time, certain age or operation time of the component [4]. *Condition-based maintenance* that tries to predict failures and the need for maintenance by monitoring the condition of equipment. The monitoring can be carried out through periodical inspections or automatically by measuring devices and analysis of measurement results [4].

### 3.2 Complexity of Maintenance

Maintenance has an essential role in a very complex system. Moreover, it has substantial effects upon a large and complex system (i.e. organization + customers + spare part suppliers). Subsystems such as production control and maintenance are integrated and highly interdependent. The complexity stems from these interactions, time delays, uncertainties in equipment failure rates and maintenance activity, as well as human activity and decision making etc. In addition to this, there is a huge amount of detail complexity distracting us from seeing the feedback structure that determines the essential patterns of the complex dynamic behavior. According to Sterman [13], methods such as statistical tools, commonly used in maintenance management, can deal with the detail complexity, but fail to capture the dynamic complexity. Here the focus is on understanding some features of the dynamic complexity.

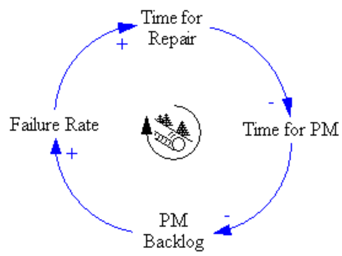


Fig. 3 Repairs eat up preventive maintenance

The dynamic complexity of maintenance systems has been studied moderately. Thun [14] studied the complexity associated with TPM (Total Productive Maintenance). Honkanen [15] examined the role of the automatic condition monitoring in system's dynamic behavior. Jambekar [16] presented a qualitative model for maintenance and quality programs and studied the system and the behavioral aspects with the help of systems thinking. Sterman [13] examined the problems that Dupont's maintenance management had run into because of deficient mental models. Bivona *et al.* [8] studied the interactions between maintenance and other processes of the organization. Many of the papers [14, 8, 13] stressed the tendency of the maintenance system to follow *"worse-before-better-behavior"* [13] (also known as *non-minimum phase behavior*) which means that the short term consequencies of different policies are opposite to the ones of the long term. Consider the following simplified example. To get cost savings or other beneficial effects, one has to invest on preventive maintenance. In short term, these actions produce costs but in the longer term the beneficial effects of decreased breakdown rate and improved plant reliability will prove to be worth the effort. Short sighted cost cutting policy is more harmful. Attempts to get immediate cost savings by reducing preventive maintenance will lead to problems in the long term. In the course of time, increasing breakdown rate keeps the maintenance workers busier and busier fixing the equipment. Eventually, this leads to "repairs eat up preventive maintenance" [14] (Fig. 3) vicious cycle in which the workers, due to lack of time and work overload, cannot carry out all requested preventive maintenance tasks, which in turn, increasingly accelerates the deterioration.

As we study social systems, such as maintenance management, it is important to point out our human rationality and problem solving capabilities. For example, Dupont's case in Sterman's playing the maintenance game [13], showed that the maintenance personnel had somewhat flawed mental models and that the deficiencies were even strengthened under pressure to immediate production and cost-cutting efficiencies. According to Sterman, the deficiency of mental models applied to employees at all levels. The flaws were noticed as the personnel seemed to have a tendency to think that tightly interdependent dynamic processes can be divided into separable discrete events. This is a typical way of solving problems for people. We divide problems into smaller subproblems that seem to be easier to solve. In short term, this kind of reasoning can result in good solutions. However, in the course of time, the interactions between subsystems and their environment become more significant as the effects accumulate all around the system. These long-term interactions may incur unexpected behavior anywhere in the system if they are ignored.

In order to understand the complexity arising from the whole system, we need to examine the maintenance as one of the interacting parts in the larger whole, not as a separate and isolated subsystem. The idea is to understand the interactions, that is the feedback structure, between maintenance and other processes in the system. This is how the role of the maintenance in the organization can be understood. When the role in this large entity is clear, it is easier to set the objectives so that they serve the corporate strategy and goals in the best possible way.

