Evaluation and improvement of manufacturing performance measurement systems – the role of OEE

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Abstract *The paper identifies six requirements: four critical dimensions (what to measure) and two characteristics (how to measure) of an overall manufacturing performance measurement system. The overall equipment effectiveness (OEE) measure in such a system is assessed against these ideal requirements. The current measurement systems, and the potential of OEE, of three manufacturing organisations are evaluated with the dimensions and characteristics as comparative data. A common weakness of the systems was that they did not measure flow orientation or external effectiveness to any great extent. Another weakness was a high degree of complexity and lack of continuous improvement. Field experiments in the studied organisations showed that use of OEE in combination with an open and decentralised organisation design could improve several of those weaknesses.*

Introduction

It is not obvious how firms should measure their manufacturing performances. Various approaches, most of them with a large number of measures on different hierarchical levels, exist. Many of the measures used are considered obsolete and inconsistent for various reasons. The usefulness of most cost accounting systems, individual measures as well as more comprehensive activity-based costing systems, are frequently questioned since they do not cover manufacturing performances relative to the competitive capabilities (e.g. Dixon *et al.*, 1990, White, 1996). Another serious problem with most performance measurement systems used in firms is that they often include too many different measures, which makes it difficult to understand the “big picture” (Keegan *et al.*, 1989). Integration between measures is often problematic, and many papers have emphasised that firms have no effective system that covers all necessary performance dimensions (e.g. Caplice and Sheffi, 1995; Ghalayini and Noble, 1996; Maskell, 1991; Schmenner and Vollmann, 1994; Srikanth and Robertson, 1995). Schmenner and Vollmann (1994) showed in an empirical study that most studied companies needed seriously to consider changing their performance measurements. They argued that most firms were both using wrong measures and failing to use the right measures in correct ways. This is serious and it therefore seems important to identify the critical dimensions in a performance measurement system (what to measure) and the optimum characteristics of the measures (how to measure). Measurement systems could then be evaluated and improved with the dimensions and characteristics as

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comparative datums. Evaluation of the existing system against the identified set of dimensions and characteristics is the first step toward a more comprehensive and effective approach for measuring overall manufacturing performance (OMP). The second step is to suggest improvements of the existing performance measurement systems.

It has been identified that a large proportion of the total costs of production can be attributed to production losses and other indirect and "hidden" costs (Ericsson, 1997). The overall equipment effectiveness (OEE) measure attempts to reveal these hidden costs (Nakajima, 1988) and when the measure is applied by autonomous small groups on the shop-floor together with quality control tools it is an important complement to the traditional top-down oriented performance measurement systems. However, OEE is not a complete OMP measurement system.

It is important to evaluate individual measures as well as complete measurement systems. This paper focuses on the OMP measurement system level and not on individual measures. The OEE measure is studied, but it is evaluated from the overall systems level. The first objective is to develop a framework for evaluating overall manufacturing performance measurement systems. The second objective is to describe the OEE measure and explain how it fits into the overall performance measurement system. Three case studies are presented, which illustrate how OEE is being used in industry. These are used as a basis for showing how OEE is deficient as an OMP system but a useful part of an overall system of measurement.

Dimensions and characteristics of OMP measurement

The performance measurement system may be used for top management control or continuous shop-floor improvement. It may be compared against internal targets or external benchmarks. No matter what the objective of the system or use of the performance information, a complete OMP measurement system needs to be comprehensive and cover the most critical performance dimensions of the organisation.

We first review previous efforts to define the requirements of a good OMP system. Ghalayini and Noble (1996) asserted that to overcome the previous limitations of performance measurement systems new systems should be dynamic, stress the importance of time as a strategic performance measure and link the areas of performance and performance measurement to the factory shop-floor. Maskell (1991) stated that a good measurement system should be related to manufacturing strategy, include non-financial measures, vary between location, change over time, be simple and easy, give fast feedback, and aim to teach rather than to monitor. Caplice and Sheffi (1995) argued that a "good system" should be comprehensive, causally oriented, vertically integrated, horizontally integrated, internally comparable and useful. Lynch and Cross (1991) noted that good systems include the need to: link operations to strategic goals, integrate financial and nonfinancial information, measure what is important to customers, motivate operations to exceed customer expectations, identify and eliminate waste, shift the focus of organisations from rigid vertical bureaucracies to more responsive, horizontal business systems, accelerate organizational learning and build a consensus for change when customer expectations shift or strategies call for the organisation to behave differently, and translate "flexibility" into specific measurement.

When designing performance measurement systems it is necessary to decide first, what to measure, and second, how to measure. The dimensions "strategy", "flow orientation", "internal efficiency" and "external effectiveness" of the present framework mostly describe the "what to" question. It is not enough to identify what dimensions to measure; the measures also need to be designed so that the performance information can be successfully used. The way may differ between systems with different objectives. However, the characteristics "improvement drivers" and "simple and dynamic" describe the "how to" question. We now consider each of these dimensions and characteristics separately.

Strategy

The competitive priorities of the business or product have to be emphasised in corporate, business and manufacturing strategies, as well as in measures on various hierarchical levels. This dimension deals with two important aspects of performance measurement systems. First, the system should measure the long-term success factors (qualifying and order-winning criteria) of organisations, not just short-term departmental specific performances. Maskell (1991), for example, identified six elements of a manufacturing strategy that should be measured: quality, cost, delivery, lead time, flexibility and employee relationships. Allen (1993) further developed this list to 19 critical success factors. Second, it should emphasise that the long-term success factors have to be derived from management level to direct production personnel, and measured on all hierarchical levels of the organisation. The decisions made at different levels of the organisation vary in nature, but they should all strive towards the same overall strategy. Increased focus on quality, dependability and flexibility, and the fact that strategic priorities might vary between products, and between stages of a product's often short life-cycle, sometimes make it hard to link measures to strategies. Performance measures may even hurt a company's corporate strategy due to mismatch between goals on different levels (Caplice and Sheffi, 1995). This is serious. Lynch and Cross (1991) considered that qualitative and non-financial manufacturing performance measures can help organisations to link operations to strategic goals on all hierarchical levels, since they are easier to derive from the qualifying and order-winning criteria and easier to put into effect, but it is still necessary to link corporate, business and manufacturing strategies. To be a relevant tool for achieving the intended manufacturing strategy the performance information must be directly linked back to the personnel within the organisation.

