A Maintenance Model for Identification, Quantification and Elimination of Losses in Companies Profitability: Application Examples

Abstract
A production process includes several sub-processes, which may also be called working areas or disciplines that are responsible for performing the different tasks required to accomplish the mission of the process. It is crucial that the tasks performed in these sub-processes are synchronised with each other without unnecessary and uncontrollable gaps and overlapping, which in turn may lead to losses in production time and manpower. It is important to avoid a shortage of resources, unplanned stoppages and idle times that may arise due to the gaps. In this paper gaps are generated due to missing the tasks or inputs that are required because of deficiencies in planning, the lack of responsibilities or of knowledge and experience concerning these inputs. On the other hand, effective synchronising of production-different disciplines will enhance production process effectiveness as well as company profitability and competitiveness.

The problem addressed in this paper is: How should maintenance be considered in conjunction with plant activities, such as production, quality and personnel competence, in order to easily and effectively identify and quantify company losses in profitability and competitiveness and consequently to eliminate underlying causes? In this paper the gaps and overlapping between maintenance, production, competence and quality are defined, identified and described through a technical analysis of the production sub-processes and their respective sub-organisations. The major result achieved in this study is the development of a new model (Maintenance Function Deployment (MFD)), for an easy and effective identification and quantification of company losses in profitability and competitiveness for cost-effective elimination of the root-causes. MFD can be applied through identifying:

1. the requirements that are necessary to achieve and maintain company strategic goals,
2. tools to maintain the condition of these requirements,
3. activities for the effective utilisation of the tools above, and
4. the factors required to support the integration of maintenance with plant business for enhancing production process effectiveness as well as company profitability and competitiveness.

The structure of the quality house has been used as a platform for developing MFD model for effectively integrating maintenance with production, competence and quality. Two examples are conducted to demonstrate the possibility of applying the model and its potential for enhancing production processes profitably. The main conclusion is: applying MFD gives an enormous opportunity to continuously maintain the quality of the working areas under consideration, which makes MFD one of the company’s objective-driven tools for enhancing its profitability and competitiveness. Also, it implies the application of the PDCA cycle, which in turn improves the integration of relevant working areas cost-effectively and continuously.

Keywords: Production Process; Vibration-based Maintenance; Maintenance Integration, Authorities; Responsibilities; Organisation; Company profitability and
competitiveness; Maintenance function deployment; Gap and overlapping between working areas.

1 Introduction
The most important achievements, such as maintaining high quality production, reliable machine condition and a cost-effective production, that companies strive to approach are usually made on the basis of an effective participation of company personnel and resources from different working areas, Nakajima (1988 and 1989), Bergman and Klefsjö (1994), Al-Najjar (1997), Perez-Wilson (1999), Magnusson et al. (2000), Henderson and Evans (2000), Ingle and Roe (2001), Caulcutt (2001) and Man (2002). Thus, these achievements can be enhanced if the personnel competence and the resources in the working areas of interest, e.g. production, maintenance, competence and quality, are integrated in an effective way.

It is well known that the working areas such as production, quality, competence and maintenance in a production process interact with each other, Ben-Daya and Duffuaa (1995), Al-Najjar (1997 and 2007A) and Al-Najjar and Alsyouf (2001). We claim that uncontrollable interactions usually generate gaps, i.e. no action takes place when it is required, and overlapping between working areas where responsibilities and authorities interact, see Chapter 3. Overlapping generates a common area of responsibility and authority which may induce friction between personnel. In this paper, the analysis of the production process is used to investigate gaps and overlapping between the production, quality, maintenance, competence and economy working areas and their effects on company business.

To evaluate the condition of a production process, machine or component, or the level of the production costs, relevant data of high quality are needed, Al-Najjar (1997). These data are either available from the company's databases or need to be gathered. The available data are usually time-consuming and not easily accessible even if they can be opened in a Windows environment, because it requires opening tens or hundreds of windows (Ibid). A common database can be established where data from relevant working areas, such as production, quality, administration, maintenance and life cycle costs, are gathered without duplication in a common physical or virtual database, Al-Najjar (1997), Al-Najjar and Kans (2006) and Kans (2005). These data are necessary for performing reliable, easier and faster mapping, following up and assessment of production cost, product quality, plant condition and performance, Al-Najjar (1997) and Kans (2005).

The integrated information system provided by a common database enables the user to achieve a more accurate and comprehensive overall view and a sufficiently detailed description of the process condition, operating conditions, product quality, production cost factors, etc., Kans (2005) and Al-Najjar (2006). Consequently, many primary potential benefits, such as more accurate diagnosis, prognosis, prediction and cost-effective decisions, can be obtained, which in turn can lead to secondary potential benefits, such as:

1. increased certainty in the information acquired, which in turn enhances the quality of the decision-making process,
2. increased data availability that can be used for monitoring, mapping, analysis and decision-making,
3. better data coverage, which is required for modifying the available machine/plant or for designing new assets,
4. enhanced process stability, reliability and quality, machine and plant safety
due to detecting damage at an early stage to reduce failures and failure-based
accidents, see also Al-Najjar and Alsyouf (2001).
5. prolonged machine life length due to maintaining the quality of the machine
via reduced failures and disturbances
6. improved quality rate, due to the ability to detect and eliminate damage
causes at an early stage.
7. better opportunity for reducing long-term operating costs through better
optimisation.

See also, for example, Al-Najjar (1997, 1998, 1999, 2007A), Kans (2005) and Al-
Najjar and Alsyouf (2004). The problem addressed in this paper is: How should
maintenance be considered in conjunction with plant activities, such as production,
quality and personnel competence, in order to easily and effectively identify and
quantify company losses in profitability and competitiveness and consequently to
eliminate underlying causes?

2 Literature Survey
A wide advanced survey in the international databases is conducted. It covers all the
publications included in ELIN during the 1900-2006 period. ELIN stands for the
Electronic Library Information Navigator, which integrates information from many
publishers, databases and an open e-print archive. In this search we used first the
keyword “Maintenance AND Function AND Deployment”, i.e. like three words in the
Abstract. The result was 26 publications, but just four of them treat problems close to
the problem addressed in this paper. In Pramod et al. (2006), which is the most
relevant for this study, the authors developed a model nourishing the synergy of
quality function deployment (QFD) and total productive maintenance (TPM) to
enhance the maintenance quality of product and equipment. The model is called
Maintenance Quality Function Deployment (MQFD). It is developed by linking two
current applied methodologies: introducing QFD in TPM principles and introducing
TPM principles in QFD projects. By the model the authors tried to translate customer
voice into technical language, where costumer voice represents the condition of
different machine components and performance measures and the technical language
used to describe the quality of the machine components considered in the study
without considering the economic issue.

In Kutucuoglu et al. (2001) the authors looked at the role of performance
measurement systems (PMSs) in maintenance for developing a new PMS using QFD
techniques. Considering the key features and the complexity of the maintenance
system, the authors developed a matrix structure of QFD suitable for developing a
PMS that embraces the features demanded, which is somewhat outside the context of
our paper. The same can be said about Zhang et al. (1998), where the authors
developed a new methodology for product development or improvement called Green
Quality Function Deployment-II (GQFD-II). They tried to integrate life cycle cost
(LCC) into QFD matrices and deploy quality, environmental and cost requirements
through the entire product development process. GQFD-II elaborates on the original
GQFD, in which life cycle assessment (LCA) and traditional QFD are combined to
evaluate different product concepts. GQFD-II is a tool for product development or
improvement by virtue of improving quality, reducing cost and minimising
environmental impacts.

In Geng et al. (1996) a new system was developed called Customer-Oriented
Design Support System (CODESS), which is also outside the scope of this paper. It
aims to implement QFD into information systems more effectively and provide decision support in the conceptual phase of new product development. The paper describes CODESS and discusses a data model which facilitates the development and maintenance of CODESS and plays a key role in its integration into a corporate information system. However, none of these papers discuss the deployment of maintenance for effectively identifying, quantifying and eliminating company losses in profitability and competitiveness caused by gaps and overlapping between relevant working areas.

Additional keywords were used for making a wider survey of the 1900-2006 period, such as “Maintenance function deployment”, “Maintenance impact on company profitability”, “Maintenance impact on company losses”, “Maintenance for profitable company”, each considered as one word. The result of this search was simply: nothing found. Further search in the international databases was conducted early in 2003. The databases considered in this survey were Emerald and Science Direct alone. The search was carried out on publications before 2003 using several keywords: (1) integrated maintenance, (2) design of integration of maintenance, (3) design of integration of maintenance, production and quality, and (4) model design of integration. The result of the search using these keywords was one hundred and twenty papers. Only six were, to some extent, relevant, especially when it concerns the integration of maintenance with another working area.

