LUND UNIVERSITY

NEXT STEP in Cost-based Sustainable Production Development - Cases from different Production Operations

Ståhl, Jan-Eric

2012

NEXT STEP in Cost-based Sustainable Production Development – Cases from different production operations

Jan-Eric Ståhl

Division of Production and Materials Engineering, Lund University, 221 00 Lund, Sweden

jan-eric.stahl@iprod.lth.se

Keywords: NEXT STEP, Lean production, cost models, optimum automation

Abstract. This article discusses the NEXT STEP (beyond Lean production philosophy) and its relation to Sustainable Production Development. One of the most important factors affecting long-term sustainability is the degree to which resource-efficient production can be achieved. From this standpoint, Lean Production is similar to Sustainable Production. The research reported on here suggests there to be no contradictions between having an efficient production process and this process being sustainable from a long-term perspective. Various production-cost models that can be used for evaluating different development scenarios with the aim of achieving resource efficient production in a wide variety of situations are discussed. The production cost models taken up deal with the following: 1) general losses in connection with downtimes, rejection rates and set-up times, in particular, 2) the degree of utilization of a production system 3) optimization of batch size with regard to set-up times and inventory costs, 4) optimization of the manpower within a given production sector and 5) achievement of an optimum level of automation. The production cost models presented are applied to production elements of different types: machining operations, automated production lines for manufacturing sheet-metal products, and semi-manual assembly. This is done to exemplify the development steps necessary for achieving long-term sustainability in connection with different production scenarios.

Introduction

The term sustainable production is of strong interest from a global perspective. Although it is difficult to determine in a general sense when the concept of long-term sustainability began to have a marked effect within the production area, the Brundtland World Commission on Environment and Development [1] began to affect developments in this area appreciably from about 1987 onwards. In order to achieve full implementation of sustainable production principles within modern industry, it is important to consider issues of sustainability at least partly in economic terms. In cases in which an increase in sustainability does not go hand-in-hand with increased production efficiency, it would appear that society should act through legislation or through providing appropriate economic incentives. Legislation limiting the lead content of low alloy steel and of brass are examples of this. Different directions that the development of cutting processes can take so as to enable both effectiveness in the manufacture of different products and the long-term environmental sustainability of the manufacturing processes involved to be increased are shown in Figure 1.

Today Lean Production is a widely accepted production philosophy, one made famous by Womack et al. [2], in particular. It has also been discussed in considerable detail by Voss et al. [3], Hay [4] and Monden [5], for example. Although the articles referred to differ very much in the specific matters taken up, they have much in common, one common element being the importance placed on continual improvement, as achieved, for example, through a company's making use of the Incremental Production Improvement method.

The Lean Production philosophy has a variety of elements that attention is directed at, such as effective use of resources, visualization of problems through use of *key performance indicators* [KPI],

as well as the involvement, active participation and motivation of all of a company's employees. The effective use of resources also plays an important role in achieving *sustainable and efficient production*. The author [6] has presented, as a possible continuation of developments in this area, after full implementation of a Lean Production philosophy has been achieved, what he terms the NEXT STEP beyond the Lean Production philosophy. One aspect of the NEXT STEP philosophy is to use economic indicators as a basis for decisions. A method for this proposed, Incremental Production Development [6, 18], is discussed more thoroughly in the next section. It involves allowing operators to conduct each of the separate steps of the developmental process that is aimed at. These become part of the improvement process, a reduction in waste during machining also being achieved. The involvement of all operators in this way can result in an improvement in their knowledge in a manner that increases the likelihood that they will be able sometime in the future to help improve the production process, doing so on the basis of their own ideas and the initiatives they take. Use of an appropriate model for calculating changes in part costs as a function of changes in the process parameters involved can also help create the *clear link between technological and economic considerations* that the NEXT STEP philosophy aims to bring about.
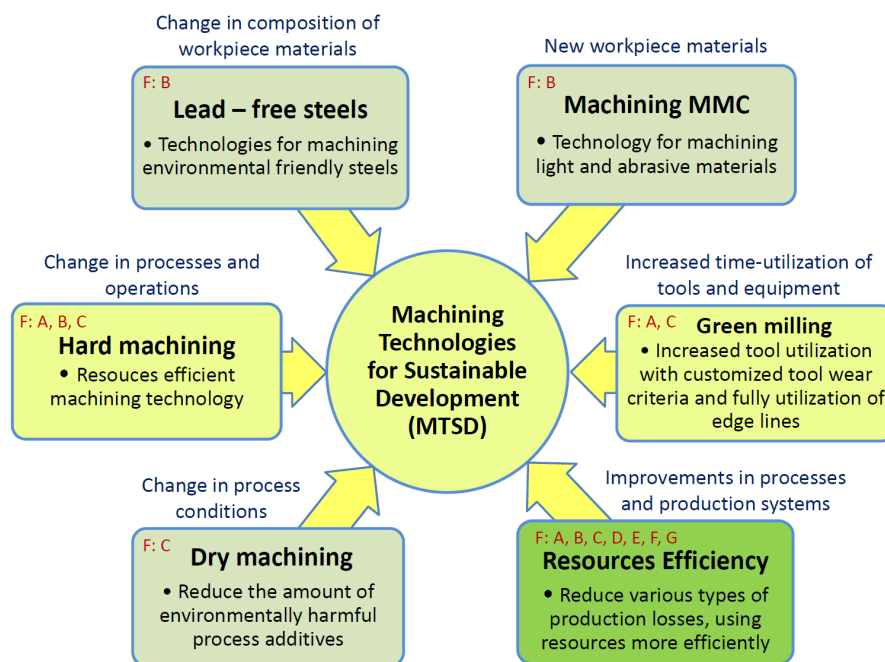