Bivona *et al.* [8] examine some of the most essential interdepencies between maintenance and other processes in the organization, especially finance, production, and asset management. They describe, for example, how difficult it is to piece together the relatioship between maintenance and finance. It is clear in short term as the maintenance produces costs. The beneficial effects of maintenance efforts, however, are not so obvious. First of all, benefits can only be seen after a long period of time, and moreover, the beneficial effects are difficult to value beforehand as there is so much uncertainty involved [8].

The objectives of maintenance and other processes are often considered to be conflicting as, for example, the preventive maintenance can be seen as a constraint to the production [8]. The objectives and the corresponding performance measures depend on the point of view as Pintelon [17] describes "accountants will think of maintenance in terms of costs, top management often is only interested in budget performance, engineers will focus on techniques, production will see performance in terms of equipment availability and support responsiveness, etc.". Tsang [18] points out that the performance measurement systems are often biased on the financial and process related measures. Moreover, according to Tsang, most of these measures are so called lag indicators which reflect only past events. In other words, they are unable to predict future performance. Such measures have a tendency to encourage managers to biased and short-sighted decision making [18]. The conflict of the objectives and the differences between viewpoints are just another reason for the maintenance management to be studied in a systemic way. The systemic approach facilitates setting logical and coherent objectives all over the organization.

# 4 Modeling

## 4.1 Problem Articulation

The purpose of this research was to study different maintenance strategies in a process plant while all the relevant interactions between maintenance and other areas of the organization are taken into consideration. To be more precise, the problem was to find out and examine the effects of different maintenance strategies on the system's behavior and how to develop an effective (capable of achieving the goals), efficient (cost effective), and robust maintenance strategy. In this paper the examination concerns maintenance portfolios consisting of 4 different maintenance policies: run-to-failure, periodical maintenance, periodical inspection, and automatic condition monitoring.

One of the most fundamental problems related to preventive maintenance is: How to choose the components which should be maintained (replaced, overhauled) during the next maintenance break. It is difficult, because the methods to predict the need for preventive maintenance are all inaccurate in some sense. Automatic condition monitoring is able to predict only a fraction of all failure types. Same goes also for the inpections. The timing accuracy of pre-determined maintenance is highly dependent on the component lifetime estimates. If the reliability data, utilized in estimation, involves a large standard deviation, the timing accuracy is probably poor. Moreover, it is difficult to know how the risk of failures evolves in the course of postponing the maintenance break. There is a risk involved also in uncertainties all over the system and system's environment. This is because nothing works exactly like it was planned or assumed. In addition to the risk of failures due to too sparse maintenance interval and to different uncertain assumptions, there is a risk of too frequent maintenance interval and the consequential waste of resources.

Planning the maintenance portfolio is difficult as all the maintenance policies, depending on the application, involve different weaknesses and strengths. Therefore, the optimal maintenance portfolio is a combination of these policies. The strategy is highly dependent on the overall corporate strategy and objectives as the most fundamental aim of the maintenance is to support them. Furthermore, it is dependent on the time span over which the evaluation is done in the strategy formulation, as we know the system tends to follow "worse-before-better-behavior". Hence, short term planning results in significantly dissimilar strategies than long term planning.

## 4.2 Dynamic Hypothesis

High availability and low maintenance costs are considered to be the primary objectives of maintenance [19]. Nevertheless, the most cost effective maintenance strategy includes probably a risk of being too sensitive to changes in the environment or in the assumptions made in strategy formulation. The risk associates with confidence in uncertain assumptions and the system structure which may cause the system to fall into a vicious cycle. Therefore, it is necessary to be prepared for such uncertainties. That is to say strategy must be robust.

Robustness, in this study, can be achieved by overestimating the weight of equipment effectiveness relative to the most cost effective maintenance strategy. The idea is to broaden the safety margin so that there is some room for errors.