Leger et al. (1999) present a methodology approach to designing a new distributed maintenance system solution. This solution includes the integration of maintenance in general, a definition of pertinent maintenance user requirements and the mapping from the requirements to the technologically distributed maintenance system. In Hassan et al. (2003) the results are presented of the analysis of the design process employed in the design and integration of a company and of how safety is integrated into the design process.

Jonsson (2000) claims that the companies with heavy investments in advanced manufacturing technology had developed the infrastructure and maintenance (prevention and integration) aspects to a greater extent than low-investors. Incorporating maintenance and quality as excellence, value, conformance to specifications and meeting/exceeding customer expectation has been discussed in Swanson (1997). The maintenance/production interface and importance were based on data gathered from 293 Swedish companies. He also emphasises the importance of integration for organisational design and strategic planning.

One of the most interesting papers with a context close to this paper was written by Ip et al. (2000). It describes research work that has been carried out using the integrated definition method (IDEF) model to systematically integrate maintenance into Manufacturing Resources Planning (MRPII). It claims that proper design and the integration of maintenance into MRPII enable the manufacturer to manage production planning, scheduling activities as well as analysing their maintenance theory, carrying out cost analysis and studying the failure trends to determine how the available labour and maintenance material can be used effectively. The major focus of the study presented in Ip et al. (2000) is on how to integrate maintenance activities on the operative level into MRPII in order to analyse manpower and maintenance productivity. However, no study was found discussing the problem addressed in this paper.
3 Interactions between working areas and their impact on Company Business

Production is responsible for making goods, but an efficient maintenance policy influences the capacity of production, the capability of the machine and, consequently, company profitability and competitiveness, Al-Najjar et al. (2001), Al-Najjar and Alsyouf (2004) and Al-Najjar (2007A). The production personnel’s technical knowledge and experience in machine construction and functions influence production and maintenance costs as well as machine performance efficiency, because they affect the way of using and maintaining the machine quality (technical specifications). McKone and Weiss (1998) cited that the amount of money spent company-wide on maintenance by du Pont in 1991 was roughly equal to its net income.

3.1 Interactions between Quality, Production, Competence & Maintenance

From everyday experience, changes in any working area, such as production, quality or maintenance, influence the other closely related working areas due to their internal interactions. Also, product quality, production cost, machine condition and its life length are usually influenced by the quality of the input elements involved in the production process, such as raw material, production tools, methods and procedures, operating and maintenance staff competence and operating conditions, and not just by the type of production machinery and maintenance policy. Bad raw material or badly trained operating and maintenance staff often lie behind the initiation (or development) of damage in the component/equipment or cutting tool, which in turn results in production and financial losses, Al-Najjar (1994). Thus, the quality of the essential elements involved in production process is a key factor influencing overall equipment effectiveness (OEE).

In general, neglecting maintenance and its role in the production process may lead to a faster degradation of machine and product quality. It is well known that a process or machine in a bad condition cannot, in general, be expected to be capable of long-term high quality production delivered on time at a competitive price. But, the real status of maintenance in company culture has not yet been recognised, because of the lack of research highlighting the maintenance impact on company business, Al-Najjar (2006). This is due to many causes such as:

1. Maintenance having, in general, been considered as a cost and not as a profit centre
2. Complex maintenance interactions with (and impacts on) other working areas, such as production, quality, personnel competence, operating environment and life cycle cost (LCC).
3. Therefore, identifying, quantifying and following up the impact of maintenance on company business are not an easy task. It is rather time- and labour-consuming, which makes the maintenance engineer abandon it.

A machine associated with failures often produces defective items, Ahlmann (1994) and Al-Najjar and Alsyouf (2004). From everyday experience, a machine with frequent failures that produces a high percentage of defective items increases the probability of delivery delay and high production costs, which in turn reduces profit and increases the risk of losing market shares and thus endangering the survival of the organisation in the long term. Reducing production losses and enhancing product quality always yield greater profit and improvement in the company's competitiveness, Al-Najjar (2007A).

In general, the role of maintenance has not been effectively and quantitatively highlighted; see Al-Najjar (2007A) and Chapter 2 of this paper. This is because the
major part of the profit that an effective maintenance may generate demands a big amount of effort to assess, whereas it is often easier to only measure maintenance costs, Al-Najjar and Alsyouf (2004). By applying effective maintenance, such as Total quality maintenance (TQMMain), a company's profitability and competitiveness can be enhanced through the continuous cost-effective improvement of production and maintenance processes, Al-Najjar (1996, 1997, 2006 and 1997A). The latter can be achieved via maintaining and improving the quality of the elements involved in the production and maintenance processes continuously and cost-effectively, see for example Al-Najjar (2006,2007A).

In this paper the role of effective maintenance is defined as: a means for detecting and controlling the deviations in the condition of a production process/equipment, production costs, the working environment and product quality in order to interfere when it is possible to arrest or reduce the deterioration rate before the process condition and product characteristics are intolerably affected, and to perform the required action to restore the process or equipment/component to as good as new. All these should be performed while continuously reducing cost per unit of quality product.

3.2 Gaps and Overlapping between Quality, Production, Competence & Maintenance

A lack of or shortages in the raw material, machine availability or a competent operator will, in general, generate gaps between production and production logistics, production and maintenance, and production and human resources, respectively. The same can be said about the passive role of the operator in controlling product quality or maintaining the condition of the machine, which generates gaps between production, on one hand, and quality system and maintenance, on the other. Therefore gaps are generated because no action takes place when it is required, i.e. the failure of delivering on time what is expected by the production process. Thus, a gap occur due to bad (or degradation in) the quality in one or more of the elements involved in production and maintenance processes, such as managerial tools, machines and equipment, working environment, competence, monitoring and controlling systems, which result in one or more of the following:

1. Unclear responsibilities and authorities of the different working areas in providing the services required for a production process, such as the confusion in providing a maintenance action necessary for avoiding a failure, whether it is the maintenance technician’s or the operator’s responsibility.

2. Deficiencies in the planning, e.g. the services expected are not delivered on time.

3. A lack of the knowledge and experience (or possibly the technology, such as condition monitoring) necessary to detect and eliminate that gap. For example, special technology and experience for detecting the causes of initiation of damage are required in order to eliminate the root causes before it is too late and too expensive.

Failures, planned stoppages and other production disturbances may happen randomly in time due to gaps, i.e. unclear responsibilities/authorities or the lack of/inefficient planning/knowledge and experience/technology for detecting and localising the damage causes and initiation, damage development and imminent failures. The identification and elimination of these gaps help to recover the losses incurred by ignoring damage initiation, its development and imminent failures, Al-Najjar (2006, 2007A). Technical knowledge, personnel competence and the reliable
utilisation of the available technology, such as condition monitoring (CM) systems, increase the chances of avoiding these gaps (Ibid). Besides, an organisational analysis covering the responsibilities and authorities of staff work in the areas of maintenance, production and quality is quite helpful to identify and eliminate gaps and overlapping to make the sub-organisations synchronise smoothly with each other. An example of such organisational analysis is illustrated in Section 6.2.

Overlapping occurs when more than one of the personnel have the same task in his/her responsibility/authority, which creates more allocations of resources and time than is actually required. For example, when we do not have faith in a quality control system, we may ask additional personnel, such as the operator or someone else to spend more time and labour in controlling production quality and observing changes in the technical specifications. Furthermore, when we do not believe in the current condition-monitoring system, it may result in applying additional condition-monitoring systems, e.g. temperature in addition to vibration, or asking the operator to utilise human senses to report changes in the condition of the machine. In these cases, overlapping is generated between production and quality, and between production and maintenance, respectively.

The overlapping in the responsibilities/authorities is confusing and may result in the task not being done or in an unnecessary increment in resource consumption when more than one person plan and/or perform identical actions. In other words, the task required is either performed twice/more times or is not performed at all. In both cases losses are generated due to either additional costs when all those involved try to perform the same task (and consequently friction between personnel of different responsibilities and authorities can be expected) or to losses in the production time caused by failures or by producing defective items when no one has performed the task required. This is very obvious when it comes to data gathering. The same data can, in many cases, be found in the databases of different working-areas. In the rest of this paper, except in Section 6.2, we will focus mainly on the gaps between working areas and their effects on company business.

4 Quality Function Deployment (QFD)

Applying the concept of total quality management (TQM) leads to designing, producing, transporting and installing high-quality production machines, see for example Bergman, B. and Klefsjö (1994) and Hermann et al. (2006). QFD is mainly a tool to help companies focus on what customers perceive as important and certify that the desired abilities exist in the final product or service, Hermann et al. (2006). The authors listed the benefits that may be acquired by applying QFD, based on the analysis made using about 81 papers and books published about QFD applications in the 1979-2002 period. These benefits are: reduced design cost and development time, Nicholson (1990) and Hofmeister and Slabey (1988). Additional benefits include improved communication and cohesion within product development or the improvement of team and solidifying design decisions early on in the development cycle, Morrell (1987) and Neumann (1996). Approximately the same results have been achieved by Cheng (2003). Equivalent results have been achieved in the survey done by Akao (1990) in determining the benefits of QFD within Japanese industry.

