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2012

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Windmark, C., Ståhl, J.-E., Gabrielson, P., & Andersson, C. (2012). *A production performance analysis regarding downtime and downtime pattern*. Paper presented at 22nd International Conference on Flexible Automation and Intelligent Manufacturing, FAIM 2012, Helsinki, Finland.

Total number of authors:
4

A production performance analysis regarding downtime and downtime pattern

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ABSTRACT

In order to compete on the international market, companies today need to optimize their production continually. One way to achieve this is to minimize the frequency and length of downtime in the production. The downtimes in a particular manufacturing line were classified on the basis of what generated them; a production performance analysis was carried out, and then a cost model was applied to the results. After an initial study of all the products involved, five products were selected for more detailed analyses. Manufacturing costs were found to differ between products and also between batches of the same product. There appeared to be considerable potential for improvements.

1. INTRODUCTION

Since continuous optimization of production is essential in order to compete on the market, companies today need to know their strengths and weaknesses in order to continually improve and develop their production. It is important to know where problems occur and how they affect the final cost to be able to prioritize among different improvement actions. In companies with a larger product portfolio, some products or production lines could have better performance than others; therefore, systematic comparison between these could make it possible to identify the actual differences. Comparisons between different products and systems could also make the decision-making easier when establishing where to make efforts in order to achieve the most advantages from investments.

Today many companies make efforts to establish philosophies and work approaches in their organization in order to reduce waste and losses and to streamline the organization. This often makes higher demands on production systems, making it even more important to properly identify weaknesses and quickly find possible solutions to potential problems. If the system is not ready for the "new" approach, the production could in worst case end up starving due to late deliveries or downtimes in one or more of the stations in the production line. This makes it more important to complement different methods with each other in order to get the correct representation of the production line. The present article will show a model used for evaluating production system performance, targeting related losses in terms of cost per unit and present simulated potential for improvements. As a part of the study two different approaches regarding production efficiency have been analyzed and compared. The model in this article particularly focuses on production performance in order to evaluate and calculate manufacturing cost.

2. LITERATURE REVIEW

There have been many researches that use production time when evaluating production performance, and many methods have been developed for calculating manufacturing cost. When it comes to continuous improvements, there are many approaches and philosophies at hand. One of the most widely used is Lean Production [1], focusing on reducing waste by introducing standards and reducing stocks and buffers. In connection with Lean Production, companies today often implement Total Productive Maintenance (TPM) based on Overall Equipment Efficiency (OEE), originally defined by Nakajima [11]. Ljungberg [5] discusses the importance of using a well-functioning data collecting system, without which there would be a high risk that the data used for calculations and verifications cannot be used to correctly describe the system. Furthermore, an analysis could never be better than the information used. In the article Ljungberg also mentions that the dominating losses in the actual survey were performance losses and downtime losses. Below follow other methods where time is used as one important feature when evaluating the production and calculating the manufacturing cost.

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One method was established at Harvard Business School, the Time-Driven Activity-Based Costing [2], which uses a developed ABC model based on time. Kaplan and Anderson present a concept method for calculating the unit cost. This model is used for estimating the overhead cost of products more than cost associated with losses in performance.

Productivity, the differential between output and input, is a common key performance figure when evaluating production. Craig, Harris and Clark [3] describe a method for calculating both total productivity and partial productivity based on input, such as the cost of labor, raw materials and purchased parts, and output, such as the selling price of the physical volume. This method was refined by Son Young and Park [4] with further parameters taken into consideration.

Reducing downtimes to improve the efficiency is a well-known concept, but the implementations vary considerably. Murty and Naikan [6] suggest that it is easy to over-spend when investing to reduce downtimes, and present a method used for evaluating the optimum availability. The foundation in the method reported in this article is based on a downtime analysis that is connected to an economical equation [7],[8]. It is then possible to find out the cost of different downtimes and simulate the possible profit when reducing them. This analysis is similar to the one presented by Heilala et.al. [9], which is based on OEE and Cost on Ownership (COO).

3. RESEARCH METHOD AND QUESTIONS

The present survey is a case study based on the report from a semi-automatic data collecting system where the operators manually report downtime causes over a specific time period. The aim of the present study was to investigate the downtimes occurring on one fully automated production line and the downtime parameters involved. The production line is a combined line with two or three production stages and with automated peripheral equipment before, after and in-between them. It was done by analyzing both DT (Down Times) and TBF (Times Between Failures) and using a production performance analysis matrix for structuring the information, in addition to generating the potential for improvement. The intention was to answer the following questions:

- Are there any similarities or patterns in downtime occurring for different products in the production line, making it easier to find accurate improvement activity?
- How large is the potential for improvement for different products?
- How well does the Manufacturing economic efficiency correspond to OEE?