As can be seen in Fig. 4 the system structure consists of several feedback loops. The most essential factors here are *failure rate*, limited *available resources*, and slow adaptation of PM. The system includes few reinforcing feedback loops (*R1, R2,* and *R3* dash line) which may turn to vicious cycles if they start to dominate the system's behavior. In other words, if the PM policies are inadequate the increasing *failure rate* causes *consequential damage* (R1), and more *wastage* production (R2). It means that the *available resources* are spent more on the CM and less on the PM (R3). This leads to the accelerating deterioration. The balance is achieved when low operation rate slows down the wear-out rate of equipment. Unfortunately this is hopelessly far from being affordable. The risk, mentioned before, associates to these reinforcing loops. That is to say, failures have a tendecy to cause more costs than it seems at the first blush.

### 4.3 Model Formulation

The process plant is modeled from the maintenance management viewpoint. One of the most important focus areas in this research is on the model's modularity so that the model could easily be used as a starting point in various cases. Therefore, the model was constructed from 7 modules: equipment degradation and maintenance, maintenance planning, worker allocation, hiring, know-how and training, production process along with reputation as a reliable supplier. Additionally, there is a set of financial, process related as well as equipment related performance measures for the strategy evaluation. The measures are simplified to emphasize the maintenance viewpoint.

In the model the equipment of the process plant is divided into five segments that are connected to the system in different ways. They represent equipment in different production phases. Segments 1 and 2 are the most critical and expensive. Moreover, segment 2 has considerable influence on the quality of the product. In practice, it means that failures in segment 2 tend to decrease product quality, and thus, increase wastage production. Other segments (3, 4, 5) have relatively minor effects on the systems behavior.

In more detail, the equipment degradation and maintenance level (Fig.5), for example, describes how components wear out and eventually fail. Component degradation is modeled with an "aging chain" [13] (see Fig. 5 the horizontal line of stocks from *new components* to *critical failures*). In the course of time and usage, components ascend rightwards and degrade in accordance with lifetime distributions which are determined by series of first order time delays in the aging chain. Moreover, it describes how components can be maintained by PM and CM. Some of the failure types, such as software bugs, are impossible to predict and can occur at any time. They are called sudden failures.

### 4.4 Tuning, Testing, and Validation

The research is funded by several companies, and thus, the model does not represent any specific process plant. On the contrary, it was tuned to represent a generic process plant. Equipment reliability related model parameters are rough estimates based on OREDA's [20] data.

The model was tested with various tests including extreme condition tests, sensitivity tests etc. The model was validated with the help of maintenance experts.

## 5 Simulations

The model was used for planning maintenance strategies. Strategies were generated with Vensim optimization tool [21]. Optimization criterion (see equation 2) was accumulated weighted sum of *profit* (net present value) and *OEE*. Decision variables were the weighting of condition inspections and of periodical maintenance. The rate of automatic condition monitoring was fixed. The idea was not to find the global optimum but to examine how different preferences in planning may affect to resulting strategies.

The objective function used in the optimization is

$$max J = \int_0^T (C_{profit} \cdot profit + C_{OEE} \cdot OEE) dt, \quad (2)$$

where $C_{profit}$ is the weight of profit, $profit$ is sales proceeds less costs, $OEE$ overall equipment effectiveness, and $C_{OEE}$ is the weight of overall equipment effectiveness.

Time span $T$ was also varied from 12 to 36 months. The weight of profit ($C_{profit}$) was 1 and the weight of OEE ($C_{OEE}$) was varied between 20000 and 50000. Maximizing only another one of them resulted in very poor strategies. As already mentioned, finding the global optimum was not of interest. Nevertheless, in order to avoid poor local optimums, optimization was done with multiple initial values.

### 5.1 Basic dynamics of examination

In order to study the basic dynamic behavior of the system and the significance of the time span over which the strategies are evaluated, Cases 1 - 4 were generated (see Tab. 1). The period of time varied from 12 to 36 months while rest of the parameters were kept constant.