4.1 Phases of QFD

The production process is usually constituted based on the customer needs and expectations, and with respect to the competitors’ products. Quality function deployment (QFD) is seeing what the customer needs, how it is possible to make the
product better and how the manufacturing process can be improved. It has the customer in focus through handling what the customer wants, his/her satisfaction with the product, etc. However, it does not offer a way to integrate maintenance with other relevant working areas for the identification, quantification and consequently elimination of losses due to degradation in the quality of the elements involved in the production process, such as maintenance policy, machinery, methods and systems for achieving the company’s strategic goals cost-effectively. QFD includes four phases: product planning, product design, process design and production design, Sandholm (2000), see also Fig. 1.

In the first phase the customer needs are converted into product characteristics that aim to:
1. identify customer needs and expectations and their importance,
2. find customer wishes that can be used as important sales arguments,
3. decide the product characteristics according to the customer wishes and
4. set up target values for the product characteristics.

In the second phase the design concept is chosen, i.e. the one that is best suited to satisfy the customer needs of the product characteristics, aiming to:
1. select the best design concept to fulfil the product-characteristic target value,
2. identify the components that will be critical for the product,
3. decide the part characteristics the same way as was done with the product characteristics in Phase One,
4. identify the critical part characteristics and
5. acknowledge where there are further needs for research or development to satisfy market demands.

In the process design phase critical parameters in the manufacturing process are identified, and the maintenance routines, mainly based on manufacturer recommendation and company experience, are decided, i.e.:
1. choosing the best production process so that the component and part characteristics are fulfilled,
2. identifying the production processes that are critical and
3. identifying the needs for research and development, for new and more effective production processes.

**In the final production design phase** manufacturing instructions are identified. This is done so that the operator knows which parts have to be measured, how often, how many parts should be observed and with what tool, i.e.:
1. Documenting the production process.
2. Creating the foundation for working instructions.
3. Identifying the operator’s educational needs.

QFD is a structured technique, which is mostly used on new product/service development, but which can also be used to improve existing systems or processes. It promotes cross-functional communication between marketing, engineering, manufacturing staff etc., and the translation of customer needs into operational realities. In these four steps a house of quality can be developed, where the Whats are the customer needs and expectations of the product, which can be achieved by market investigations, brainstorming, etc, Ottosson (1993) and Hermann et al (2006). The Hows are the product characteristics that are necessary for manufacturing the product and fulfilling the needs. The Hows are decided on the basis of the conditions of the Whats.

### 4.2 Quality Function Deployment and Maintenance Requirements

However, it does not matter how robust the machine design is and how accurately the operating conditions and instructions are set up and followed, the deterioration of the component/equipment cannot be avoided. In other words, it is one of the laws of nature, i.e. every thing/component or equipment has its birth/installation and death/replacement moment. For example, total productive maintenance (TPM) is introduced as an alternative to handling the losses that arise due to failures, disturbances, bad quality production, i.e. the six types of losses, Nakajima (1988), even when applying TQM. The maintenance role is then to reduce the deterioration rate and prolong component/equipment life length as much as possible through maintaining its technical specifications, i.e. maintaining its quality. This task demands special requirements, resources and arrangements known for centuries as maintenance technology.

According to Hermann et al. (2006), QFD should be implemented in the very early phases of the product development cycle to make sure that all major design conflicts and problems are solved before production is started. Notice, QFD cannot answer the questions about how we should solve the problems arising due to a faulty use of machinery (human error), deterioration in producing assets, degradation in the working environment or deficiencies in the personnel competence, commitment or communications, and the economic losses incurred by these problems, see Survey in Chapter 2. Thus, focusing on the role of QFD may lead to neglect the role of maintenance in fulfilling the expectation of the company in producing items to the predetermined specifications and those of the company board in achieving company strategic goals expressed in environment-friendly production delivered on time at a competitive price, Al-Najjar (2006 and 2007A).
In general, the modification or improvement of a component/equipment or process is not always acceptable if it is not cost-effective, i.e. the cost of modification/improvement should be justified by the increment in the economic results in the form of more quality production, less production cost or more profit margins. Therefore, in many cases continuous/never-ending improvement is not always satisfactory if it is not cost-effective. This is why total quality maintenance (TQMain) advocates the concept of cost-effective and continuous improvement, Al-Najjar (1996, 1997, 2006 and 2007A).

Quality circles and circles for TPM are usually activated when there is an actual failure/problem. The main purpose of quality circles or circles for TPM is to analyse failures and suggest modifications or improvements to eliminate the causes behind failures, Hari et al. (2007), keeping in mind that failures mean unavailability and economic losses. Nowadays, due to the hard competition, this technique is not as valuable as during the 1980s and 1990s, because companies struggle to avoid all failures, Al-Najjar (2007A). Applying TQMain enables the company to plan and perform maintenance actions at the damage cause phase, i.e. earlier than damage initiation and imminent failures, which in turn reduces failures and their consequences dramatically Al-Najjar (1997, 1998, 1999).

There are three phases describing a component deterioration process that is damage initiation, damage development and imminent failures, Al-Najjar and Wang (2001). Relevant CM technology can provide real-time data required for detecting changes in the condition of the component/equipment, while TQMain management is responsible for planning and performing maintenance actions before (possibly) even the damage is initiated, Al-Najjar (1997 and 2007B). In other words, applying TQMain makes it possible to integrate data and experience from human expertise, CM technology, historical data and knowledge systematically (ibid), while quality circles and circles of TPM originally did not advocate that integration properly.

To reduce the amount of losses due to bad quality production, it would be more cost-effective to detect deviations in the quality (technical specifications such as tolerances) of every item during the processing time instead of applying the traditional quality control schemes, such as the Shewhart chart, on the final production, Al-Najjar (2001). The information provided by applying vibration-based maintenance (VBM) policy, using vibration spectral analysis, gives a reliable real time opportunity for achieving this goal, while neither TPM nor TQM is capable of doing so (ibid). Therefore, integrating the data and knowledge acquired through relevant CM technology with that from other plant activities to form the common database advocated by TQMain provides a reliable opportunity for identifying and quantifying the losses in the company profit and competitiveness for eliminating their root-causes.

Although many studies can be found investigating the benefits of QFD, no comprehensive model was developed relating these benefits to financial measures, Hermann et al. (2006). Relating the operative level activities, such as maintenance action planning and performance, to those at the strategic level, such as strategic planning, market share, profit and investment, means translating technical terms in the form of running time, failures, repair time, spare parts, etc. into financial terms, e.g. economic losses, maintenance savings, profit and investments. This translation is rather important to be able to use a normalised measure, e.g. money, which is understandable to everybody in the company from the floor worker to the company board and can be used for expressing successes or failures.

QFD mainly focuses on how to reduce design cost and product development time, improve communication and achieve cohesion within product development or team
improvement and solidify design decisions early on in the development, see above. Maintenance as a means to maintain the quality of all the elements involved in the production process is responsible for making the assets required for producing quality production cost-effectively available and able to perform efficiently. Therefore, some of the requirements needed by QFD are assumed to be fulfilled by the maintenance department, see for example Jalhanm and Abdelkader (2006).

In the quality house the importance of the relationships between theWhats and the Hows is usually expressed in linguistic terms, such as very weak, weak, more or less weak, strong, more or less strong, very strong, see for example Kutucuoglu et al. (2001), Hunt and Xavier (2003), Migul, P.C. (2005), Chan and Wu (2005), Ginn Zairi (2005), Yung et al. (2006) and Herman et al. (2006). However, identifying and quantifying the losses generated due to the lack of or inefficient maintenance are expressed in the absolute values of losses to make it more understandable and for justification, i.e. to be compared with the capital needed to be invested to eliminate the root cause. Further, the real data needed for assessing the real losses and profits are, in many cases, available in the company databases.

In Phase Three of QFD, i.e. the process design phase for new and more effective production processes, the way to achieve that is not described. The main objective of this paper is to develop a model that makes the production process more effective technically and economically through identifying problems, quantifying economic losses and eliminating the underlying causes that prevent the realisation of the company strategic objectives cost-effectively. This is why we will use another concept, i.e. TQMain, than QFD for achieving the goals that QFD cannot attain.