Comparing downtimes for different batches of a given product reveals variations and similarities between them. It is then possible to answer the question of whether any particular types of downtime occur repeatedly in connection with the product in question. If all batches of a product for a given time period are viewed as a whole, one can also make comparisons to determine whether there are some problems that are specific for the product at hand. When comparing data from a batch of one type of product with data from batches of products of a different type it is possible to establish if there are differences and similarities in the problems leading to downtimes between the different products. This makes it possible to determine the solutions that are required for improvements at the following levels of the production:

- Single batch.
- Single part.
- Production generally.

In order to find out the degree of homogeneity in the downtime patterns of different products, comparisons on different levels have been conducted, as shown in Figure 1.

Single batches of one product have been compared with each other and with batches of other products, and all batches of one product have been compared with all batches from other products. The performance of one product has also been compared with the performance of the whole production system.

The data not regarding downtime was collected through interviews, observations at the production site and by the company's internal documentation. Collecting data for all the batches of each of several different products for a given year made it possible to extract the average cost of downtime for all the products manufactured on the production line that was studied. After comparing these different products, five of them of the company's choice were selected for further investigation. They were selected to obtain a mix of product dimensions, and they will henceforth be referred to as Product 1 to Product 5.

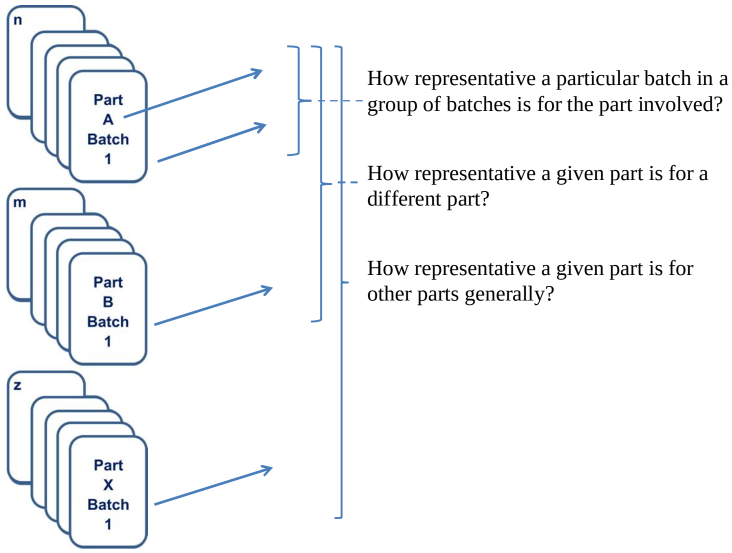

Figure 1: Different levels of investigation.

4. List of symbols

The parameters listed below are used in the article.

DT	Downtimes	min
E_{PBB}	Average time use during an unattended time	-
η_E	Manufacturing economic efficiency	-
k	Cost per part	SEK/unit
k_A	Equipment cost	SEK/ unit
k_B	Material cost per part	SEK/ unit
k_{CP}	Hourly machine cost during production	SEK/h
k_{CS}	Hourly machine cost at downtimes and adjustments	SEK/h
k_D	Salary cost	SEK/h
k_{ideal}	Ideal part cost	SEK/ unit
k_{mean}	The average cost per part	SEK/ unit
k_{real}	True part cost	SEK/ unit
Δk	Change in part costs	SEK/ unit
MTBF	Mean Time Between Failure	min
N_0	Nominal batch size	unit
n_{OP}	Number of operators during manufacturing	-
$n_{OP,su}$	Number of operators during the adjustment of equipment	-
OEE	Overall Equipment Efficiency	-
q_P	Relative rate reduction	-
q_Q	Rejections rate	-
q_S	Downtime proportion	-
Δq_s	Change in downtime proportion	-
S	Probability	-
t_0	Nominal cycle time per part	min
TBF	Times between Failure	min
t_p	Production time per part	min
t_{PBB}	Average time when an equipment is operating during an unattended time	min
T_{pb}	Production time for one batch	h
T_{plan}	Planned production time during a given period	h
T_{su}	Time for adjustments	min
U	Utilization	-
U_{RB}	The utilization rate at a reduced occupancy	-

5. METHODOLOGICAL BACKGROUND

The method used in the present study is based on a methodology developed at Lund University[8]. It is based on an economic model for manufacturing that provides a part cost after considering different costs and conditions in the production, for example material cost, wages, machine cost, facility cost, production time per part, rate of poor quality and downtime, and batch size. This model can also be used as a simulation tool to simulate different scenarios that affect the part cost.