Tab. 1 Cases for basic dynamics examination

| | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| $T$ [months] | 12 | 18 | 24 | 36 |
| $C_{profit}$ | 1 | 1 | 1 | 1 |
| $C_{OEE}$ | 30000 | 30000 | 30000 | 30000 |
| Goal Prod. | 7200 | 7200 | 7200 | 7200 |

Short term planning (12 and 18 months) results in somewhat conservative preventive maintenance strate-

 

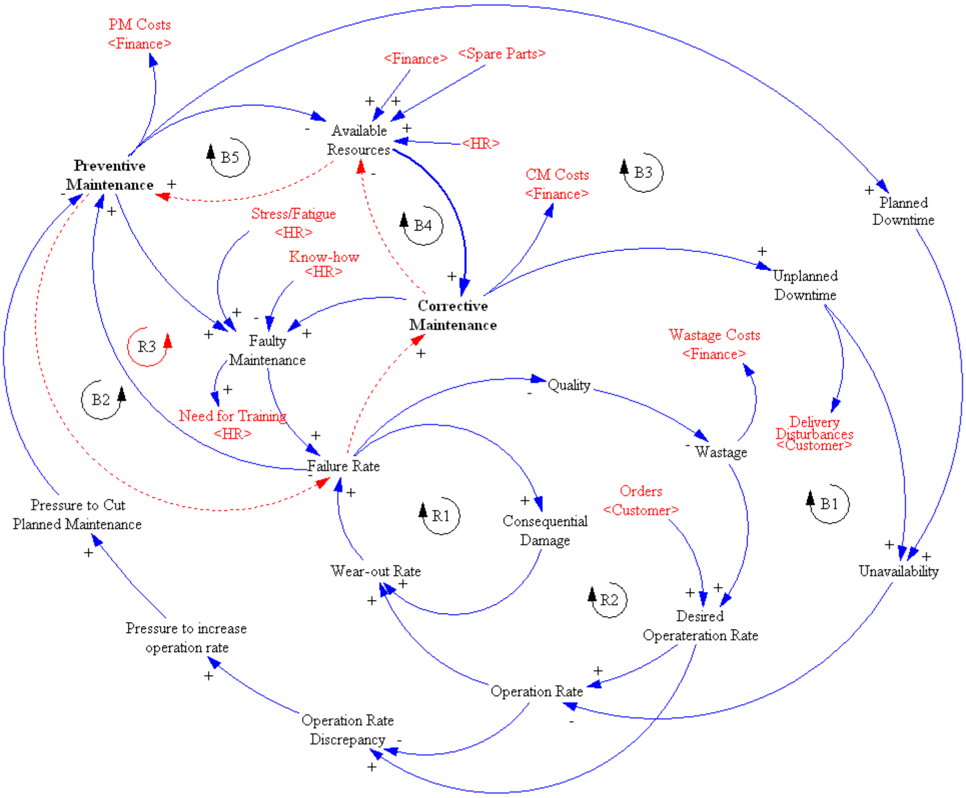


Fig. 4 System's feedback structure and essential connections with other processes in the organization