Fig. 1 *Examples of research projects aimed at developing long-range sustainable products, together with the production technology required and its effect on different factor groups (e.g. F: A and C; see also Figure 2), [1].*

Generic production cost model

Although many different cost models have been described in the literature [7, 8], few of these are sufficiently detailed to allow one to assess, compute or simulate in a precise way part costs in relation to various technical or organizational parameters. Models to be used for providing decision support in product development need to include a description of the losses and the improvements that a developoment of some type can be expected to result in. Models of this sort that are of special interest have been presented in particular by H. Yamashina and T. Kubo [9] and N. Chiadamrong [10]. The present author [6, 7, 11, 12] has presented a cost model based on Eq. 1, one that includes the parameters of central interest along with variables that affect part costs, these involving such loss terms as *rejects* (q_Q), *downtimes* (q_S), *rate losses* (q_P) and *material waste* (q_B).

$$k = \frac{K_A}{N_0}\left[\frac{1}{n_{pA}}\right]_a + \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)\cdot(1-q_B)}\right]_b + \frac{k_{CP}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right]_{c1} +$$

$$\frac{k_{CS}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\cdot\frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right]_{c2} + \qquad \text{Eq. (1)}$$

$$\frac{n_{op}\cdot k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right]_d +$$

$$\frac{1}{N_0}(K_{AUH} + K_{CUH} + K_{GUH})_e + \frac{1}{N_0}(K_{HL} + K_{Tno} + K_{RW})_h$$

Definitions of the parameters and variables included in this cost model are presented in [6]. The parameters k_{CP} and k_{CS} are equipment costs per hour for production and for downtimes, respectively, for a given machine or production line. The product $n_{op}\cdot k_D$ represents salary costs per hour for production carried out there, where n_{op} is the number of operators involved and k_D is the average cost per hour for each operator. The parameter U_{RP}, describing the degree of utilization of the production system, is used in adding additional time to that involved in manufacturing a specific batch, its being added to a degree corresponding to the ratio of the total free capacity (overcapacity) to the total payed production time. This results in a cost increase associated with the use of this free capacity corresponding to the extra time added for manufacturing the batch in question (T_{pb}). It can be advantageous to compute the loss terms q_Q, q_B, q_S and q_P or t_0 here using data from a PPM (Production Performance Matrix) such as that shown in Figure 2. A PPM is also used to clarify the causes of a disturbance or a loss. The data a PPM contains can be collected either automatically or manually. The length of the downtimes and the operational times can be registered by a computer-based data-collection system, whereas the causes of disturbances in terms of factor groups or individual factors usually need to be specified by the machine operator.

Factor groups A-G and H		Quality parameters $Q_1, Q_2, ... Q_n$	Downtime parameters $S_1, S_2, ... S_n$	Prod. rate parameters $P_1, P_2, ... P_n$	Environm. and recycling $ER_1, ER_2 .. ER_n$	Σ Factor
A.	Tool and tooling systems					ǁ
B.	Workpiece materials					ǁ
C.	Process and process data	Sustainable Production Development				ǁ
D.	Personnel and organization					ǁ
E.	Maintenance and service					ǁ
F.	Special factors					ǁ
G.	Peripheral equipment					ǁ
H.	Unknown factors					ǁ
Σ Result parameters		=	=	=	=	ǁ

Fig. 2 The basic structure of a PPM (Production Performance Matrix) [1].