Flow orientation

Effective manufacturing contributes to efficient flow of materials, with high quality and short throughput times. We should therefore measure horizontal business processes, that cut through the firm, instead of functional processes, i.e. by products rather than shops. It is becoming more important to view manufacturing and business from supply chain perspectives, consisting of vertically integrated processes and firms, and chains of suppliers and customers. This makes performance measurement even more difficult to carry out, and leads again to flow-oriented measures. One way of switching to flow orientation is to measure times and throughput volume (e.g. Azzone *et al*., 1991). A time-based approach does not necessarily lead to a "flow measure", though. First, it has to be vertically integrated and not just "inward looking", and then it has to be comparable to other measures. For example, inventory levels, turnovers, throughput times and service levels are more important from a supply chain perspective than from a functional production perspective. The measures are comparable if they cover the same functions and processes along the ever-more-integrated supply chains. Caplice and Sheffi (1995) argue that a flow-oriented system actively encourages inter-organisational co-operation and innovative approaches to the organisation. They mean that focus switches from orders already placed to trying to modify the order patterns by working with customers and suppliers as partners.

Internal efficiency

The objective of the internal efficiency dimension is to identify performances of a function. Use of financial metrics for internal efficiency can simplify trend identification and comparison of the overall internal efficiency between departments. Trade-off analyses between various performances can easily be carried out if they are all measured in financial terms as "costs" or "profits". However, several measures of internal efficiency, such as lead time, are difficult to operationalise with financial measures. Non-financial and qualitative measures are important complements to traditional financial measures, especially when it comes to day-to-day control of the manufacturing, as they are often more flexible and give fast feedback to the organisation (Maskell, 1991). It is often advantageous to use operational and qualitative measures as improvement drivers in quality circles and project teams, while aggregated financial measures are more important for management, although mixing the two types of measures is necessary to cover all internal efficiency dimensions. However, mixing financial and non-financial measures can be considered complex from an overall management, as well from a shop-floor, perspective. To decrease the complexity of the overall measurement system, it is therefore important to focus on a small carefully-selected set of financial and non-financial measures of internal efficiency.

External effectiveness

This dimension deals with measurement of customer satisfaction and fulfilment of the competitive priorities. Service level and quality measures, on both strategic and operational levels, are often used for measuring external effectiveness in firms, but they are not enough for measuring total customer satisfaction, or to cover competitive priorities. The definitions of quality often deal with product quality and internal efficiency, rather than customer satisfaction based on external data. Customer satisfaction research is neither quick nor easy. A significant commitment of company personnel is necessary, even if an outside research company manages the main part of the interviewing and analysis phase of the customer satisfaction measurement. Dutka (1994) argues that six months elapsed time from developing a request for a customer satisfaction proposal to receiving the first customer satisfaction ratings is not uncommon. To be able to fulfil customer requirements direct production personnel have to be given more authority and more direct contact with external customers. This leads to identification of customer-oriented measures to be carried out on shop-floor level (Maskell, 1991). A practical problem in several firms is that measurement systems are often split between internal efficiency and external effectiveness. This might create a "measurement gap", that sometimes is considered to be a big obstacle. An important objective of the measurement system should be to bridge this gap (Andersson *et al.*, 1989), and establish the relationship between the internal measures (causes) and the external measures (effects).

Improvement drivers

According to Ishikawa (1982), the reason for collecting data should not be to present neat figures, but to create a base for action and development of processes. This is very much linked to what data are collected, how the analysis is carried out and how the performance information is used. The data source may be internal or external, the data type subjective or objective, the focus may be on the process input or outcome, the reference external benchmark or internal target (White, 1996). There are three aspects of future performance improvements. First, the set of measures should cover those aspects that indicate potential future improvements. Worker empowerment, job fulfilment and managerial commitment are not directly linked to process outcome, but are often considered vital conditions for improvement in performance (Deming, 1986). These more or less subjective aspects could therefore be used as indicators for potential future improvements, even if it is difficult to directly link them to the final result. Second, the measure should in itself identify and generate continuous improvements, instead of working as passive control. This is especially true for operational measures focusing on non-value added activities, such as OEE. Third, when measuring long-term rather than short-term performance on a continuous rather than a periodic basis the performance measurement system can work as an important component of a continuous improvement program.

Simple and dynamic

The measure should be simple and easy to understand, calculate and use, and not necessarily have fixed format. This is true for the individual measure, as well as for a system of several measures. Keegan *et al.* (1989) considered that the problem with most OMP systems is that there are too many obsolete and inconsistent performance measures. Schmenner and Vollmann (1994) showed in a survey that most manufacturing companies need seriously to consider changing their performance measurements. Most firms both used wrong measures and failed to use the right measures. Too many or too complex measures might lead to a reactive system, focusing on checking and controlling the past, or end up being ignored or discarded after a relatively short period of time. There probably exists no panacea that works well in all organisations, but the key is to evolve one's own – dynamically and iteratively. Table I provides a summary of OMP dimensions and characteristics

No single measure can possibly cover all these aspects on the management as well as the shop-floor level, but a structured set of measures and a balanced management interpretation is probably more suitable. Sets of integrated performance measurements, such as the SMART system (Lynch and Cross, 1991), balanced scorecard (Kaplan and Norton, 1992) and other synchronised measures (e.g. Ghalayini and Noble, 1996; Maskell, 1991; Srikanth and Robertson, 1995) have been proposed in order to link internally and externally focused measures and to give an overall view of companies' performances. Ghalayini and Noble (1996) emphasise the following limitations of existing integrated performance measurement systems (i.e. SMART and balanced scorecard) they are mainly constructed as monitoring and controlling tools rather than improvement tools; they do not provide any mechanism for specifying which objective should be met in a specific time horizon; they are not dynamic systems; they do not look ahead to predicting, achieving and improving future performances; they do not provide any mechanism to achieve global optimisation especially at the operational level; they do not stress the importance of time as a strategic performance measure; and none of the models provides a specific tool that could be used to model, control, monitor and improve the activities at the factory shopfloor.