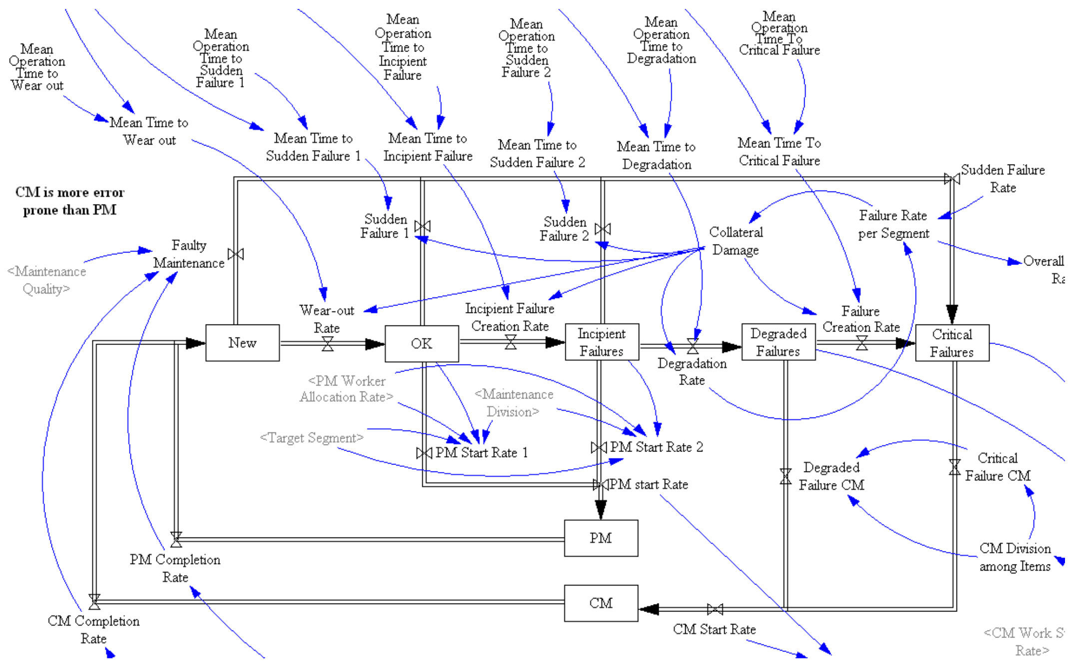


Fig. 5 A part of equipment degradation and maintenance module

gies. The idea of these strategies is to prevent only the most critical failures and to avoid unnecessary maintenance breaks and waste of resources (see Fig. 6). In Case 1 almost all of the preventive maintenance takes place only if the components are diagnosed (through inspections or through automatic condition monitoring) to need maintenance for sure. In Case 2 the strategy is rather different as it does not merely rely on inspections and automatic condition monitoring. It clearly puts some effort on periodical maintenance as well.

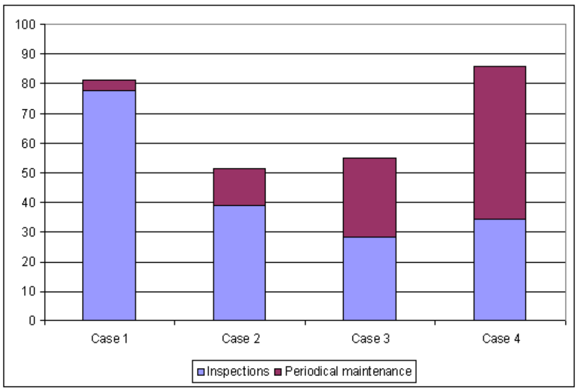


Fig. 6 Maintenance allocation in cases 1 - 4

The flaw with these strategies is too short time horizon in planning compared to the components' expected life times. The flaw associates with worse-before-better-behavior. Cutting out the preventive maintenance does not cause new failures or production losses and indirect costs immediately. On the contrary, in short term, the costs of maintenance decrease and the availability of equipment increases due to the cut out planned maintenance breaks in production (see Fig. 7 and 8).

These kind of strategies are, indeed, the best - at least in terms of the equipment and financial measures in Fig. 7 and 8 - but only if we look at that short period of time. In the long run, these strategies clearly prove to be untenable as the continuous short-sighted decisions and timorous preventive policies lead to problems. Both

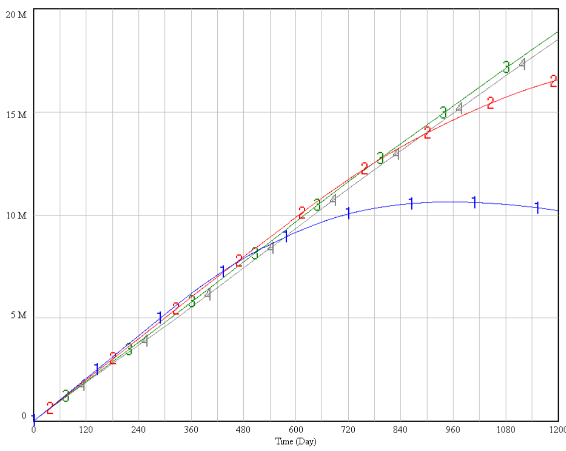


Fig. 7 Net present value of profit (cases 1 - 4)