The selection of the most suitable maintenance strategy and policy and the planning of maintenance actions can be made in different ways, such as applying probabilistic or/and deterministic models using objective measurements or linguistic data, see for example Al-Najjar (1997, 1999), Al-Najjar and Alsyouf (2003) and Al-Najjar et al. (2004). In this paper, the major characteristics specifying a production process that are of significance from the maintenance point of view are:

1. failures and all different unplanned stoppages and disturbances, and their consequences, i.e. whether leading to just economic losses such as machine failures in the engineering manufacturing industry or possibly exposing the surroundings to catastrophic hazards, such as the case at a catastrophic failure in a nuclear power station,

2. the condition of producing machines and assisting equipment,

3. the production rate of high quality items and the economic losses per one-hour production stop and per one scrapped item,

4. the maintenance competence and experience available in the production department,

5. the type of production machines, production and rotational speeds, and loading frequencies and

6. the working environment.

These characteristics influence the overall equipment effectiveness (OEE) and, consequently, the process of deciding the maintenance strategy or policy that should be implemented, see for example Al-Najjar (2007A).

In the next chapter a model for easily and effectively identifying and quantifying company losses in profitability and competitiveness for eliminating underlying causes is developed and discussed. This model is not to replace QFD but it is a necessary tool for determining and establishing maintenance requirements for achieving company business objectives cost-effectively.
5 Model Development

In this section the quality house is simplified to fit this specific application. The major focus has been given to the Whats and Hows in the model’s four phases required to reflect how the main objectives of a production process (or a production station in a production line) are converted to specific actions necessary for eliminating losses and maintaining the quality of the elements involved in the production process cost-effectively. To avoid complexity in the model at this level of the development and to facilitate the understanding of its role and potential benefits the following elements are not considered in detail in MFD:

1. Importance: the importance of each What/How in MFD can be assessed by the accumulated effects of each row/column, respectively. The accumulated effect can be positive or negative, i.e. profit or loss.
2. Competitive assessment: any similar or equivalent machine to that in question (in the same company or in other companies) can be considered as competitive. This is why the importance of Whats/Hows in the MFD of the machines under consideration can be used for comparison.
3. Target value: the target value in MDF can be different for different Whats, i.e. it can be different for any element in the matrix. It represents in this context the maximum losses allowed or the minimum capacity utilisation acceptable for the elements under consideration.
4. The improvement direction, correlation matrix, sum of correlation and relationship matrix can be applied in MFD as well.

The final outputs of the production process (or station), which are stated in the first phase as Whats, are considered as the reference for the outputs that should be provided by a production process (or station) to be able to fulfil its mission, see Figs 2 and 3a,b,c & d.

5.1 Model Construction

Assume that the differences between stations are negligible, which is not an unrealistic assumption. For simplicity, we focus on a production station instead of the whole production line or plant. The generalisation of the results of handling one production station to the rest of the production line, taking into consideration the essential differences, will then not be impossible.

We consider that the stations’ outputs should be achieved to fulfil the company’s strategic goals. These objectives are usually specified in technical terms, such as the characteristics of the production expressed in dimensions, tolerances, surface finish, product quality and production rate, as well as in financial terms, such as the cost factors of the production, economic losses and profit margin. From industrial experience, maintaining the condition of the production assets and reducing their share of pollution to the environment are, in many cases, also considered as essential elements in the outputs of a production process and, consequently, of production stations.

Achieving the planned outputs of the production process/stations is necessary to preserve the continuity in the production process at the pre-determined specifications; otherwise it will not be easy in the long term to maintain a profitable business. From everyday experience in production planning it is possible to determine the inputs and anticipate the outputs of every production station in a production line.

In Fig.2 we use two types of arrows. The bold-style arrow is used to indicate the direction of the model development, i.e. the model is developed
backwards from the company’s strategic goals towards the factors required to support the integration of maintenance with plant activities. The reverse arrow is used to indicate the direction of applying the model in reality, i.e. starting from the factors required to support the integration of maintenance with plant activities forward to achieve the company’s strategic goals.

Fig. 2. Schematic description of the model’s four phases.

The outline of the model Maintenance Function Deployment (MFD) is shown in Fig. 2. MFD consists of four phases:

**I. Phase One:** It starts by identifying the output that should be achieved by the production station under consideration. In this paper, we specified five outputs, which are more or less common objectives of the production process/stations (or company’s strategic goals) in a very wide range of companies and industries:

1. High quality of the final product or the semi-manufactured items that will be processed in the following production station or delivered to the customer. It basically covers the technical specifications of the final product/semi-manufactured item
2. Delivery on time. It is important to maintain the continuity of the material flow between production stations and to deliver the product to the internal and external customers by the time agreed on. Otherwise, financial losses and penalties can, in many cases, be expected
3. Competitive price. In order to enhance company competitiveness, the profit margin should be big enough to enable the company to offer its customers a product price that strengthens the company’s competitive position in the market. This is not possible to achieve without a rational production, i.e. rational production stations where economic losses in the production are continuously minimised, Pehrsson and Al-Najjar (2005)
4. Environment-friendly production process and product. Environmental issues have recently become increasingly important as a selling argument. Environment-friendly production is, in general, a production process that does not expose the working and the global environments to hazards. At the same time, the life cycle of the product is also required to be environment-friendly, (ibid)
5. A production machine in a reliable condition; in other words, maintaining the condition of a machine means preserving its technical specifications required for effectively performing the tasks that it has been designed for. It provides the company with a reliable opportunity to sell the machine after its designed life instead of paying a scrapping fee, Al-Najjar (2007).
These outputs, i.e. the Whats, are stated as the objectives that every production station strives to achieve. They are highly influenced by the elements involved in the production process, such as the condition of the machines, the working environment, personnel competence, maintenance policy, raw material, production method and procedures, cutting tools and quality system, etc.

In order to achieve, maintain and improve the outputs that are necessary for a company to attain its strategic goals, the requirements needed for that, i.e. the Hows, should be specified, using a technical analysis of the company's strategic goals, production process (production line) and the production station in question. In Fig. 3a we identify the most important requirements for achieving, maintaining and improving product quality, delivery on time of production that is accepted by the society at a competitive price, and keeping the manufacturing machine in a predetermined condition. It also entails providing a production station with the requirements needed for a production process, such as reliable quality and production logistics systems, a good working environment, production machines operating and a maintenance staff expected to produce a product of high quality at the required production rate and at a competitive price.

Maintaining the high quality of the raw material, a reliable quality system and a competent staff, in addition to maintaining the producing machine and tool condition at a pre-determined level, will ensure the production of high quality products, Al-Najjar (2006) and references cited there. If the elements, such as raw material, energy and operator, are available at the required quality, one or more of the following causes can result in a stoppage and probably a delivery delay of production to an internal or external customer:

1. The condition of the machine (availability)
2. The condition of the tool
3. Disturbances in the production logistic system that influence the availability of the logistic system
4. Variations in the production rate
5. The machine capability of producing high quality products, Pehrsson and Al-Najjar (2005)

The price of a product is usually decided on the basis of internal and external factors. The internal dominating factors that influence the price of a product include: machine and production station unavailability due to failures or other disturbances, the cost of bad quality, quality system malfunction, incompetent personnel, a bad machine condition, energy consumption, a waste of raw material, the insurance premium, material flow problems, etc.

The external factors are mainly dominated by raw material cost, market demands, competition, crises, wars and currency value. In this paper we consider only the internal factors, because they are of major interest for maintenance, while the external factors lie outside the context of the maintenance influential area, Al-Najjar and Alsyouf (2004) and Al-Najjar (2007A). On the basis of the internal factors (and neutralising the external factors) we realise that the control of production losses has an influential impact on the profit margin and consequently on the product price giving that all the production can be sold, Al-Najjar and Alsyouf (2004) and Pehrsson and Al-Najjar (2005).

Taking into consideration the increasing number of people who are conscious of environment problems, a production that does not expose society and the global environment to unacceptable hazard, pollution and harm is more acceptable nationally and internationally. The requirements that help to achieve a better environment are
those, for instance, which are related to the condition of the machine, losses in material and production and the rational use of machinery and energy. At the same time these requirements also increase the probability of preserving the producing machines in a reliable condition.

<table>
<thead>
<tr>
<th>Outputs to be achieved, maintained and improved (Whats)</th>
<th>Target value (Max. losses or minimum allowable utilisation level)</th>
<th>Requirements for achieving, maintaining and improving the outputs (Hows)</th>
<th>Accumulated effect, i.e. the importance or share ofWhats</th>
<th>Priority list of the actions required for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>High quality production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivery on time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Competitive price</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment friendly production accepted by society and internationally</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintaining manufacturing machines in a reliable condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.3a. Phase I. The requirements whose condition should be maintained in order to maintain the company’s strategic goals

For simplicity, the lateral interactions between the columns, i.e. Hows, are ignored in this paper. These interactions can be exemplified by the impact of operator knowledge and experience, especially in the way of running the machine according to the operating specifications for machine reliability, availability and productiveness. Further, if the operating conditions deviate from the pre-determined levels, the performance of the machine and, consequently, the output of the production process will be affected.