Dimensions/ characteristics	Description
Strategy	The measurement system translates the corporate and business strategies to all levels of the organisation
Flow orientation	The measurement system integrates all functions, activities and processes along the supply chain
Internal efficiency	The measurement system makes productivity control and comparison between internal functions possible
External efficiency	The system interacts with customers and measures the level of customer satisfaction
Improvement drivers	The measurement system not only works as passive control, but is instead used for continuous improvement
Simple and dynamic	The measurement system is simple and dynamic, since several dimensions are to be included and since the circumstances for measurement are fast changing

Table I.
Dimensions and characteristics – a summary

The OEE measure

To be able to record key figures and investigate how manufacturing contributes to the overall performance it is of vital importance to measure and understand how to conduct measurements of disturbances in the manufacturing process. Disturbances can, according to Ljungberg (1997), Nord *et al.* (1997) and Tajiri and Gotoh (1992), roughly be divided into the two categories, chronic and sporadic, depending on how often they occur. Chronic disturbances are usually small, hidden and complicated because they are the result of several concurrent causes. Sporadic disturbances are more obvious since they occur quickly and as large deviations from the normal state. They occur irregularly and their dramatic effects are often considered to lead to serious problems, but instead there are chronic disturbances that result in the low utilisation of equipment and large costs because they occur repeatedly (Nord *et al.*, 1997). Chronic disturbances are more difficult to identify since they can be seen as the normal state. Identification of chronic disturbances is only possible through comparison of performance with the theoretical capacity of the equipment.

The six big losses

Chronic and sporadic disturbances in the manufacturing process result in different kinds of waste or losses. These can be defined as activities which absorb resources, but create no value. The objective of OEE is to identify these losses. It is a bottom-up approach where an integrated workforce strives to achieve overall equipment effectiveness by eliminating the six big losses (Nakajima, 1988):

Downtime losses

(1) Breakdown losses categorised as time losses when productivity is reduced, and quantity losses caused by defective products.

(2) Set-up and adjustment losses result from downtime and defective products that occur when production of one item ends and the equipment is adjusted to meet the requirements of another item.

Speed losses

(3) Idling and minor stoppage losses occur when production is interrupted by a temporary malfunction or when a machine is idling.

(4) Reduced speed losses refer to the difference between equipment design speed and actual operating speed.

Quality losses

(5) Quality defects and rework are losses in quality caused by malfunctioning production equipment.

(6) Start-up losses are yield losses that occur during the early stages of production, from machine start-up to stabilisation.

The six big losses are measured in terms of overall equipment effectiveness (OEE), which is a function of availability (A), performance rate (P) and quality rate (Q). The exact definition of OEE differs between applications and authors. Nakajima (1988) was the original author of OEE and De Groote (1995) is one of several later authors (see Table II).

The availability measures the total time that the system is not operating because of breakdown, set-up and adjustment, and other stoppages. It indicates the ratio of actual operating time to the planned time available. Planned production time (or loading time) is separated from theoretical production time and measures unplanned downtime in the equipment, i.e. by this definition unavailability would not include time for preventive maintenance. This definition gives rise to planning of preventive activities, such as preventive maintenance, but it might lead to too much maintenance of the equipment and too long set-up times. If planned downtime is included in the production time, the availability would be significantly lower, but the true availability would be shown. That would create motives for decreasing the planned downtime, e.g. through more efficient tools for set-up and more efficient planned maintenance.

The performance rate measures the ratio of actual operating speed of the equipment (i.e. the ideal speed minus speed losses, minor stoppages and idling) and the ideal speed (based on the equipment capacity as initially designed). Nakajima (1988) measures a fixed amount of output, and in his definition (P) indicates the actual deviation in time from ideal cycle time. De Groote (1995), on the other hand, focuses on a fixed time and calculates the deviation in production from planned. Both definitions measure the actual amount of production, but in somewhat different ways.

The quality rate only takes into consideration the quality losses (number of items rejected due to quality defects) that happen close to the equipment, not the quality losses that appear downstream. This is a very introspective approach. A wider definition of (Q) would be interesting, but would complicate the calculations and interpretations. It should be according to which process is to blame, and this is not always easy to identify.

Owing to different definitions of OEE and other varying circumstances between companies, it is difficult to identify optimum OEE figures and to

	Nakajima (1988)	De Groote (1995)
Availability (A)	$\frac{\text{Loading time} - \text{downtime}}{\text{Loading time}}$	$\frac{\text{Planned production time} - \text{unplanned downtime}}{\text{Planned production time}}$
Performance (P)	$\frac{\text{Ideal cycle time} \times \text{output}}{\text{Operating time}}$	$\frac{\text{Actual amount of production}}{\text{Planned amount of production}}$
Quality (Q)	$\frac{\text{Input} - \text{volume of quality defects}}{\text{Input}}$	$\frac{\text{Actual amount of production} - \text{non-accepted amount}}{\text{Actual amount}}$
OEE	$(A) \times (P) \times (Q)$	$(A) \times (P) \times (Q)$

Table II.
Definitions of OEE variables

compare OEE between firms or shops. Some authors have tried to do it though; e.g. Nakajima (Raouf, 1994) asserted that under ideal conditions firms should have A > 0.90, P > 0.95 and Q > 0.99. These figures would result in an OEE > 0.84 for world-class firms and Nakajima considers this figure to be a good benchmark for a typical manufacturing capability. Kotze (1993), on the other hand, argues that an OEE less than 0.50 is more realistic. This figure corresponds to the summary of different OEE measurements presented by Ericsson (1997), where OEE varies between 0.30 and 0.80. These disparate figures indicate the difficulties of comparing OEE between processes.

Data collection

Collection of data about the losses is an important phase of continuous improvement and performance measurement. What has not been measured, can not be improved. Critical parameters of the six big losses can be identified by using the existing competence in each process. The data collection should be at such detailed level that it fulfils its objectives without being unnecessarily demanding of resources. A too detailed data collection may result in unmotivated personnel and reaction against the measurement.

Sometimes the process in itself is so complex that it is impossible to avoid a detailed data collection. The data collection can then be facilitated by measuring the actual time of each downtime and speed loss, instead of measuring the frequency of these losses. Measuring the actual time of the losses gives more correct data, but measuring the frequency is often enough. The reason for this is that the most important objective of the OEE is not to get an optimum measure, but to get a simple measure that tells the production personnel where to spend their improvement resources. Variations that are built into the organisation, such as different shifts and weekdays, have to be considered. There are also variations in the market, such as seasonal demand. The period for a data collection should be adapted so that these variations are equally considered.