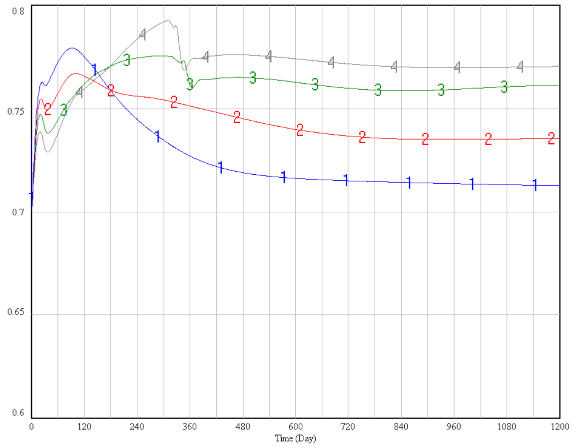


Fig. 8 Overall equipment effectiveness (cases 1 - 4)

strategies run into trouble when the failure rate begins to increase. The reinforcing loops of *Consequential damage*, *quality erosion*, and *repairs eat up prevention* (Fig. 4: *R1, R2,* and *R3*) increasingly accelerates the deterioration. Exponentially increasing failure rate eats away the equipment availability as well as production speed and quality. Finally the system reaches its steady state as the decreased wear-out rate and failure rate, consequent upon lowered operation rate, balances the behavior.

Decreased production rate is not a problem as long as there are enough products in the invetory stock. Little by little, as the production rate falls behind the order rate, inventory level drops below the safety stock buffer level. As soon as the inventory level decreases below the safety buffer, the order fulfillment rate tends to drop - there are no ordered products in the inventory. This increases the delivery delay, which in turn, degrades the reputation as a product supplier. Moreover, when the inventory is below the safety stock, unpredictable failures in the system have a substantial effect on the product deliveries. They tend to cause unforeseen delivery disturbances that are harmful to the reputation and customer satisfaction. Therefore, both the unpredictable delivery disturbances and the delivery delay in general are compensated with price cuts.

In cases 1 and 2 the overall maintenance costs are lower due to the savings in material costs. In long term they turn out to be false economy. Nevertheless, the compensated selling price, due to poor reputation and customer satisfaction, has the most dramatic effect on the overall profit.

Long term planning (24 and 36 months) results in more systematic preventive maintenance strategies (see Fig. 6). Only the failure types that can be tested with ease are inspected in case of incipient failures. For the most part, failures are predicted only by usage - periodical maintenance. The waste of resources, consequent upon policy's inaccuracy of timing, as a cost is smaller than the avoided indirect costs. Run-to-failure policy is applied only for the least critical components.

As the "worse-before-better" states, the idea is to invest effort in the beginning to solve the problems in the system. In short term this means that production gets limited by the grown rate of preventive maintenance breaks. In long term, after the problems have been solved, the failure rate decreases. This desirable progress is accelerated by the same reinforcing loops as in the cases 1 and 2. *Consequential damage* reinforcing feedback is dampened down. Decreased wastage production decreases the pressure to keep the process running - reverse *quality erosion*. Along with decreasing failure rate the need for corrective maintenance is decreasing as well. This means that there is more available resources for the preventive maintenance - reverse *repairs eat up preventive maintenace*.

In cases 3 and 4 the direct maintenance costs are high in short term due to big investment in the preventive maintenance policies. Nevertheless, after a year the costs return to the original level. The production becomes more efficient (see Fig. 8) as the maintenance orderliness increases. Thus, the production is able to reach its objectives.

### 5.1.1 Robust strategy formulation

Additionally, in order to study more elaborate strategies Cases 5 and 6 were generated (see Tab. 2). The difference here, compared to the previous cases, is increased production goal. These cases examine the significance of weighting the overall equipment effectiveness in strategy formulation.