5.1. THE PRODUCTION PERFORMANCE ANALYSIS MATRIX (PPAM)

There are different factor groups (A-H) below related to production methods, that is a tool for structuring different root causes to performance losses. These factor groups can provide the basis for developing a production performance analysis matrix that can be used to identify the causes to any losses in production performance. The PPAM can also be used for manufacturing cost analysis. The factor groups in question are[8]:

A. Tools.
B. Work piece materials.
C. The manufacturing process.
D. Personnel and organization.
E. Wear and maintenance.
F. Specific process behavior.
G. Peripheral equipment and inner logistics.
H. Other factors that one is unable to identify.

Making production effective and minimizing disturbances, such as rejections, downtimes and losses in speed, is a clear production performance aim. One can describe the results obtained at different processing stations and production sections in terms of the relevant performance parameters, which generally can be expressed in absolute terms. Classification of production performance is done mainly in terms of three main categories [10]:

- **Quality parameters,** linked with requirements placed on of the dimensions of the product, its surfaces and other properties, Q_1, $Q_2 \ldots Q_n$.
- **Downtime parameters,** related to events in the process that result in downtime, S_1, $S_2 \ldots S_n$.
- **Production speed parameters,** which describe the number of parts produced per given time unit P_1, $P_2 \ldots P_n$.

The production performance analysis matrix (PPAM) is a matrix in which the performance parameters and factors of interest are combined as shown in Figure 2. The matrix can be used in the following areas [10]:

- Monitoring production processes.
- Documentation aimed at possible improvements of future production methods and approaches.
- Making estimates of performance parameters and assessing the implications of various decisions related to different factor groups.

	Result parameters			
Factors	Quality parameters Q	Downtime parameters S	Speed parameters P	∑ Factors
A. Tools				
B. Work material				
C. The conversion process				
D. Personnel and organisation				
E. Wear and maintenance				
F. Specific process behaviour				
G. Peripheral equipment				
H. Unknown factors				
∑ Result parameters				

Figure 2: Various principles that can be applied to a Production-performance-analysis-matrix [10].

5.2. THE COST MODEL

Estimates of the proportion of downtimes are based on the reported downtimes (DT) and the time elapsed between different production downtimes (Times between Failures, TBF). A calculation of the proportion of downtime, q_S, can be carried out by use of equation *(1)*[8].

$$q_S = \frac{\Sigma DT}{\Sigma DT + \Sigma TBF} \qquad (1)$$

The part costs can be computed using equation *(2)*[8] for one planning point. This is also illustrated in Figure 3.

$$k = \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)(1-q_B)}\right]_b + \frac{k_{CP}}{60\ N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right]_{c1} + \frac{k_{CS}}{60\ N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RB}}{U_{RB}} T_{Pb}\right]_{c2} + \frac{k_D}{60\ N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)(1-q_S)} + T_{su} + \frac{1-U_{RB}}{U_{RB}} T_{Pb}\right]_d \qquad (2)$$

The input parameters are given in section 4.

There are different ways of calculating the degree of cost change Δk_i in costs per part k_i for selected variables in the cost equation. Doing this, it is possible to allocate the saving potential when changing different parameters. An approximate approach can be made using equation *(3)*[8]. By calculating the cost of the derivative, it is possible to obtain the maximum theoretical change in cost when reducing the size or strength of a parameter, z.

$$\Delta k_i = \frac{\partial k_i}{\partial z} \cdot \Delta z \qquad (3)$$

5.3. OEE AND MANUFACTURING ECONOMIC EFFICIENCY

Many companies make use of OEE (Overall Equipment Efficiency) for calculating their equipment performance. This measure originates from the concept of TPM, Total Productive Maintenance. There are different ways of calculating OEE. The model the company here examined uses is as follows [11]:

$$\text{OEE} = \text{availability} \cdot \text{performance} \cdot \text{quality} \qquad (4)$$

Availability means the amount of time the equipment is planned to be in operation. Performance is a measure of the time that was utilized. The quality, finally, is the proportion of products produced correctly.

In the present article, another way of calculating OEE is used, shown in equation *(5)* [10].

$$OEE = \frac{N_0 \cdot t_0}{T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)} + \frac{1-U_{RB}}{U_{RB}} T_{Pb}} \qquad (5)$$

In their study Andersson & Bellgran [12] show that OEE does not capture all changes in productivity and should be complemented by the use of methods that capture equipment investments.

In using OEE, it is important that the cycle times are well defined, otherwise there is a risk that certain problems may be neglected. By using cycle times that are too long unwarrantedly high OEE values may be obtained, reducing the incentives to the development needed and to the investment that this calls for. The principles involved are the same as those applying to high stock levels, where buffers make it difficult to get a perspective of the problems connected with production.