In each of the four phases the model provides a possibility to allocate the accumulated share (importance) of theWhatsand Hows in developing the accumulated effect for each What and the current situation experienced by each of the Hows. For example, the share of every column (Hows) in the economic losses is generated by bad quality production, additional production expenses due to delivery delay or environment damage penalties, etc. Besides, the accumulated effect of each of theWhatsis generated by the shares of all the participating Hows in that What.
Allocating these shares can be done on the basis of past production station data. This will be described in the example introduced in Section 6.1.

For example, to determine the impact of the condition of a machine on the production cost, which influences the possibility of offering the market a lower product price, we should assess the economic losses generated due to failures and disturbances affecting the production cost and consequently the product price. In the same way we can assess its impact on the production delivery schedule, e.g. the more failures and disturbances, the greater risk of delivery delay and, consequently, of additional production expenses due to delivery delay penalties. When these shares are clearly determined, it would be possible to develop a priority list of the tasks, indicating which of the Whats based on its accumulated effect or importance, should be considered for deeper analysis for achieving a cost-effective improvement.

II. Phase Two: The requirements needed for achieving, maintaining and improving the outputs described in Phase One, i.e. the Hows, are moved to the column ofWhats in the Phase Two matrix. In order to describe the new Hows, a spectrum of the tools that are necessary to preserve the condition of the requirements shown in Phase One should be specified. It is important to treat every requirement individually to facilitate the tracking of the cause-result links for each particular area. By proceeding through this systematic analysis, a large number of tools of different correlations and impact importance will be approached. The interactions between these parallel chains of links would also be necessary to be considered in the analysis.

In this paper we focus on the most essential tools related to maintenance and its impact on the company’s business to avoid unnecessary and unmotivated difficulties in this stage of model development. In general, it is possible to identify the major attributes (the sub-How) required to determine the tools needed for maintaining the condition of any of the requirements. For example, the attributes/sub-How that are needed for selecting a cost-effective and comprehensive maintenance policy can be summarised by:

1. the identification and quantification of production cost and machine failure rate and its consequences,
2. the identification of the significant elements in the production process/machines that should be maintained for the maintenance of the condition of the whole machine and process,
3. assessment of economic losses per one-hour production stop,
4. the available knowledge of and experience in maintenance,
5. criteria for selecting the most cost-effective maintenance strategy/policy, see for example Al-Najjar (1997, 2006 and 2007) and references cited there,
6. the quantification of the impact of failures on the working environment.

Furthermore, a cost-effective and continuous improvement policy can be considered to consist of several sub-How, such as failures and their consequences (e.g. losses in company profitability and market share), training programs for enhancing the competence of maintenance and operating staff, failure impact on the working environment and deficiencies in the maintenance policy. We need to keep in mind that the traditional never-ending improvement policy would not assure a cost-effective continuous improvement of the product quality and process profitability and competitiveness without realising the cost-effectiveness of every effort that has been spent on improving the process, Al-Najjar (2006 and 2007A).

To keep to the paper context and scope, and for simplicity, we considered only the Hows that are necessary for maintaining the condition of the requirements needed for
achieving, maintaining and improving company strategic goals without taking their sub-Hows into consideration. Developing and applying the model on this level of the tools allow us to better understand the model’s role in integrating maintenance with the other working areas of the plants, and to easily generalise it to the other requirements and sub-Hows later.

<table>
<thead>
<tr>
<th>Requirements for achieving, maintaining and improving the outputs (Whats)</th>
<th>The tools that are necessary to preserve the condition of the requirements (Hows)</th>
<th>Cost-effective and comprehensive maintenance policy</th>
<th>Measuring and analysis system and policy, such as CM system</th>
<th>Standard and instructions for doing maintenance actions properly and continuous improvement policy</th>
<th>Accumulated effect, i.e. the importance or share ofWhats</th>
<th>Priority list of the actions required for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production machine is at a predetermined condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine tool is at a predetermined condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appropriate working environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production rate according to the specification, e.g. m/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The condition of the product quality system is at a predetermined level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The competence of the operating and maintenance staff is at a predetermined quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The condition of the production logistics system is at a predetermined level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current situation (The share or importance of each How in developing the current situation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3b. Phase II. Tools to maintain the condition of the requirements mentioned in Fig. 3a above.

In order to maintain the condition of significant modules and components constituting a production machine, tool and process, it is necessary to apply a relevant maintenance policy that fulfils the expectations. In order to achieve the predetermined results, this maintenance policy should be the most cost-effective and comprehensive when there are several technically applicable policies. It might, consequently, be any of these: breakdown maintenance, preventive maintenance (PM), condition-based maintenance (CBM), reliability-centred maintenance (RCM), TPM or TQM/

In general, applying any maintenance technique except a breakdown strategy demands a suitable measuring and analysis system for providing maintenance staff with relevant information to achieve high maintenance efficiency. Maintenance policies demand measuring and analysis systems of different architecture and contents. For example, when applying age-based maintenance, the age of the
component/equipment (sometimes including the operating conditions) is the most important. But when using CBM, measurements and analysis from condition monitoring (CM) parameters are demanded, which in turn demands different database architecture to cover a wider data surface and make it easily accessible. The database required for TQMMain includes a wider range of data, i.e. data from CM systems, operating condition and from organisational and accountancy systems.

A clear and obvious measuring and analysis policy can be considered as a separate tool or as a tool included in the comprehensive maintenance policy, which is responsible for maintaining the quality of all the elements involved in the production process, such as the working environment, quality system, production logistics system, accountancy system, information system, maintenance system, etc. and not just the machines and tools.

The maintenance standard and instructions for applying high quality maintenance are very important in order to avoid faulty and irrelevant actions, which in turn reduce the losses and increase process profitability. The tools for maintaining the condition of the requirements, such as maintenance policy, cost-effective continuous improvement policy, measuring and analysis system and a standard for doing maintenance properly, are specified in Fig. 3b as the new Hows.

III. Phase Three: In this phase the Hows represent the activities that are necessary for the effective utilisation of the tools used for maintaining the condition of the requirements expressed in Phase Two. In general, it does not matter how reliable the tools are that have been selected for maintaining the quality of the input elements in a production process, such as machines, personnel competence, and the working environment. Due to deterioration and aging, these tools should be continuously maintained and improved to be accommodated to the changes in the production process and operating conditions.

Therefore, a reliable training programme for enhancing the competence of the operating and maintenance staff, considering real production process demands, new experience, edge knowledge and instrumentation, is very important to prevent the recurrence of problems and eliminate their root causes. This reduces the efforts required for maintaining the quality of all the input elements in the production process. Further, it will enhance the precision of the repeatability of the procedures of applying maintenance actions, which in turn reduces the probability of bad quality maintenance actions, such as the adjustment, replacements and repair of the deteriorated components, and consequently increases the probability of maintaining the processes, the machine and the cutting tool at an acceptable level.

From everyday experience training and re-training the operator, maintenance staff and other personnel whose expertise is related and significant to the production station can be done effectively if there is a special programme controlling this. However, we should keep in mind that selecting and applying the best cutting tools, methods, machines, etc. will not guarantee keeping them best in time without a clear and well stated policy for cost-effective and continuous improvement, see also Fig. 3c.
Fig. 3c. Phase III. Activities necessary for effective utilisation of the tools applied in phase II.

Techniques for monitoring the condition of the production process, such as that required for monitoring the production rate, are significant for achieving the productivity and consequently the profitability level predetermined by the company. Applying technical and economic measures for monitoring the performance of the whole process provides a reliable opportunity for mapping, analysing and judging the effectiveness and productivity of the production process, Al-Najjar (2007A).

The mapping of production and maintenance processes, including the following-up and analysis of the situation to detect deviations at an early stage and perform improvements cost-effectively can normally not be done effectively without a reliable data- and knowledge base providing a wide coverage of relevant information, knowledge and experience concerning these processes and their constituents.