The data collection should be carried out by personnel that can affect the measured parameters. Nearness is an important aspect in continuous improvement and therefore the result of data collection should not only be summarised to a key figure as a part of the measurement system, it should also be used as input in small group activities. The links between OEE and dimensions and characteristics of OMP measurement are summarised in Table III.

Methodology

The aims of the case studies were to examine the generality of the dimensions and characteristics of a comprehensive system of measuring OMP and the contribution of the OEE measure for fulfilment of the dimensions and characteristics. We therefore wanted to study cases in various environments. The three cases were chosen because they were medium- or large-sized manufacturing firms from various industries and with different measurement systems.

Dimensions/ characteristics	Links to the OEE measure
Strategy	When applied in a TPM/TQM environment, i.e. as a bottom-up approach with focus on a total perspective and participation of everybody, it requires common goals and strategies throughout the organisation
Flow orientation	No link to OEE
Internal efficiency	The OEE measure is a simple, but comprehensive measure of equipment efficiency. However, it cannot always be compared between functions or organisations
External effectiveness	No link to OEE
Improvement drivers	The greatest contribution of OEE is probably achieved when it is used as an objective performance indicator in a continuous improvement process
Simple and dynamic	Focus on OEE, instead of several different measures for internal efficiency, simplifies the total measurement system. However, OEE has to be complemented by several other measures

Table III.
OEE vs. dimensions and characteristics

One of the selected cases was a medium-sized process industry. The others were large mechanical engineering firms. The studies were carried out in two steps. The first dealt with the general manufacturing performance measurement system and the second was about OEE. The first step was mainly based on interviews and secondary data, while the second was carried out through field experiments and interviews.

By conducting interviews with production managers, workshop managers and foremen for specific workshops and collecting secondary data from annual, monthly and weekly reports, qualitative data about the present performance measurement systems were captured. The objective was to gain knowledge about the design of the measurement systems and about the performance measurement processes on various levels of the organisations. The interviews were structured, that is there were guidelines and specific questions. The selected interviewees were considered to be involved in the performance measurement process at various levels of the organisations.

The studied firms had not implemented OEE in the measurement systems. Consequently, to be able to study the effect of OEE on the respective measurement system we had to implement OEE into the systems or derive similar measures from the information system. In the two first case studies we implemented OEE through “field experiments” and in the third case we derived similar measures from existing data.

The collected data gave information about the design and use of the respective performance measurement systems at various levels of the organisations. A comprehensive analysis of the firms’ measurement systems compared to the OMP measurement dimensions and characteristics gave information about the fulfilment of the dimensions and characteristics in the actual cases. Analysis of the contribution of OEE to fulfil the OMP measurement dimensions and characteristics gave indications of the generality of OEE for performance measurement.

Case study I

The company is a process plant and manufactures metal profiles. Its toughest competitor is a larger local manufacturer. It is the smallest and youngest of the studied cases. The production process consists of three core processes, the press, anodeing and end-preparation processes. The process for pressing the profiles consists of the four sub-processes; casting saw, base oven, temper oven and press. The production system is managed as a pull system and based on make-to-order plans. The OEE study was delimited to the press process, while the studied OMP system covered the entire production process.

The measurement system

Most data, such as the financial data, were derived from the management information system. Operation data were collected by direct production personnel and used in active improvement work before being reported further to production management.

The measurement system (see Figure 1) consisted of three hierarchical levels: production management, workshop and group and individual level. The strategic goals were based on six criteria:

(1) customer orientation (customer satisfaction, service level):

(2) health, environment and safety (job rotation, recycling, accident reports);

(3) working methods (standardisation, job enlargement);

(4) process measures (service level, lead-times, tied-up capital);

(5) competence development (skill of personnel, need for improvement);

(6) solving day-to-day problems (PDCA-cycle, motivation, commitment).

The measurement system had a lot in common with the process and structure of Malcolm Baldrige Quality Award, i.e. the criteria include a measurement system that is consistent with total quality management (TQM) and focusing

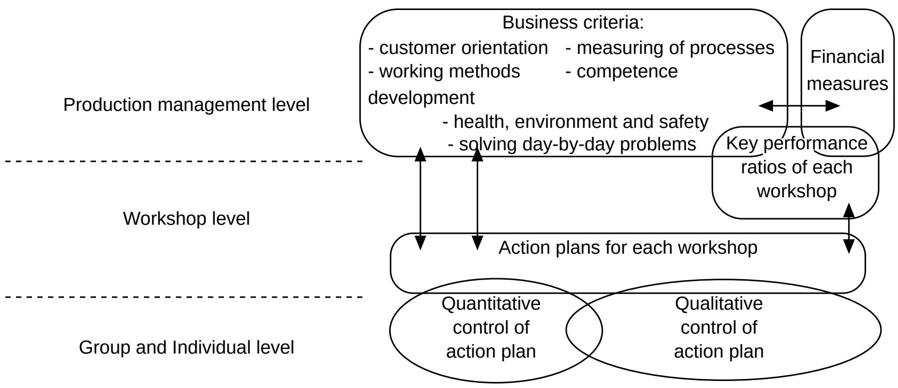

Figure 1.
The measurement system of case study I

on preventive measures and continuous improvement. The firm also had an internal quality award, where the separate workshops compete against each other. This quality award approach ran all through the measurement system and the organisation.

Each workshop linked its own action plans to the strategic goals of the firm. The plans were quarterly, controlled mainly through qualitative measures. The quantitative control focused more on trends than absolute figures.

Performance ratios of a defined set of key performances were followed up at workshop level on monthly basis and were revised each quarter for the following 12 months. Each workshop summarised the key performances in a measure for "total productivity".

$$\text{Total productivity} = \frac{\text{actual amount of production} - \text{non-accepted amount}}{\text{loading time} - \text{unproductive time}}$$

The total productivity measure leaves unproductive time out, but it is still calculated and used at shop-floor level. Financial measures for personnel, energy, maintenance, quality deficiencies costs, education and training were controlled and up-dated each month.