The interaction between systematic production analysis, computation of the indata for the cost equation to be employed, simulation of the part costs for different developmental scenarios that are seen as possible, and the formulation and carrying out of different production-related developmental projects (P1-P4) are illustrated in Figure 3.
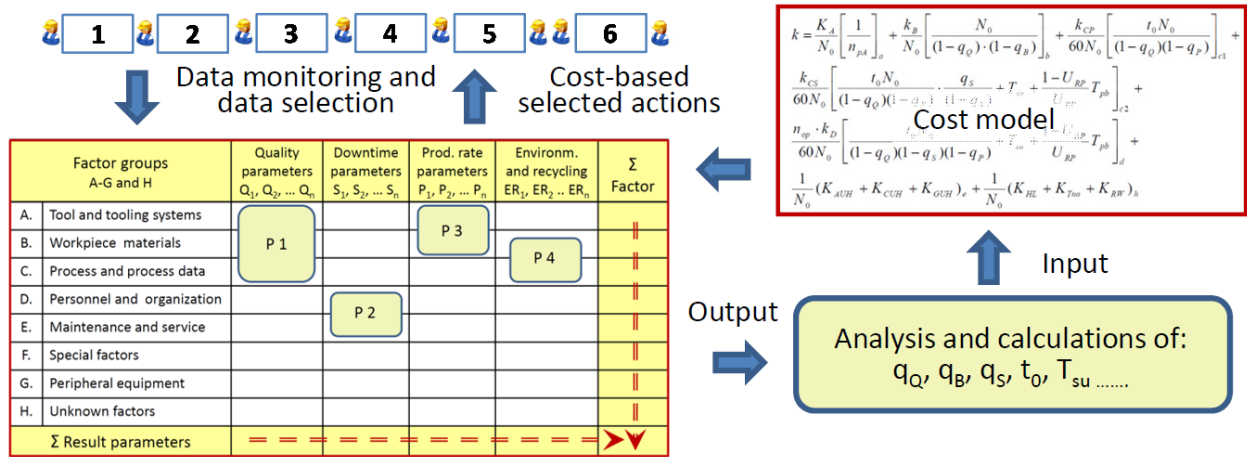
Fig. 3 *Collection of the production data for a PPM (Production Performance Matrix), computation of the indata for the cost model, analysis of the developmental scenarios with the help of the cost model, and cost selection of the developmental measures to be employed (Project: P1- P4).*

Figure 4 exemplifies use of the cost model for studying part costs k as a function of batch size N_0, downtime rate q_S and cycle time t_0 for each of 2 different salary levels k_D, those of 50 and of 200 SEK/h, respectively. In examining the diagram in Figure 4, one can note that, despite the large difference in salary costs between the two, the same part-cost level can be obtained for both if one makes appropriate changes in the parameters N_0, q_S and t_0 in making adequate use of different advances in production techniques that have taken place.
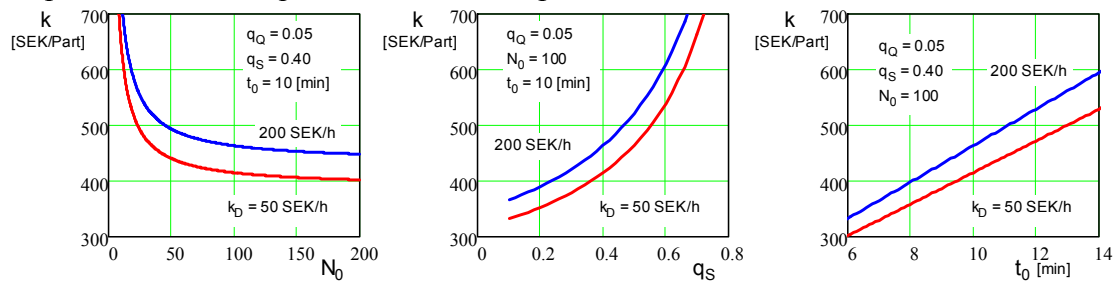

Fig. 4 *Examples of computed part costs k expressed in terms of SEK/part, shown as a function of series length N_0, downtime rate q_S and cycle time t_0 in minutes, for two different salary levels, k_D = 50 SEK/h (the lower red curve) and k_D = 200 SEK/h (the upper blue curve).*

The cost model here can be developed further for use under more complex conditions, as exemplified in a number of cases presented below.