Tab. 2 Cases 5 and 6

| | Case 5 | Case 6 |
|---|---|---|
| T | 36 | 36 |
| $C_{profit}$ | 1 | 1 |
| $C_{OEE}$ | 20000 | 50000 |
| Goal Prod. | 7300 | 7300 |

In cases 5 and 6 the planning is done in long 36 months term. The difference between cases 5 and 6 is the weights of OEE in planning. Case 5 emphasizes the overall equipment effectiveness and case 6, in turn, the cost efficiency. The weight of OEE, as dynamic hypothesis suggests, is supposed to improve the strategy robustness. Strategy 5 puts substantially more effort on preventive maintenance. However, Fig. 9 and 10 show that at least these measures are unable to tell the differences between the strategies. Fig. 9 tells also that the increased planned production rate does not increase the accumulated profit even if the production objectives are achieved. This is because the pressure, caused by increased production objectives, forces to put a huge effort on planned maintenance. The increase in the direct costs of maintenance is bigger than the increase in sales proceeds.

The accuracy of the component lifetime estimates was considered to be especially relevant uncertain factor in the model. In sensitivity tests the estimates of equipment lifetime were varied between 80 - 120% relative to the expected value. The variation was uniformly dis-

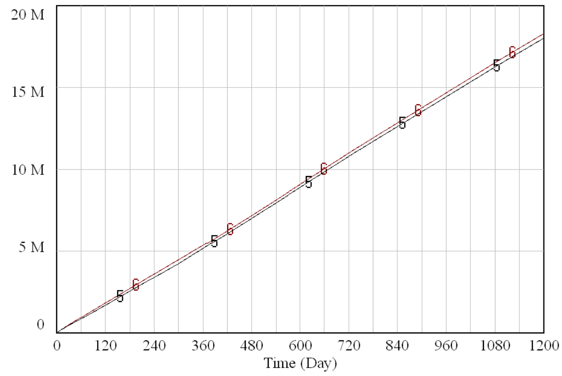


Fig. 9 Net present value of profit (cases 5 and 6)

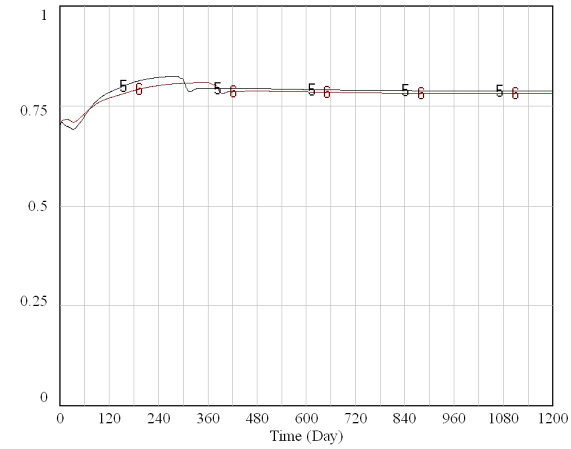


Fig. 10 Overall equipment effectiveness (cases 5 and 6)

tributed. For example Fig. 11 (net present values with varied lifetime estimates) shows that strategy 5 is significantly more robust than strategy 6. Even though the expected accumulated profit looses only slightly. (The thin black line in the middle is the expected value.) The most cost effective maintenance strategy is usually close to the minimum preventive maintenance strategy that still prevents the reinforcing loops of *consequential damage*, *quality erosion*, and *repairs eat up preventive maintenance* from dominating the system's behavior. The stress on OEE in planning broadens the margin to the minimum required effort on preventive maintenance. The increase of direct maintenance costs is relatively insignificant compared to the avoided risk of increasing indirect costs.

## 6 Summary and Conclusions

In the formulation of maintenance strategy whole organization (i.e. production + finance + human resources etc.) has to be taken into account. Maintenance should aim to the same targets as the other parts of the organization. In this research the purpose was to study different maintenance strategies and their effects on the behavior of different parts of the organization.