All workshops used a bottom-up approach when measuring performances. Autonomous small groups were responsible for the measurement and continuous improvement of their processes. The organisation's culture was characterised by customer and quality orientation. Customer satisfaction was always a priority at workshop level. Most personnel were frequently in contact with the external customers and an internal customer-supplier relationship was well established. For example, cross functional "customer contact" teams were formed by personnel from the production, logistics, design and sales departments to promote understanding of each others' needs.

The links to dimensions and characteristics

Flexibility and service level were considered to be the most important overall strategic priorities. Flexibility concerned both the dynamics of the organisation and the ability to carry out short set-ups, fast changes in the production process and produce small batches. The service level criterion mainly considered short lead-times and delivery reliability. Service level aspects were highly prioritised on all levels of the performance measurement system. Flexibility, on the other hand, was not even mentioned in the measurement system. However, the entire organisation was considered to be aware of the importance of both flexibility and service levels.

The logistics department was responsible for recording different time-based metrics, such as total through-put time and turnover. These measurements covered, from a macro perspective, several departments and functions in the flow of material. The weakness of this approach was the loss in nearness to the process measured and the lack of involvement of direct personnel. Most employees were aware of the importance of applying a customer-supplier approach, both internally and externally, but they applied no measure for this. The same was true for the flexibility capability, mentioned above. Several of the measures used could easily be changed from the present introspective perspective to a more flow-oriented approach.

Most of the input to the small group activities could be derived from measures of internal efficiency, such as measures for lead-times, tied-up-capital, availability and quality defects. The internal efficiency dimensions were not considered to be more important than any others. The consumption of resources (personnel, energy, maintenance, training, education) was measured by financial metrics (direct costs).

The overall measurement system and the organisation as such focused sharply on customer satisfaction and external effectiveness. The customer contact was carried out at group level and quality problems were mostly solved at this level or in the specific customer contact groups. Delivery reliability of every order was followed up and reported back to the organisation. This passive way of measuring service levels was complemented by annual customer satisfaction surveys. These surveys were important parts of the quality improvement work.

The measure "total productivity" was used as a measure for internal efficiency, and each variable was broken down and used as input to the quality improvement work, e.g. the variable unproductive time consisted of three types of downtime: equipment based, material based and planned. The production department was responsible for the data collection as well as the analysis of the measure.

A primary strength of the entire organisation and the overall manufacturing performance measurement system was the decentralised authority, which resulted in improvements devised and executed by shopfloor workers. Worker empowerment and commitment among the personnel were significant throughout the entire organisation. Most measures were critically analysed in autonomous teams, leading to continuous improvements.

Another strength of the measurement system was its simplicity and dynamics. The six strategic goals of the organisation were evaluated and adjusted on an annual basis. This sometimes resulted in a new set of variables being used in the performance measurement system. To make this change possible the goals are obvious for the entire organisation and the measurement system is simple and has a clear structure.

The OEE measure

We conducted, during a period of two months, data collection and analysis of OEE variables (see Table IV). OEE could be measured by complementing the

Measure		Downtime losses	
Availability	0.87	Process waiting time	0.25
Performance	0.94	Lack of material	0.14
Quality	0.91	Set up	0.17
OEE	0.74	PM	0.13
		Breakdown	0.31
		Total	1.00

Table IV. OEE measure and downtime losses (study I) existing variables for downtime, i.e. the existing measure for total productivity, with variables for speed losses and quality losses. Speed losses were difficult to measure, because optimum speed was not defined clearly. The optimum speed depended on different factors in and around the process. Quality of the material was an important factor affecting optimum speed. Quality was measured in two sub-processes. First the waste from the casting saw and then eventual scrap among profiles leaving the press process was identified. Data were collected during 260 working hours.

Downtime losses due to process waiting time were difficult to improve, since their causes derived from the design and construction of the equipment. Several changes in the work process had been conducted lately without modifying the equipment. Most breakdown losses were due to waiting and carrying out maintenance.

Performance was measured by quoting actual speed and optimum speed. The optimum production speed differed between each profile and was sometimes difficult to define. What is important is that the same speed is used for a specific profile at every single measurement. Otherwise it will not be possible to compare measurements over time. A variable of performance was "minor stoppages". These had not been thought important before the study, but the data showed that they amounted to 20 per cent, short periods up to 49 per cent, of total stop time.

Quality losses in production due to quality defects seemed not critical, because most of the unacceptable material could be recycled back into the process again. There are still extra costs for the rework (such as additional costs of energy and material handling) and most of the quality losses appeared downstream in the flow of material. An important limitation of OEE is that it only covers quality losses within the measured process and not losses that occur elsewhere.

There is already a great emphasis on team work and continuous improvement, and a measure similar to OEE exists. The present measure, total productivity, is an important input to the improvement work. A more detailed OEE measure would probably make it easier to focus on different causes of losses.

Case study II

The company manufactures large construction vehicles and its main competitor is a large North American manufacturer. It is a part of one of the largest corporations in Sweden. The corporate headquarters influences the company to a great extent. The production process is based on assembly-to-order plans and consists of three functional workshops: sheet-metal working, painting and assembling. The total throughput time from raw material to final product is about 14 days. The sheet-metal workshop is equipped with several industry robots and other advanced manufacturing technology machinery. The studied OMP system covered the entire plant, but we measured OEE in a section of three robots in the sheet-metal workshop.

The measurement system

The measurement system was based on existing data collected from the internal management information system (MIS).

The performance measurement system (see Figure 2) followed a complete top-down approach, and was not used as input at the operational level or used as an important tool for strategic management decisions. It was hierarchically controlled by the headquarters of the large corporation and the management of the plant mostly put together and reported the data. The firm has started to "smooth" the tight control structure of the organisation, but this change is in the early stages and it is still quite a formal and bureaucratic organisation, where the employees focus on their own, often delimited, activities without getting the big picture of the organisation and business.

Five levels of the organisation structure and measurement system were identified: corporate level, plant production management level, workshop level, group level and individual level. Goals for quality, lead-time, flexibility, internal efficiency, continuous improvement and turnover rate were identified at corporate level. The plant then transformed these goals into plant-specific manufacturing performance measures at production management level. These specific measures were broken down to action plans at workshop level and mostly controlled through quantitative measures. The workshop managers reported these measures to production management monthly.