Manufacturing economic efficiency, calculated as in equation *(6)* below, represents an alternative way of calculating OEE [10].

$$\eta_E = \frac{k_{ideal}(q_Q = 0, q_S = 0, q_P = 0, T_{su} = 0, U_{RB} = 1)}{k_{real}} \qquad (6)$$

Here k_{ideal} represents the cost incurred when q_S, q_Q, q_P and T_{su} have a value of zero and U_{RB} has a value of 1.0. In the equation, k_{real} corresponds to the true and actual costs. Manufacturing economic efficiency is a measure of what proportion of the ingoing resources provides benefit for the customers. Thus it shows the potential for improvements that are available, while also providing a measure of how large a part of the ingoing resources is wasted. Estimates of the values for manufacturing economic efficiency for industrial production are between about 0.4 and 0.8 [10].

5.4 STATISTICAL MODELS

It can be very useful to know how long it is likely that production will continue without disruption. It is possible through the use of statistical models to obtain an overview of what controls the interference, with what intensity it arises, and with what statistical distribution. Exponential distributions, Weibull distributions and gamma distributions are commonly employed distributions in connection with production when continuous systems are involved [10]. Demonstrations have been conducted, including Vineyard, Amoako-Gyapah and Meredith. [13] and J. Ericsson [14], which investigate different downtime causes and linked distributions, and Jones, Jenkinson and Wang [15] have analyzed delay-time and linked exponential distribution. These systems can be described in terms of either a frequency function f(x), the corresponding probability function, or the distribution function F(x) [10].

6. ANALYSIS OF DOWNTIME COSTS

In the case study it was necessary to introduce some delimitations and modifications in the economic model. Since the material cost for the studied production is much higher than the actual manufacturing cost, the material cost was not included in the analysis, in order to make changes in the manufacturing cost visible. After careful consideration the author has chosen not to take any rejections into account due to limited access to information where the obtained rejections are correctly attributed to specific operations and specific batches. The reported rejections result in a very small proportion of rejection rates (q_Q). The author has also chosen not to take the production rate losses (q_P) into account, since it is very unclear what the nominal production rate is. These two omissions result in lower manufacturing costs, since both rate losses and quality losses cause an increase in cost. Some other modifications have also been done on the part cost equation because of the different number of operators during operation and setup. The modifications in salary cost are shown in Figure 3.

Equipment costs for production — Equipment costs through downtimes

$$k = \frac{k_{CP}}{60N_0}\left[t_0 N_0\right]_{c1} + \frac{k_{CS}}{60N_0}\left[t_0 N_0 \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RB}}{U_{RB}} \cdot T_{pb}\right]_{c2} + \frac{n_{OP} \cdot k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_S)} + T_{su} + \frac{1-U_{RB}}{U_{RB}} \cdot T_{pb}\right]_{d1} + \left[\frac{n_{OP,su} \cdot k_D}{60N_0} \cdot T_{su}\right]_{d2}$$

Salary costs — Salary costs for rigging

Figure 3: The different cost groups in the economic equation.

6.1. DEVELOPMENT OF THE COST CHANGE EQUATION

A disadvantage of equation *(3)* is that it is an approximation, and the error it entails becomes considerable when the change in downtime, Δq_S, is greater than 0.4 and when the change in rate loss, Δq_Q, is greater than 0.1 [8]. To handle cost allocations associated with large value for q_S, a new equation has been developed. Equation *(7)* was used for calculating changes in cost per part, Δk_i for a specific parameter and equation *(8)* for calculating changes in cost associated with the different factor groups, where *j* = A – H and *i* represents specific batches. In equation *(7)*, $k(z_0)$ stands for the part cost when the parameters of interest are set to zero, and $k(z_0 + \Delta z)$ gives the total part cost. In the equations, Δk_i is the part cost allocated to a specific parameter, such as for example downtime. It therefore gives the downtime cost, and it is then possible to calculate the downtime cost for a part for each factor group, $\Delta k_{i,j}$.

$$\Delta k_i = k(z_0 + \Delta z) - k(z_0) \tag{7}$$

$$\Delta k_{i,j} = \Delta k_i \cdot \frac{\Delta q_{S,j}}{\Delta q_S} \tag{8}$$

Figure 4 shows how costs of downtime are distributed over downtime rate, q_S, for each factor group for calculations based on equation *(8)*.

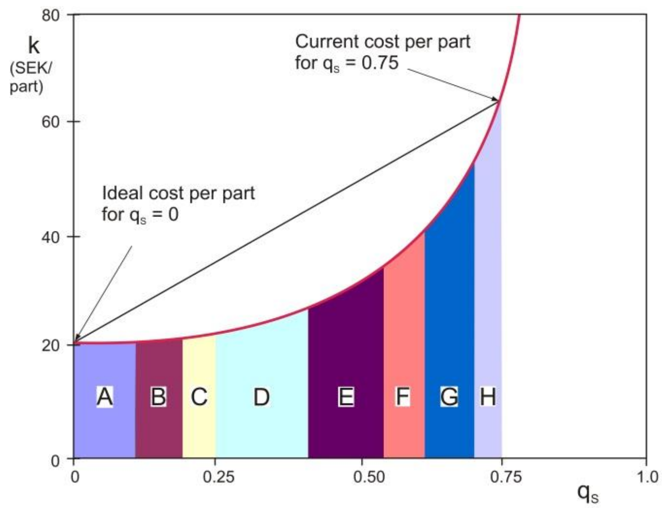

Figure 4: Example of the distribution of downtime costs in proportion to the share of q_S for each factor.