**IV. Phase Four:** In this phase, the Hows from Phase Three become the Whats of Phase Four, Fig. 4d. The new Hows are the factors required to support the integration of maintenance with plant business, which can in many cases be considered crucial for a company in order to achieve their strategic goals. For example, the commitment of a chief manager confirmed by a decision and a special budget from the Company Board describing and supporting, respectively, the significance of the maintenance role in the company’s business and promoting its integration with the company’s other activities to achieve its strategic goals is very necessary for realising and enhancing the maintenance role on the operative level.
The activities that are necessary for effective utilization of the tools in phase two (Whats) | The factors required to support integrating maintenance with plant business (Hows) | Strategic plan for integrating maintenance with plant business | Risk capital for integrating maintenance with plant business | Knowledge and experience in the production machines and process | Effective managerial and organisational tools, such as clear descriptions of authorities and responsibilities | Criteria for selecting tools, methods and policies, such as the most informative CM parameter and system, and the most cost-effective maintenance policy | Accumulated effect, i.e. the importance or share of Whats | Priority list of the actions required for improvement
--- | --- | --- | --- | --- | --- | --- | --- | ---
Training program to enhance the operator and maintenance staff competence | | | | | | | | |
Technique for monitoring and adjusting production rate and working environment | | | | | | | | |
Measures for monitoring process performance and cost-effectiveness | | | | | | | | |
Suitable data- and knowledgebase | | | | | | | | |
**Current situation** (The share or importance of each How in developing the current situation)

Fig.3d. Phase IV. The factors supporting the integration of maintenance with the plant business

The budget considered for integrating the maintenance strategy with the strategies of the relevant working areas, such as production, quality, management, etc., may be considered as a risk capital and not a direct maintenance cost, because it can be regarded as an investment to improve the production process output. Therefore, the new output should always justify the investment, which is generally possible, see for example Al-Najjar (1997, 2007A) and Al-Najjar and Alsyouf (2004).

Organising the production process in a transparent way makes the authorities and responsibilities clear and obvious to every one so as to avoid overlapping and gaps between different authorities and responsibilities in the related working areas. Thus, a comprehensive analysis of the sub-organisations belonging to the production process/station would lead to the identification of one of the major root causes for production losses. Gaps, which are the phenomenon most emphasised in this paper, lead to a lack of action when that is required.

In all the activities that may be performed at a company there are almost always several options to choose from. In order to select properly, the company needs to apply relevant criteria for selecting the methods, policies and tools suitable for its production process. The word ‘suitable’ can be defined with regard to different perspectives for different circumstances and companies. It may be considered with respect to the safety/environment, as is the case in the airplane industry/nuclear power stations, and to organisational or financial aspects, as is the case in paper mills and engineering manufacturing companies. In this paper we consider the latter aspect, i.e. selecting the most cost-effective method, policy and tool.
When selecting a cost-effective maintenance policy for ensuring the expected outputs of a production station and plant, it is necessary that it is preceded by a training programme for the personnel describing the policy, its implementation, advantages and shortages. Developing and improving the tools expressed in Phase Two should be done with respect to both technical feasibility and cost-effectiveness; otherwise it might be easy to achieve high technological solutions albeit at very high and unacceptable costs. Therefore, relevant technical and financial criteria for selecting the most cost-effective maintenance policy, measuring and analysis system and organisational and managerial tools are very important.

Technical knowledge of and experience in the behaviour, failure rate and consequences of the essential elements in the production process under consideration are necessary for performing a successful selection of the relevant measuring and analysis system, maintenance policy and training programme.

6 Examples Describe the Potentials of MFD

Technical and economic data are always required for analysing production and maintenance processes and identifying maintenance role, Al-Najjar (2007A). These data are also necessary to identify the behaviour of the strategic goals and follow up their developments and effects on company profitability and competitiveness, see Pehrsson and Al-Najjar (2005). In this paper, the losses/profits generated in a company are classified with respect to the company’s strategic goals, i.e. quality, delivery on time, etc., see Phase I and Fig. 3a. Thus, the importance of each of the Hows in Phase I is defined by its role in influencing the output of the company’s strategic goals. Therefore, the share of each of the Hows in the losses (or profits) generated can be used to label its importance. If the total losses of a company are considered as one unit, then the percentage of that unit generated by each of the Hows (requirements) represents its importance.

For instance, consider Phase I of the model and assume that the contributions of the A and B requirements are 65% and 5% of the total production losses, respectively, then requirement A is more important than requirement B. By analogy, the importance of the tools, activities and factors introduced in Phases II, III and IV can be determined by carrying on the analysis of these phases in the cause-result form as it is expressed above.

The application of the model demands the identification of the Whats and Hows in the model’s four phases and the determination of (quantifying) their importance. This step is necessary for including all relevant Whats and Hows and devoting the attention required with respect to their importance. Then, a deeper analysis and improvements in one or more of the strategic goals (Whats) can be planned effectively according to the prioritising list that can be developed in each phase. The output of these improvements can roughly be estimated in advance to be used for controlling whether it justifies the investments suggested or not. After performing the improvements a more accurate control of cost-effectiveness can be made.

6.1 Example 1

In this section we will describe the application of the model, putting special focus on the role of maintenance in company business, using typical data based on the author’s experience, see Al-Najjar et al (2001), Al-Najjar and Alsyouf (2003, 2004), Al-Najjar et al. (2004), Al-Najjar (2006) and Al-Najjar (2007A). Classify the total financial losses assessed in units in groups with respect to the company’s strategic goals described in Phase I of MFD, see Table 1.
<table>
<thead>
<tr>
<th>Loss Category according to the (Strategic Goals)</th>
<th>Losses Units</th>
<th>Share of losses</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bad quality (Product quality)</td>
<td>90</td>
<td>9%</td>
<td>Losses due to internal causes, e.g. scrap, reworking, and external causes, e.g. compensations for customers, warranties, etc.</td>
</tr>
<tr>
<td>2 Less delivery accuracy (Delivery accuracy)</td>
<td>130</td>
<td>13%</td>
<td>Penalty expenses due to delivery delay</td>
</tr>
<tr>
<td>3 Less profit margin, which influences product price (Competitive price)</td>
<td>650</td>
<td>65%</td>
<td>Unnecessary production costs due to failures, short stoppages and disturbances</td>
</tr>
<tr>
<td>4 Negative impact of production process on the environment (Environmental-friendly production)</td>
<td>60</td>
<td>6%</td>
<td>Expenses for special treating of the product when its life length is terminated, e.g. batteries. Special expenses for adapting the production to the national/international legislation on environment</td>
</tr>
<tr>
<td>5 Worse machine condition (Machine condition)</td>
<td>70</td>
<td>7%</td>
<td>The losses due to losing some of the machines’ value, i.e. machine life length, due to rapid deterioration compared with the case when the machines are in better condition</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1000</strong></td>
<td><strong>100%</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. The loss categories are classified according to the company strategic goals.

When applying MFD, the causes behind the losses mentioned in Table 1 must be identified in order to facilitate the elimination of the root causes and the prevention of their recurrence. The identification of the causes and their shares in generating losses can be made by analysing the technical and financial data of the production and maintenance processes with respect to the Hows stated in Fig. 3a (Phase I). In Table 1 we consider the shares of just five groups (Whats) of losses and their causes. The number ofWhats in Table 1 can be accommodated with respect to the enterprise strategic goals.

We classify the causes (Hows) that lie behind changes in the company’s (or production station’s) strategic goals in four groups in accordance with the model’s four phases. Since the production processes in different industries are unlikely to be similar, we tried to consider the causes (Hows) that are common to many production processes. However, the number and types of the Hows in each phase of the model in different applications are not necessarily similar. Therefore, adding or eliminating causes (Hows) is acceptable for fitting the model to a particular application.

Phase I is essential for identifying the problem area that should be prioritised for further analysis and improvement processes. The losses assumed at each strategic goal have been distributed among the Hows according to their roles in generating losses, as shown in Fig. 4a. To highlight the role of maintenance in a company business, we allocate the highest share of the losses to the Whats that may in the first hand be influenced by maintenance, such as competitive price, which is among others based on production cost and delivery delay. This is why the maintenance of the condition of the machine stands for 49% of the total losses in the strategic goals. The machine condition usually influences both the production rate and the working environment, which acquire the second biggest shares of 16% and 10%, respectively. The target value can be determined based on the total losses and the available technologies for detecting and eliminating the root causes behind the losses, which to avoid model complexity is not considered in this example.
<table>
<thead>
<tr>
<th>Losses category (Outputs to be achieved, maintained and improved)</th>
<th>Target value (Max. losses)</th>
<th>Requirements necessary for achieving, maintaining and improving the outputs (Hows)</th>
<th>Production machine condition</th>
<th>Machine tool condition</th>
<th>Working environment</th>
<th>Production rate, e.g. m/min</th>
<th>Condition of the quality system</th>
<th>Competence of the operating and maintenance staff</th>
<th>Condition of the production logistics system</th>
<th>Importance of Whats (Total)</th>
<th>Priority list of the actions required for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad quality</td>
<td>3%</td>
<td>1%</td>
<td>0</td>
<td>0</td>
<td>3%</td>
<td>2%</td>
<td>0</td>
<td>9%</td>
<td></td>
<td></td>
<td>Third priority (plans for deep analysis and actions may also be required)</td>
</tr>
<tr>
<td>Delivery delay</td>
<td>5%</td>
<td>1%</td>
<td>1%</td>
<td>3%</td>
<td>0</td>
<td>1%</td>
<td>2%</td>
<td>13%</td>
<td></td>
<td></td>
<td>Second priority (plans for deep analysis and actions may also be required)</td>
</tr>
<tr>
<td>Lost profit margin (due to failures)</td>
<td>30%</td>
<td>4%</td>
<td>7%</td>
<td>13%</td>
<td>0</td>
<td>6%</td>
<td>5%</td>
<td>65%</td>
<td></td>
<td></td>
<td>First priority (plans for deep analysis and actions are required)</td>
</tr>
<tr>
<td>Deviation from the Environment-friendly production</td>
<td>4%</td>
<td>0</td>
<td>2%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bad machine condition</td>
<td>7%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Importance of Hows (Total)</td>
<td>49%</td>
<td>6%</td>
<td>10%</td>
<td>16%</td>
<td>3%</td>
<td>9%</td>
<td>7%</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4a. The shares of the How’s in generating the losses are classified according to the company’s losses categories (strategic goals)

In the model’s four phases, the sum of the percentage shares of the losses according to the Hows represents the importance of that loss category (What). When the importance of all the Whats (and that of Hows in the final matrix) is determined, the enhancement work can be planned according to a priority list, i.e. the list prioritising the Whats (and the Hows of the final matrix) according to their importance as assessed in the model.