The links to dimensions and characteristics

A weakness was the lack of horizontal integration of the strategy and the performance measurement system. Product quality, in terms of performance of the product and its life cycle costs, was considered to be the most important competitive capability of the plant. However, no specific emphasis was put on this capability in the overall manufacturing performance measurement system, neither at management level nor operational level. This led to a lack of awareness of the strategic importance of product quality on workshop, group and individual levels.

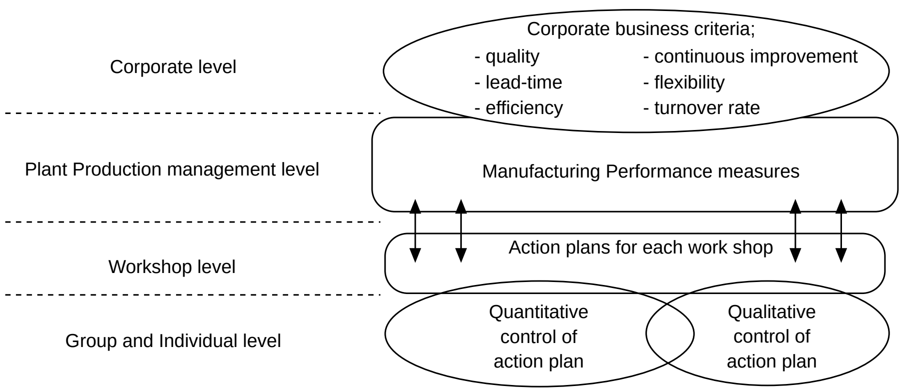

Figure 2. The measurement system of case study II

The measurement system was not very flow-oriented. Throughput time was measured, but it was isolated to each workshop and did not consider processes up-stream or down-stream. However, internal customer-supplier relationships existed to some extent.

Much emphasis was put on the internal efficiency dimension. Several time-based measures for internal efficiency existed, e.g. turnover rates, technical availability and throughput time. No financial measure was reported to production management, but such measures actually were available at workshop level.

Small group activities existed, but they were not fully integrated into the organisation. Data about breakdowns and downtime of the equipment were continuously collected by the direct production personnel and the maintenance department. These data were summarised in the "technical availability" ratio on monthly basis. The measure was not used as input to any small group activity, but reported to shop-floor and plant management.

The measures for external effectiveness and customer satisfaction were under-developed. However, customer satisfaction studies were conducted at corporate level three times a year. The results were distributed to plant production management level. No active customer contact existed at workshop level. The lack of such active and continuous customer contact was serious, especially since product performance and life cycle costs were the most important strategic capabilities.

A significant weakness of the measurement system was its top-down approach and lack of bottom-up involvement. It did not in itself drive any improvements. It was used more as a passive control than an active improvement generator. The personnel were informed about the measurement figures on boards in their group rooms. No information was available elsewhere. Monthly meetings were held at workshop level to inform the personnel about last month's result. The internal environment (individual leadership, efficiency, motivation and commitment) was analysed through an annual survey distributed to all employees. The objective was to investigate the competence and need for education and training. Autonomous small groups did not exist to any greater extent. However, during the next year all employees will get one week of education about team work, leadership and quality. Most measures were analysed in absolute terms, and no long-term trends were identified or studied.

The top-down approach and similarity between functions of the measurement system made it quite simple and easy to understand and change.

The OEE measure

We conducted an OEE measurement for a short period of time in a section of three robots in the welding department. The objective of this "field experiment" was to exemplify the use of OEE in the organisation, to link it to the OMP dimensions and characteristics, and to analyse the causes of low and high OEE figures in the studied section of the plant. In order to separate internally- and externally-caused machine failures, the availability measure was divided into support efficiency and availability. Support efficiency considered the externally caused machine stops, not due to machine failure (e.g. waiting for material), and availability considered the internally caused machine stops, due to machine failure (e.g. waiting for maintenance and conducting repair). Bad activities, such as machine stops and reduced speed, were observed in a frequency analysis. About 500 observations per robot were carried out. The time between successive observations averaged five minutes. The remaining data, such as reports of scrap, inspection and quality, were collected through secondary data from quality reports and product revisions made by the quality department and operations. Quality was measured separately in each robot, but the estimation was used as an average for all robots. The efficiency was measured as the number of observations with bad activities in relation to total number of observations. The corresponding measures are shown in Table V.

The main causes for low OEEs were lack of material, breakdown, corrective maintenance and time for programming the flexible manufacturing systems (FMS). The lack of material was considered to be an internal logistics problem that to some extent could be overcome if the internal customer-supplier relationships and flow of material perspective were further understood and developed. There were several causes for machine failure and breakdown, but the most important was that the transfer carriage stopped, when moving and transferring goods along the FMS. Corrective maintenance and time for programming were in themselves significant causes for breakdown and adjustments losses. Robot 2 showed much higher availability compared to the other robots. The main fact for this was considered to be that this was the first robot installed.

Most of the breakdowns could probably be overcome by simple preventive maintenance, such as cleaning the sensors and lubricating the equipment, by the direct production personnel. This would lead to less losses due to corrective

	Robot 1	Robot 2	Robot 3	Average (1-3)	Range
Measure					
Support efficiency	0.72	0.67	0.70	0.70	0.05
Availability	0.37	0.92	0.56	0.61	0.55
Performance	0.92	0.89	0.85	0.89	0.07
Quality				0.93	
OEE	0.23	0.51	0.31	0.35	0.28
Downtime losses					
Lack of material	0.31	0.68	0.44		
Material handling	0.05	0.18	0.05		
Human aspects	0.01	0.00	0.00		
Breakdown	0.42	0.11	0.28		
Programming	0.14	0.00	0.07		
Corrective maintenance	0.07	0.03	0.16		
Total	1.00	1.00	1.00		

Table V. OEE measurement and speed losses (study II) maintenance, as well. The losses due to programming were mainly caused by lack of knowledge about programming.

There are great potentials for incremental improvements and decrease of the losses by applying a bottom-up approach, especially since several losses are caused by lack of maintenance and education about programming. The use of the factors making up OEE as an improvement tool in autonomous teams would probably contribute to improved fulfilment of the improvement driver characteristic of the manufacturing performance measurement system. Recently started education programmes in teamwork, leadership and quality is the first step toward better environment for continuous improvement in the future.