The difficulty in the strategy formulation is system's dy-

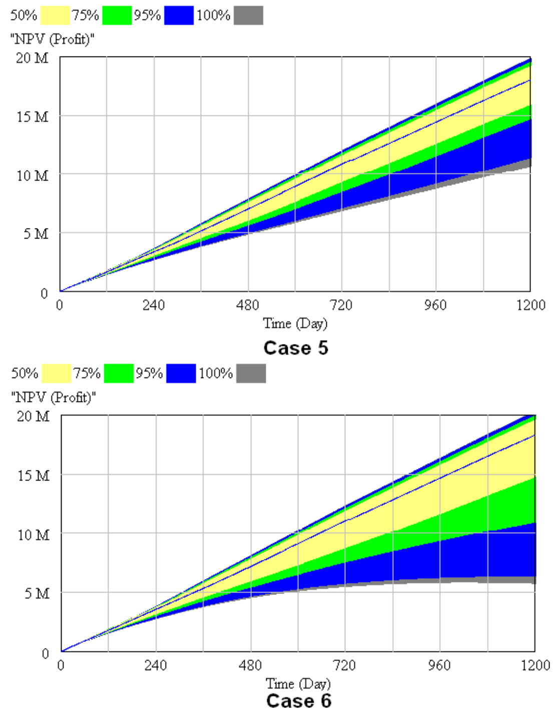


Fig. 11 The net present value sensitivity to the life time estimate accuracy.

namic complexity. Basically, system's complexity and nonlinearity make it difficult to understand the behavior. A minor change in some part of the system, may trigger a drastic systemwide change in the behavior, or on the contrary, even the most vigorous effort on the policies that seem intuitive, may be dampened down by the system's response. The behaviour may seem to be counterintuitive if the time horizon is too short or the perspective to the system too narrow. Together the parts of the system are much more than the sum of individual parts.

A system dynamics model was built for the maintenance strategy evaluation. With the model, different strategies can be evaluated through simulations. In addition to the model, a causal diagram of system's feedback structure was constructed in order to make rough interpretations of the system's behavior. Thus, it is possible to find best policies with simulations and to explain the idea in these policies with rough structural analysis.

The focus is on different maintenance policies and their combinations. The maintenance portfolio is comprised of run-to-failure, periodical maintenance, inspection based maintenance, and automatic condition monitoring. The objective was to find good maintenance portfolios by weighting different preferences in the strategy formulation. The preferences are the period of time over which the strategy is evaluated, the cost-effectiveness, and the overall effectiveness of equipment.

Today's business environment is tempting to myopic thinking as the financial positions of companies are viewed quarterly. When it comes to maintenance, if the policies to respond to certain events in the system are too shortsighted, the desirable results last often only a short period of time. Nonetheless, when the undesirable long term effects appear the response is usually the same shortsighted policy which was the original cause of the problem. This leads to accelerating deterioration of system's behavior. This was the case in strategies 1 and 2.

On the other hand, even if the behavior is evaluated over a long time horizon, but with too narrow a perspective, the results may be poor considering the performance of the whole organization. This is the case if we compare Strategies 3 - 4 to Strategies 5 - 8. The increased production goals did not increase the profit (strategies 5-8), even if the goals were achieved. In practice, the real nature of the problem would have never been revealed, if we would have examined the production's performance only.

The structure includes a risk that the ineffective proactive policies turn, due to reinforcing feedback loops, to reactive policies. The ineffectiveness may be related to the over-confidence in or to the optimism about the assumptions that are made in strategy formulation. The risks of over-confidence can be reduced by increasing the proportion of planned maintenance. The increase in costs is relatively small compared to the risks.

The model, presented in this paper, includes probably many defects and over simplifications. Considering the initial problem, nonetheless, the model makes it easier to understand the dynamic complexity of the problem and reveals some aspects about strategy formulation.

This research is funded by several companies, and thus, the model does not represent any specific process plant. On the contrary, it represents a generic process plant. Nonetheless, one of the most important focus areas in this research is on the model's modularity, so that the model could easily be used as a starting point in various cases. The model is in the process of being calibrated to different process plants.

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