In Fig. 4b, the tools that are necessary to preserve the condition of the requirements play different roles, where the lack of or inefficient work for selecting and implementing the most cost-effective maintenance policy acquires 43% and is followed by the lack of or inefficient cost-effective and continuous improvement policy, which stands for 23% of the problems in maintaining the condition of the machine at a predetermined level. The remaining Hows together account for 34% of the total losses. In the same way we continue breaking down the cause-result links to come across the basic causes behind deviations experienced in Fig. 4b, so that the solutions required can be identified, such as a lack of or an inefficient training programme for enhancing the operating and maintenance staff competence, which stands for 49% of the total losses, see Fig. 4c. In the second place comes the lack of or an inefficient data- and knowledge base, which stands for 32% of the total losses. The lack of or inefficient measures for monitoring the process performance and its cost-effectiveness generates 12% of the total losses. These three factors are more important...
than technique for monitoring and adjusting the production rate and working environment, amounting to 7% of the total causes.

Finally, we can see that the priority list established in Fig.4d is based on the shares allocated for the factors required to support the integration of maintenance with plant activities. In Fig.4d we allocate the highest shares to the first two Hows, i.e. the lack of or an inefficient strategic plan for integrating maintenance with plant business and the lack of or an insufficient risk capital for integrating maintenance with plant business, which stand for 32% and 28%, respectively. Thus, to achieve a cost-effective improvement it would be more convenient to consider the Hows that acquire high proportion of the losses and can influence several Whats simultaneously, such as the case in the first two Hows, Fig.4d, which acquire 32% and 28% respectively.

<table>
<thead>
<tr>
<th>Losses category (Requirements for achieving, maintaining and improving the outputs (Whats))</th>
<th>Target value (Max losses)</th>
<th>The tools that are necessary to preserve the condition of the requirements (Hows)</th>
<th>Importance of Hows (Total)</th>
<th>Priority list of the actions required for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production machine condition</td>
<td>21.0%</td>
<td>8.0%</td>
<td>13.0%</td>
<td>7.0%</td>
</tr>
<tr>
<td>Machine tool condition</td>
<td>2.0%</td>
<td>2.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Working environment</td>
<td>3.0%</td>
<td>2.0%</td>
<td>3.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Production rate, e.g. m/min</td>
<td>7.0%</td>
<td>4.0%</td>
<td>4.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Condition of the product quality system</td>
<td>1.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Competence of the operating and maintenance staff</td>
<td>5.5%</td>
<td>1.5%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Condition of the production logistics system</td>
<td>3.0%</td>
<td>2.0%</td>
<td>0.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Importance of Hows (Total)</td>
<td>43.0%</td>
<td>20.0%</td>
<td>23.0%</td>
<td>14.0%</td>
</tr>
</tbody>
</table>

Fig.4b. The shares of the tools in causing problems for the requirements.

We believe that without reliable commitment supported by a decision from the Leading Board of the company and a special budget for promoting the integration of maintenance with the company’s business, it may not be easy or even, in many cases, possible to integrate maintenance in the way offered by MFD, Al-Najjar et al. (2001). Still, the maintenance integration may not be accomplished without reliable knowledge of and experience in the machine function and its problems. This is why it
acquires 17%. In the third place come the effective managerial and organisational tools, which acquire 18%. The latter category constitutes one of the most common problems influencing maintenance performance, see for example Al-Najjar (1998). More clarification concerning the role of the managerial and organisational tools in maintenance performance will be given in Example 2 below.

<table>
<thead>
<tr>
<th>Losses category (The tools that are necessary to preserve the condition of the requirements (Whats))</th>
<th>Target value (Max losses)</th>
<th>The activities that are necessary for effective utilisation of the tools in phase two (Hows)</th>
<th>Priority list of the actions required for improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of or inefficient maintenance policy</td>
<td>26,0%</td>
<td>3,0%</td>
<td>8,0%</td>
</tr>
<tr>
<td>Lack of or inefficient measuring and analysis system</td>
<td>7,0%</td>
<td>3,0%</td>
<td>2,0%</td>
</tr>
<tr>
<td>Lack of or inefficient cost-effective and continuous improvement policy</td>
<td>11,0%</td>
<td>1,0%</td>
<td>2,0%</td>
</tr>
<tr>
<td>Lack of or inefficient standard and instruction for doing maintenance properly</td>
<td>5,0%</td>
<td>0,0%</td>
<td>0,0%</td>
</tr>
<tr>
<td>Importance of Hows (Total)</td>
<td>49,0%</td>
<td>7,0%</td>
<td>12,0%</td>
</tr>
</tbody>
</table>

Fig. 4c. The shares of the activities in causing problems for the tools.
6.2 Personnel Responsibilities and Authorities; Example 2

In this section the role of the analysis of managerial and organisational problems, such as personnel responsibilities and authorities in maintenance performance, are discussed using an example from sawmills. In this analysis we consider only the departments of production, quality and maintenance of a typical sawmill, see Högsvik and Welander (2001) and Al-Najjar (2003).

Denote production, quality and maintenance activities by p, q and m, respectively. Now, if we label every station in Fig.5 by the activities which are performed there, we may experience a repetition of all the three labels on all these stations. This is because at each station we have a part of the production process, its requirements and a product of a particular quality that should be maintained. However, the working areas’ shares in maintaining the quality of the machine, product and other requirements are not necessarily equal.

In this paper the technical analysis of the working areas in question is considered important to determine the interactions between these working areas for accomplishing an effective integration between them and achieve a cost-effective never-ending improvement process. In the process industry, especially in paper- and sawmills, material flow is handled automatically. Therefore, the means for transporting the material are considered parts of the paper/saw machine itself, except...
in the parts where the material is moved manually. In Fig. 5 all the stations in a typical sawmill are listed.

![Production line in a sawmill](image)

**Fig. 5. Production line in a sawmill**

The production line in a process industry, such as paper, pulp and sawmills, is a collection of serially connected production stations. The working areas, such as production, maintenance and quality, interact at almost each production station, Al-Najjar (2003). The common activities of these production stations and the interactions between them can be highlighted by partitioning the production process into production stations and analyse each station technically. This analysis can be necessary for:

1. assigning responsibilities and authorities to the personnel belonging to the working areas involved directly in the production station/process,
2. identifying if there are gaps or overlapping:
   - ♦ resulting in some of the necessary tasks not being done, because they fall outside the authorities’ border so that no one is directly responsible,
   - ♦ and consequently generating problems and increasing the economic losses,
3. highlighting the actions that should be performed at each of these stations,
4. identifying the relevant data to be gathered without duplication,
5. analysing and utilising the gathered data effectively,
6. easily determining the input and output at each station for assessing its effectiveness and productivity,
7. identifying the input and output at each production station at 6 above and thus facilitating the identification and elimination of the basic causes behind technical and economic losses and,

The quality of every input element required in each production station should be maintained in order to secure the technical specifications demanded in the output of the station, i.e. garbage in garbage out. Notice that in this production process, quality control is conducted in two stations, one for the input material (the logs control station) and the second for final product quality, i.e. the adjustment station.

In general, for every production station there are always some requirements that should be fulfilled in order to secure the performance of the production process and achieve its objectives. For example, at saw machine 1, the machine quality can be
described, for instance, by its rate of production, which in turn is defined by its condition and technical specifications. The latter cannot be maintained without applying an efficient maintenance policy. This is why it is necessary for the saw blade to be maintained at the level required to achieve the planned production.