6.2. PRODUCTION PERFORMANCE ANALYSIS

As previously mentioned, the data was collected from a semi-automated reporting system, where most of the reported downtimes were reported directly from the system. Longer downtimes were reported manually, leading to a part of the reporting being influenced by interpretations and personal opinions about what caused the problem. Through discussions with the involved operators and managers at the line, it was possible to secure much of the original problem.To obtain an overview of production disturbances, the different batches for given products were divided in terms of downtimes (DT) and linked to each stop that prolongs the production time. In the present section, it will be described how batches were merged for the year of 2010, for analysis of the set of downtimes they represent. Just as in Jönsson et al.'s study [16], the set of downtimes was first divided in terms of the factors that caused them, and secondly in terms of the length of their duration. Downtimes and operating time are reported in bar graphs, the number of downtimes being presented on the y-axis and durations of production and of stoppage on the x-axis. This provides an overview of the different patterns involved, and the investigation level mentioned in Figure 1 is to see how representative one product is for the whole range of products manufactured in the production line. Figure 5 presents an example of downtimes for one of the five products, the results being divided in terms of the different factor groups and of the time intervals involved. The first diagram shows the sum of all downtimes. Diagrams 2 to 9 show the downtimes divided in the 8 different downtime categories discussed in section 5.1. The y-axis represents the number of downtimes and the x-axis represents the length of the downtimes, and the diagrams show the distribution of the downtimes.

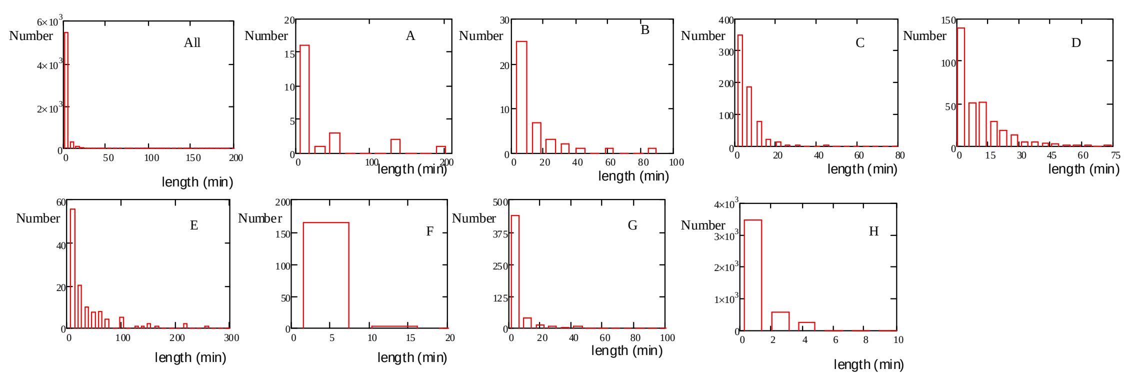

Figure 5: Example of DT-analysis where downtimes are broken down in terms of both the factors involved and duration.

For the product under investigation, the average time between downtimes (MTBF) is 5.2 minutes and the distribution of all downtime periods can approximately be described by an exponential distribution. For example, in determining the probability that the production line still is in operation after a 5-minute coffee break that began when the operator restarted the line can be obtained by using the following equation [10] where 64 % is the probability for an on-going production line:

$$E_{PBB} = \frac{1}{t_{PBB}} \cdot MTBF \cdot \left(1 - e^{-\frac{t_{PBB}}{MTBF}}\right) = \frac{1}{5} \cdot 5.2 \cdot \left(1 - e^{-\frac{5}{5.2}}\right) = 64 \ \% \qquad (9)$$

6.2.1 Downtime costs

Relevant estimates of manufacturing costs were carried out on randomly selected batches, evenly distributed over the year, for the five different selected products. For each batch, a downtime rate was calculated on the basis of the downtimes reported by the operator. The manufacturing cost per part was obtained by the use of the cost model in equation *(2)* through insertion of the overall downtime rate for the batch into the model. From the manufacturing costs, it is possible to get the downtime costs through the use of equation *(7)*, where z_0 corresponds to Δq_S. Thereafter, the relative impact of each factor group on the downtime costs was calculated using equation *(8)*. Examples of the results obtained for a particular product can be seen in Figure 6 and Figure 7. What emerges very clearly is that the dispersion between the different factor groups and between the different batches is large. In Figure 6 the investigation level mentioned in Figure 1 is between different batches of one product and in Figure 7 the investigation level is between all batches for the five products.