Case study III

The third company manufactures a wide range of pumps. It is world market leader in one niche. The products are customer-oriented and the manufacturing processes are based on assembly-to-order plans. The production system consists of a casting department, engine department and five workshops. The five workshops are organised according to the size and capacity of the products they manufacture. They contain sheet-metal working with heavy investments in advanced manufacturing technology (such as industry robots, flexible manufacturing systems and computerised numerical control machines) and assembling that is based on products with several features and options. Each shop is a profit centre and controls its own purchasing, manufacturing and delivering.

The study was conducted in two separate workshops (A and B) with different manufacturing layout strategies. Shop A is an automated flow oriented shop producing few product variants in long runs and shop B has a functional layout and a complex product mix with shorter runs.

The measurement system

Data were collected by the management at workshop level in shop A and by direct production personnel and workshop management at shop B. Quantitative data were derived from the management information system and qualitative data directly from the processes.

The overall objectives of the measurement systems differed in the shops. In shop A the measures were used for daily control and improvement work in self-managed-teams. In shop B the measures were used as input to the wages of the direct production personnel. However, both shops reported their performance figures to the management level for internal comparison between the shops.

In the performance measurement system (see Figure 3) four organisational levels could be identified:

(1) production management;

(2) workshop;

(3) group level; and

(4) individual level.

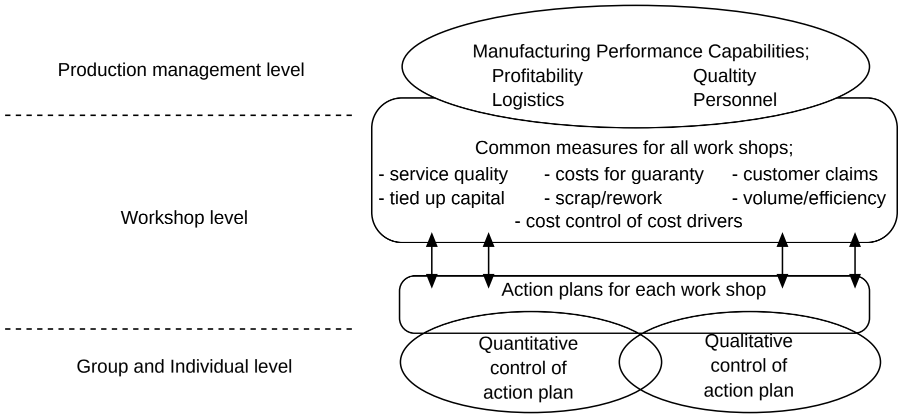

Figure 3. The measurement system of case study 3

The business strategy identified four manufacturing performance capabilities: logistics (service level and lead time), profitability (efficiency, costs and working capital), personnel (personal competence) and "quality" (product revision, scrap and customer claims). These capabilities represented the tasks that should be performed by manufacturing in order to support the business strategy. Measures of the four types of capabilities were reported monthly to production management level, and compared between different workshops. Quality and service level were considered to be the most important competitive priorities, and were consequently getting most emphasis in the organisation, both in the strategic planning and the measurement of manufacturing performance.

Fulfilment of the four manufacturing performance measurement dimensions was planned through action plans for each workshop. These action plans were controlled through several quantitative and qualitative measures. Performance measurement (i.e. action plans) on group and individual levels was carried out somewhat differently in the two workshops studied. The manager of workshop A measured several financial and productivity measures of cost, dependability, quality and availability at quarterly or monthly intervals. Delivery times, delivery reliability, inventory turnover, and proportion of productive production time were communicated to the production personnel, since they affected their wages. In shop B, performance control was decentralised to group level. Autonomous teams reported quantitative (overhead costs, product quality, availability and service level) and qualitative (practice, training, job enlargement/enrichment, education/courses, safety, work organisation, etc.) performance measures to the workshop manager.

Shop B focused more on social and environmental aspects than shop A. Qualitative action plans for training, practice, safety and work environment existed, for individuals as well as teams. Several improvements that could be considered indicators for future potential efficiency and effectiveness improvements were identified within these areas, e.g. 10 percent improved work satisfaction during the last Shop A followed up infrastructure aspects through individual training plans, number of accidents and personnel turnover.

The links to dimensions and characteristics

The primary strength of the performance measurement systems of both shops (A and B) was that they gave holistic perspectives. They were derived from the competitive capabilities at production management level and covered all hierarchical levels of the organisation. Dependability and quality were considered to be the most important strategic priorities for the organisation. Although both shops probably need to be flexible (Shop A is dependent on short set-up times and shop B has a complex product mix that demands flexible production), no emphasis was put on flexibility. Dependability and quality were the measures most emphasised by management in shop A, but they were not emphasised further down the hierarchy. In shop A most performances were controlled by quantitative measures at workshop level. In shop B, the four overall objectives were broken down to availability, quality, service level, production cost and a set of qualitative action plans, at group level. A reason for shop B being able to implement measures at group level was its management and work organisation. It had decentralised authority and relied heavily on autonomous small groups.

Both shops suffered from lack of flow orientation. Time measures were used for throughput efficiency, though. Shop A measured availability, inventory levels, lead times and quality levels in the entire process, but only within its own department. The importance of internal or external customers or suppliers was discussed, but was not included in any measure. The same was true for shop B. In both systems it should be possible to use more flow oriented approaches. For example, shop A used a measure for the cost for adjustment and rework in the shop. This measure could be changed so that it instead measured the cost for adjusting and reworking, due to failures caused by shop A, and in other parts of the plant separately. The same holds for inventory turnover rate and service level.

External effectiveness was measured through product quality and service level measures. Most quality measures, except for warranty work, were more focused on internal efficiency, such as scrap and rework, than external effectiveness and customer satisfaction. Both shops had a passive way to measure external effectiveness, since they had no system for exceeding customer satisfaction. Their measures made them wait until the customer had already complained.

Internal efficiency was measured in several productivity measures. Costs, availability, inventory levels and quality levels were compared between departments, but also to other organisations. This is not always accurate, though, because of different circumstances. Most measurement was conducted at system level in shop A, but at group level in shop B. This made it difficult for shop A to identify non-value-added activities and improve its processes. The measures did not indicate any future improvement, but were in themselves simple measures that were easy to understand and that generated process improvements.