<table>
<thead>
<tr>
<th>Quality activities</th>
<th>Responsibility</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production stations</td>
<td>To sort out bad quality boards</td>
<td>None</td>
</tr>
<tr>
<td>Drying station</td>
<td>To achieve board correctly dried</td>
<td>None</td>
</tr>
<tr>
<td>Adjusting station</td>
<td>To control board quality and dimension</td>
<td>To spread information about bad quality boards and make changes in the saw line</td>
</tr>
<tr>
<td>Packing station</td>
<td>To pack the boards and label deliveries to the right customers</td>
<td>None</td>
</tr>
<tr>
<td>Cutting tool man work</td>
<td>To make sure that the tool is maintained, assembled &amp; sharps</td>
<td>To purchase new cutting tools</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance activities</th>
<th>Responsibility</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor</td>
<td>To avoid unplanned stoppages</td>
<td>Send work order to the maintenance team</td>
</tr>
<tr>
<td>Maintenance personnel</td>
<td>- To maintain machines</td>
<td>Purchase spare parts needed for maintenance</td>
</tr>
<tr>
<td></td>
<td>- To manage spare parts storage</td>
<td></td>
</tr>
<tr>
<td>Operators</td>
<td>To report faults and problems</td>
<td>None</td>
</tr>
<tr>
<td>Cutting tool man</td>
<td>To make sure that the tool is maintained, assembled and sharps</td>
<td>To purchase cutting tools</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production activities</th>
<th>Responsibility</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor</td>
<td>- To reduce sawing process disturbances</td>
<td>He/she can stop the process if it is needed</td>
</tr>
<tr>
<td></td>
<td>- To reduce stoppages</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- To use the right saw program for every dimension</td>
<td></td>
</tr>
<tr>
<td>Cutting tool man</td>
<td>- To use the right tool for every dimension</td>
<td>To purchase tools</td>
</tr>
<tr>
<td></td>
<td>- To make sure that the tool is mounted correctly</td>
<td></td>
</tr>
<tr>
<td>Litter laying station</td>
<td>To put litter between the boards correctly for making the drying process effective</td>
<td>None</td>
</tr>
<tr>
<td>Drying station</td>
<td>To dry the boards to the right dampness</td>
<td>To dry the boards once more if it wasn't done right the first time</td>
</tr>
<tr>
<td>Adjustment department</td>
<td>To assort right dimensions and quality boards</td>
<td>To cut or reject bad quality boards</td>
</tr>
<tr>
<td>Packing station</td>
<td>To pack right boards dimensions and quality on the same pallet</td>
<td>Can reject bad quality boards</td>
</tr>
</tbody>
</table>

Table 2. Responsibility and authority analysis

In general, operators and maintenance staff should be trained to acquire the predetermined competence required for performing their tasks effectively. Furthermore, maintaining the quality of the working environment is important for fulfilling the regulations and technical specifications for this particular job. The condition of the quality and production logistic systems should also fulfill the production requirements necessary for achieving the objectives of the production station, line and plant. One of the reasons behind losses in a production process is the occurrence of gaps between related working areas, such as production, maintenance and quality. Gaps generate losses because the necessary tasks have not been performed when they are needed, see Section 3.2. Thus, an organisational analysis covering the responsibilities and authorities of the personnel in maintenance, production and quality is quite helpful for identifying and eliminating gaps, overlapping and, consequently, the problems of making the sub-organisations synchronise smoothly with each other. An example of such organisational analysis is given in Table 2.
From Table 2 it becomes obvious that the personnel activities, e.g. at drying, adjusting or packing the cutting tool can be considered as belonging to the quality, production and maintenance departments simultaneously, but involving different authorities and responsibilities. This overlapping makes the need for designing the interactions between the activities that belong to different working areas and are accomplished by one or several persons very essential to achieve an effective integration of these activities.

Breakdown maintenance recommends not doing anything until the failure has occurred and then restoring it to as-good-as before, while preventive maintenance (PM) advocates performing regular maintenance actions according to an instruction list, regardless of the condition of the machine. When the maintenance implemented is either breakdown or PM, which is the case in general in sawmills, there is no way to avoid many of the gaps leading to failures and disturbances, and consequently resulting in economic losses. This is because the application of any of these maintenance strategies fails to provide descriptions or instructions helping the supervisor, maintenance personnel and cutting-tool man to detect damage initiation, damage development and imminent failures at an early stage, Al-Najjar (1997, 2007A).

When using preventive maintenance, it is impossible to replace all the components just before failures through applying statistical or mathematical models for estimating the time to replacement, especially when the spread in the time to failure is not very small. This is true because there are no other indicators used in PM except time, serving as a black box independent of the real variation in operating and environmental conditions, which appreciably influences the life length of the components/equipment.

Even if the statistical model used for estimating the time for action is well optimised, there is still a big risk that the machine fails. Unexpected failures, according to the application of PM models, can be avoided effectively by using CBM and TQM maintenance strategies. Securing high quality maintenance performance can be approached by achieving high maintenance organisation reliability, i.e. to do what is required on time, in addition to a well arranged inventory of spare parts and equipment to avoid waiting times as much as possible.

7. Model Discussion and Analysis
By applying MFD, it is possible to determine the requirements for achieving and maintaining the strategic goals stated by a company (or a production station). Judging by industrial work culture and experience, companies do not involve themselves in the maintenance of new machinery and its requirements as long as the manufacturer of the machine is responsible for providing maintenance services according to the agreement during the warranty period. In Phase III of QFD, i.e. the phase of process design, maintenance requirements should also be designed at an early stage for providing the factors required for integrating maintenance with the plant’s other activities at the operative level from the first moment when the production is started and not delayed several years until the warranty period, i.e. the supplier’s responsibility for maintaining the machine, is ended. In Fig. 6, MFD is integrated with QFD to fill that gap.
The work that should be done by MFD has to be planned with the start of Phase III and onwards. This is to facilitate the process of maintaining the quality of the elements, such as producing machines involved in the production process at an early stage, and to convert the losses in the company’s strategic goals to actions on the operative level. However, this does not mean that MFD cannot be used except in that order. Theoretically, it would be possible to apply MFD on any established production process even apart from QFD.

The major objectives of applying MFD are to identify, quantify and eliminate the losses in the company’s profitability and competitiveness and specify the maintenance role and impact on the company’s strategic goals (or production station objectives), i.e. it is to convert the problems of achieving the strategic goals of a company or production station to operative actions. In addition, it is to integrate maintenance with the company’s business for eliminating economic losses. This is why the strategic goals should be clearly determined and the four phases of the model be applied in the same order as described in this paper. MFD is not developed to replace QFD; it is rather a necessary tool for the enhancement of QFD application when it concerns the achievement of the company’s strategic goal by ensuring a reliable condition of the production assets.

Converting the problems of achieving company strategic goals to actions on the operative level can be done when the links (mechanisms) of transferring the impact of the Hows to theWhats in all the model phases are identified, described and quantified. These mechanisms are classified according to their impact, i.e. model phases, into the following groups:
1. Links for transferring the impacts of the requirements needed to achieve, maintain and improve company strategic goals to the output levels and quality of a production process

2. A group of links for transferring the effects of the tools necessary for maintaining the quality of the requirements mentioned in 1 above to the performance of the requirements

3. Links for transferring the effects of the activities necessary for the effective utilisation of the tools mentioned in 2 above in maintaining the requirements

4. Finally, the links for transferring the impact of the factors supporting the integration of maintenance with the company’s business to the integration process elements.

For a more detailed analysis, each column, i.e., the Hows, in the model’s four phases can be subdivided into its constituents (sub-How) to expand the matrices of the phases. For example, improvement in maintenance policy normally concerns personnel competence, working environment, diagnosis, prognosis and prediction techniques, software programs for analysis and decision-making procedures and criteria, etc.

Conclusions
Applying maintenance function deployment (MFD) gives an enormous opportunity to make significant improvements in the quality of the working areas considered in the integration. It can assist the achievement of an easy and effective identification, quantification and elimination of company losses in profitability and competitiveness. Furthermore, the implementation of MFD implies the application of the PDCA cycle and through this the integration of the working areas in question can be improved continuously and cost-effectively.

The examples conducted in this paper reveal and describe the way of application and the potential of the model in identifying, quantifying and possibly eliminating the root causes behind technical and economic deviations. MFD can also be utilised to justify the investments required for enhancing company profitability when planning for eliminating the root causes. The investments suggested for the actions in the prioritised list can be compared with the anticipated savings that can be achieved by better performance when the root causes behind the deviations have been eliminated. In other words, MFD functions can be utilised as a decision support tool for judging the cost-effectiveness of the investments in advance, which can be controlled accurately after the improvements have been done.

It is obvious that the mapping of the working areas, personnel activities, organisation, responsibilities and authorities within the company is necessary to: identify the gaps and overlapping between working areas and the responsibilities and authorities before making changes for enhancing the profitability and competitiveness of the production process. The analysis and improvement of production and maintenance processes may be carried out effectively if the causes behind deviations can be classified with respect to the strategic goals and the requirements for maintaining and improving these goals.
References