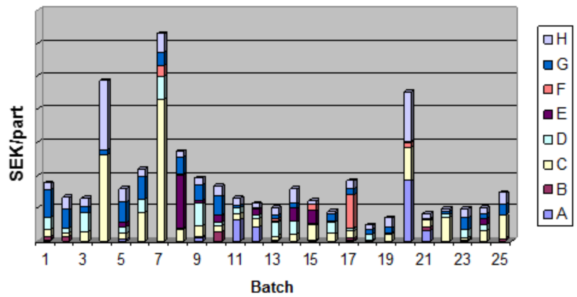

Figure 6: An example of the downtime costs obtained for different batches of one of the products for each of the different factor groups.

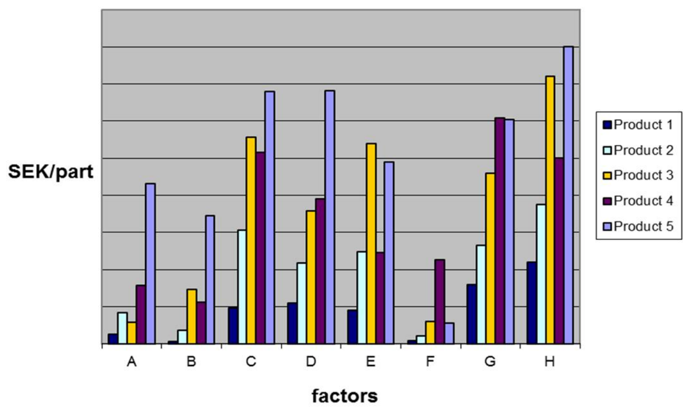

Figure 7: A comparison of the downtime cost for the five different products divided between the 8 factor groups.

6.2.2. Cost distribution between batches

The distribution of manufacturing costs was studied as a complement to the previous presentation of downtime cost. No consideration was taken to batch sizes and therefore the part cost when producing small batches will be significantly lower than those with large batches. It was found that different batches of the same product could differ widely in terms of manufacturing costs.

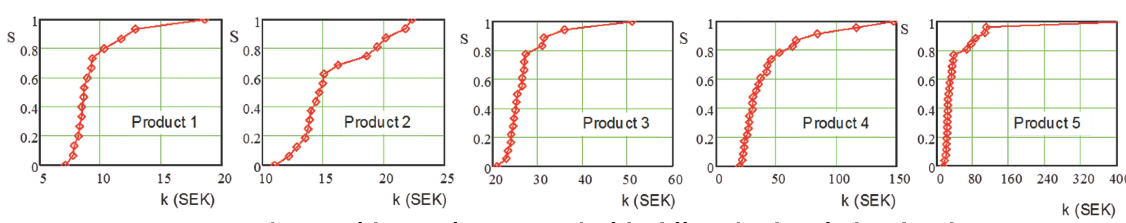

Figure 8: Distributions of the manufacturing cost k of the different batches of selected products.

The differences were significant for Products 4 and 5, the manufacturing costs per part varying between 20 and 150 SEK for Product 4 and between 15 and 460 SEK for Product 5. For most of the batches of Product 5, the manufacturing costs varied between 15 and 60 SEK per part, while the Product 4 manufacturing costs for the most part varied between 20 and 50 SEK.

6.2.3. The effects of batch size

The effects of batch size on manufacturing costs were analyzed. The results obtained with the mathematical model are shown in Figure 9A. For each product an average value to be used in the mathematical model was calculated. It was found that batches of less than 400 units in size should definitely be avoided and that batches should preferably be larger than 800 units in size. Storage cost is not taken into consideration, however.

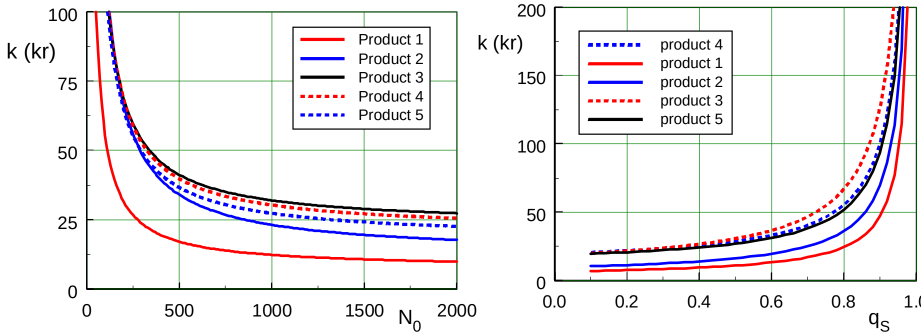

Figure 9: A: The relationship between batch size N_0 and manufacturing costs k for mean batches of the selected products. B: Production costs k shown as a function of the downtime rate q_s obtained for selected products, by economic simulations of the manufacturing process.