One of the biggest problems at production management level was the complexity of the entire performance measurement system. A large number of different measures was used and it was difficult to get the “big picture” of the entire measurement system. It was difficult to interpret and compare measures from different departments and of various capabilities. In shop B, the simplicity of the measures and goals was considered more important than the complete coverage of all four overall objectives. This approach resulted in a simpler and more comprehensive system, but it was still quite complex.

Despite the various measurement approaches, no significant difference between performances or fulfilment of the four manufacturing objectives could be identified between the two shops.

The OEE measure

The company did not use OEE, but had recently implemented a measure for availability at most levels of the organisation. However, this measure did not include set-up times. One of the most serious weaknesses of the present measurement system was that it consisted of too many different measures, leading to high complexity and difficulties in getting the “big picture”. A changed focus toward implementation of OEE would decrease this complexity.

Availability and other simple efficiency measures were measured but not further analysed in either of the two shops. However, a more comprehensive use of Ishikawa diagrams and other cause-and-effect analyses in the autonomous improvement teams would be possible in shop B, and would probably lead to a measurement system that suggested more improvements than the present one. The work organisation in shop B is ready for this change, while shop A first has to change management style and improve the commitment and participation of all employees before it can successfully implement and decentralise continuous cause-and-effect-analysis.

Discussion and conclusions

The OMP measurement framework

Four dimensions that indicate what should be measured and two characteristics that indicate how to measure in a comprehensive overall manufacturing performance (OMP) measurement system were identified. The strategy dimension indicates that the measurement system should translate the corporate and business strategies to all levels of the organisation. The flow orientation dimension means that the measurement system integrates all functions, activities and processes along the supply chain. The internal efficiency dimension emphasises the need for the measurement system to work as productivity control and comparison between internal functions. The interaction with customers and measurement of customer satisfaction is emphasised in the external effectiveness dimension. The improvement drivers, and simple and dynamic characteristics indicate the importance of using the system for continuous improvement instead of passive control, and the adjustment to the fast changing environment.

The cases

The framework of dimensions and characteristics is meant to be used when evaluating and improving a specific OMP measurement system. Here, the systems of three firms were studied. The first firm was the smallest and youngest. It relied on a flat and decentralised organisation structure. Its measurement system followed the process and structure of the Malcolm Baldrige Quality Award. The second plant belonged to a large corporation. Its measurement system was quite hierarchical and top-down controlled. The measurement system of the third plant differed between workshops in the organisation. One shop was organised according to a bottom-up approach with autonomous teams. The other shops were more top-down controlled.

A common weakness of all three measurement systems was that they did not measure flow orientation or external effectiveness to any great extent. They focused on functional measures and failed to integrate processes along the supply chain in the measurement system. Most of them used quite passive measures for controlling the external effectiveness and customer satisfaction, but all had several, more or less relevant, measures for internal efficiency.

There were several differences between the systems, as well. The holistic perspective and the measurement of the competitive capabilities of all hierarchical levels of the organisation were the primary strengths of the third system, but these aspects were weaker in the other two systems. The overall complexity was considered a problem in the system of the third plant, since it neither relied on tight control nor had decentralised authority. The only system that was considered to fully drive improvements was that of the first plant, which relied on several qualitative measures that were further analysed in autonomous teams.

All three manufacturing performance measurement systems were quite general in nature, and they could probably benchmark improvements from one another. Still, it is important to understand that each system is custom-made for its specific conditions and most likely to work best in the environment where it was developed. This is true for the studied measurement systems, as well, and it supports the statement that there does not exist any panacea of measurement systems that is applicable to most organisations. However, the presented dimensions and characteristics can be used to evaluate and initiate improvements of most specific systems.

The OEE measure

The contribution of overall equipment effectiveness (OEE) for fulfilment of the identified dimensions and characteristics of the three manufacturing performance measurement systems was the second part of the study and analysis.

The definition of OEE sometimes varies. Planned downtime was included in production time in both "experiments". In the first, the losses that affected availability were divided into stops due to and not due to machine failure. This made the status of the losses more clear and simplified the analysis. Speed losses are sometimes difficult to define, but they often make up a large proportion of the total downtime. Some authors and firms have defined performance as actual production in relation to planned production. This definition is often too simple and since planned production sometimes is only updated annually the measured figures will over-estimate efficiency. In both cases the quality measure was considered general and brief. It is difficult to get a comprehensive view of the quality of the equipment when only using OEE. A wider definition of the quality parameter would, however, decrease the simplicity.

OEE is a measure of internal efficiency. OEE figures of cases I and II could not be compared, since manufacturing conditions and data collection techniques differed. Internal comparisons between the three robots in case II were still possible. OEE does not measure the strategy, flow orientation and external effectiveness dimensions to any great extent. Most studied systems did not have proper measures for flow orientation or external effectiveness, but consequently OEE did not improve the fulfilment of these dimensions.

The greatest contribution of OEE, if used in correct way, is its focus on the characteristics improvement drivers and simple/dynamic. Two different ways of collecting data were used in the two field experiments in cases I and II. In the first the frequency of bad activities was measured, and in the second data for downtime and speed losses were collected by measuring the times that these losses lasted. The main reason for using different methods for collecting data was the difference in complexity of the measured processes. The most important objective of OEE is not to get an optimum measure, but to get a simple measure that tells the production personnel where to spend their improvement resources, i.e. it contributes to both OMP characteristics. This was possible in both field experiments, no matter which data collection technique was used. However, proper analysis of the OEE figures requires a decentralised organisation with autonomous teams. OEE does not contribute very much to the measurement system if it is used only for top-down control of the internal efficiency.

Implications for future research

There exist few general frameworks for evaluating OMP measurement systems. The present framework of four dimensions and two characteristics is quite broad and may be further developed and tested.

The OEE measure could successfully be used in all systems studied, but it is considered most applicable in decentralised organisations with clear bottom-up approaches. Its greatest contribution is that it is a simple, but still comprehensive, measure of internal efficiency and that it can work as an important indicator in the continuous improvement process. However, the importance of a comprehensive OMP measurement system for achieving proactiveness, continuous improvement and competitive advantage has not been shown. It would be interesting to analyse the role of the measurement system for achieving high performance. This could be analysed in a broad survey study.

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