6.2.4. Simulation of manufacturing cost

An overview of potential savings that could be achieved by the avoidance of downtimes and target costs can be obtained through the simulation of manufacturing costs. A target value of $q_S = 0.2$ was chosen for the cost simulation. Estimated costs were compared with the costs of a mean batch of the different products. It appears that the savings in cost that can potentially be achieved vary and are greater for Products 2, 3, 4 and 5 than for Product 1.

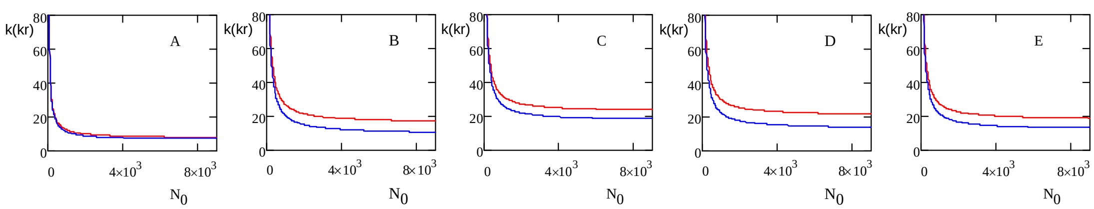

Figure 10: The Simulation of manufacturing costs per part as a function of batch size N_0 for product 1-5, the red curve corresponding to q_S for a mean batch and the blue curve corresponding to $q_S = 0.2$.

Large proportions of downtimes were found to contribute significantly to high manufacturing costs. The relationship between the proportion of downtime and the level of manufacturing costs for the different products studied is shown in Figure 9 B, where the results are based on mean values for the different batches and the use of the mathematical model. In Figure 9 B it can be seen that it is especially important that the downtime rate does not exceed 0.6, since the cost thereafter increases dramatically.

6.2.5. Comparison of OEE and Manufacturing economic efficiency

Manufacturing economic efficiency, η_E, was calculated according to equation *(6)* for each batch and for each of the five products. Figure 11 presents the distribution of the manufacturing economic efficiency value for the different batches. It can be noted that the distribution approximates a Weibull distribution. As can be seen, there is considerable variation between the different batches and between the different products. The values of Product 1 are within the range of the target value of 0.4 - 0.8, whereas the values of Products 3 and 2 are located close to the border of what is desirable.

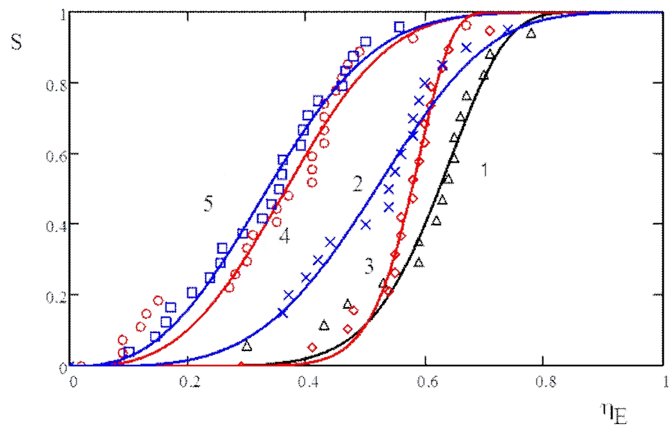

Figure 11: The distribution of the values of manufacturing economic efficiency for each of the five products. The points represent the empirically obtained efficiency values for different batches whereas the lines are approximations of the Weibull distributions.

Figure 12 indicates that there is a clear correlation between high manufacturing cost and low manufacturing economic efficiency and low values of OEE. The relationship shown here is very similar to the relationship between manufacturing costs and efficiency, and there are rather close correlations between the values of manufacturing economic efficiency and OEE calculated according to equation (5).

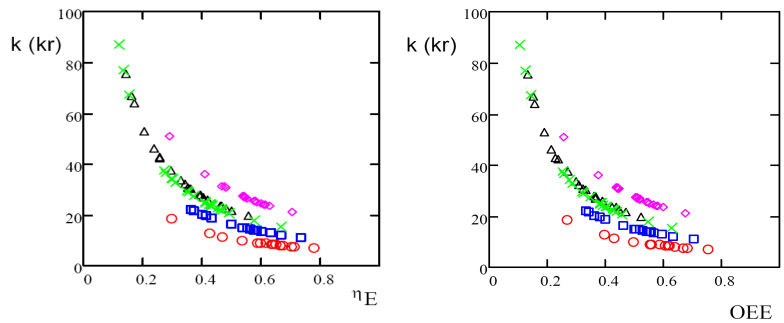

Figure 12: Production costs shown for each of the selected batches involved as a function of economic efficiency and OEE.

7. Conclusions/Discussion

The purpose of this case study was to answer the following questions:

- Are there any similarities or patterns in downtime occurring for different products in the production line, making it easier to find accurate improvement activity?
- How large is the potential for improvement for different products?
- How well does the Manufacturing economic efficiency correspond to OEE?

7.1 Similarities and Pattern

Since the production line is quite advanced, due to various production steps, the high automation level and a large variation of tools, there is a wide variety of downtime causes. As reflected in Figure 6 and later in Table 1 there are some factors that contribute more than others to the performance loses. For example problems with the peripheral equipment and inner logistics occur in the production of all of the five products. Other major contributors are factors connected to the manufacturing process. It seems however that the phenomena of downtime occur somewhat stochastically and that the problems that occur are quite product dependent.

7.2 Potential for Improvements

In Table 1, which shows the results from mean batches of each product, darker color represents the best value in each of the different categories and lighter color represents the worst. The mean values are given by the product between the individual downtime proportion q_{sx} and the actual batch size divided with the total number of unit of the part produced. In the table it is obvious that Product 1 exhibits higher performance values than the other products studied, especially regarding downtimes connected to the manufacturing process (factor group C).

Table 1: Summary of the mean results from the study for all products and batches.

	q_S	q_{SA}	q_{SB}	q_{SC}	q_{SD}	q_{SE}	q_{SF}	q_{SG}	q_{SH}	η_E	OEE
Product 1	0,33	0,02	0,01	0,05	0,06	0,05	0,01	0,08	0,11	0,62	0,58
Product 2	0,40	0,03	0,02	0,09	0,07	0,07	0,02	0,08	0,10	0,56	0,53
Product 3	0,39	0,02	0,03	0,08	0,06	0,08	0,02	0,07	0,10	0,54	0,51
Product 4	0,49	0,04	0,03	0,10	0,08	0,05	0,05	0,12	0,10	0,37	0,35
Product 5	0,53	0,06	0,05	0,10	0,10	0,07	0,02	0,09	0,12	0,36	0,33

In Table 1 the downtime proportion and the economic efficiency and OEE are reported where q_{sA} is downtime portion caused by tools, q_{sB} downtime portion caused by problems with the work piece material, q_{sC} downtime portion caused by the manufacturing process, q_{sD} downtime portion regarding personnel and organization, q_{sE} downtime portion regarding wear and maintenance, q_{sF} downtime portion caused by specific process behavior, q_{sG} downtime portion caused by problem occurring in the inner logistics or peripheral equipment, and, finally, q_{sH} is downtime portion initiated by unspecified causes.

The production methods for Product 1 are well established, which could be one explanation to the better performance values. It is therefore important that the company establish good ways of working and make personnel from the different working shifts meet and discuss different problems in the production and their solutions. The factor group with the most problems is factor group H (unknown factors). It is therefore important to identify those problems in order to be able to correct them.

In contrast with Product 1, Product 5 is a new product, still in the ramp-up phase, and a comparison between the products shows the importance of knowing the downtime causes in order to faster leave the ramp-up phase. Looking at Product 5, which is the worst product regarding performance, you can see the problems with newer products in a production line. The problems are well distributed through almost all factor groups, which indicates that the product is not well established.

The recommendation in this specific case is to focus on the problem that causes the longest downtime, because of the exponential relationship to the part cost. This recommendation is in line with the one given by Patti and Watson [17], who suggest that long, infrequent distributions have more negative impact on a product's performance than short, frequent ones. Another recommendation is to aim for larger batch sizes, especially for Products 4 and 5. There could be reason to evaluate the possibility to calculate the storage cost for certain products in order to produce larger batch sizes. Looking at the different factor groups, there are savings to be made in factor groups C, D, E, G and H.

The result gives a good understanding of the manufacturing cost allocated to production downtime. The model would describe the reality even better if scrape rate and production speed were considered. When using the model, it is most important to use correct and well-defined data, and also that the data is defined after causes and not symptoms; otherwise the result will not face the reality.

7.3 Consistency between OEE and Manufacturing economic efficiency

The company currently uses OEE as a measure of equipment efficiency. The correspondence has been shown to be good between OEE according to equation *(5)* and Manufacturing economic efficiency, and the result in the present article shows that the economic efficiency is well functioning as a corresponding method to OEE. It is important, however, that appropriate cycle times are determined so as to ensure the applicability of the results. An accurate cycle time is important here since it has a strong effect of OEE, Manufacturing economic efficiency and final manufacturing costs.

8. Acknowledgements

The authors would like to acknowledge the support provided by the Sustainable Production Initiative (SPI) and the project ProLoc, both financed by VINNOVA.

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