Adaptation of the production cost model to selected cases

Selected cases of the following character will be taken up below:

➢ Production system utilization based up on a characteristic part.
➢ Setup times and batch size optimization.
➢ Manpower optimization.
➢ Optimum automation level.

Increasing the utilization of a particular production system in the manufacture of a given part reduces the part costs involved through the investment costs being distributed over a larger number of production hours than before. The level of utilization indicates the extent to which a production time of given length, the costs of which are already determined in advance, is made use of. If one fails to utilize all of the capacity being paid for, this results in an overcapacity, also referred to as free capacity. From a production standpoint, this can be regarded as representing a downtime, even if the equipment is functioning just as it should. A certain amount of free capacity in the manufacturing system is often desirable nevertheless, through its enabling a smooth transition from one

batch to another to take place. A level of utilization U_{RP} of about 96 – 97 % is thus often advantageous.

A particular level of yearly market demand for a given part (MD) requires, for the manufacturing system involved, some specific number of production hours, which can be computed by use of Equation 2. The ratio of the demand for the part MD to the average batch size N_0 gives the number of switch-overs that would take place. Each of the parameters employed in the equation represents the average value of it during a one-year period.

$$T_{pb,tot} = T_{su} \cdot \frac{MD}{N_0} + \frac{t_0 \cdot MD}{(1-q_Q)(1-q_S)(1-q_P)} \qquad \text{Eq. (2)}$$

In selecting a planned production time (T_{plan}) for a particular production line or production section in which some family of parts (j) is manufactured, it can sometimes be practical to compute the costs of a characteristic part (c). A characteristic part is a fictitious part seen as representative of all parts produced in terms of the demand MD, setup time T_{su}, cycle time t_0, etc. involved. The characteristic data this requires is computed on the basis of average or weighted average values by use of Equation 3-6.

$$t_{0c} = \frac{\sum_{j=1}^{n_{part}} MD_j \cdot t_{0,j}}{\sum_{j=1}^{n_{part}} MD_j} \qquad T_{su,c} = \frac{\sum_{j=1}^{n_{part}} T_{su,j} \cdot \frac{MD_j}{N_{0,j}}}{\sum_{j=1}^{n_{part}} \frac{MD_j}{N_{0,j}}} \qquad N_{0,c} = \frac{\sum_{j=1}^{n_{part}} N_{0,j}}{n_{part}} \qquad n_{b,tot} = \frac{\sum_{j=1}^{n_{part}} MD_j}{N_{0,c}} \qquad \text{Eq. (3-6)}$$

The production time required $T_{pb,ctot}$ for manufacturing a family of details consisting of n_{part} different details can be computed using Equation 7.

$$T_{plan} \geq T_{pb,ctot} = T_{su,c} \cdot n_{b,tot} + \frac{t_{0,c} \cdot MD_c \cdot n_{part}}{(1-q_{Q,c})(1-q_{S,c})(1-q_{P,c})} \approx \sum_{j=1}^{n_{part}} \frac{MD_j \cdot T_{su,j}}{N_{0,j}} + \sum_{j=1}^{n_{part}} \frac{t_{0,j} \cdot MD_j}{(1-q_{Q,j})(1-q_{S,j})(1-q_{P,j})} \qquad \text{Eq. (7)}$$

The production capacity PC_c taken up can be computed as

$$PC_c = \frac{(T_{plan} - T_{su,c} \cdot n_{b,tot})(1-q_{Q,c})(1-q_{S,c})(1-q_{P,c})}{t_{0,c}} \qquad \text{Eq. (8)}$$

The degree of utilization U_{RP} of the manufacturing facilities this represents can be computed using Equation 9. The selection of T_{plan} here usually takes place stepwise in the form of computing the number of complete shifts (n) times the number of hours per year and per shift that are involved ($n \cdot h_{year}$).

$$U_{RP} = \frac{T_{pb,ctot}}{T_{plan}} \qquad \text{Eq. (9)}$$

Illustrations of the relationships that can exist between the demand MD_c for a characteristic product, the characteristic batch size $N_{0,c}$ selected, and the costs of manufacturing a part are presented in Figure 5.
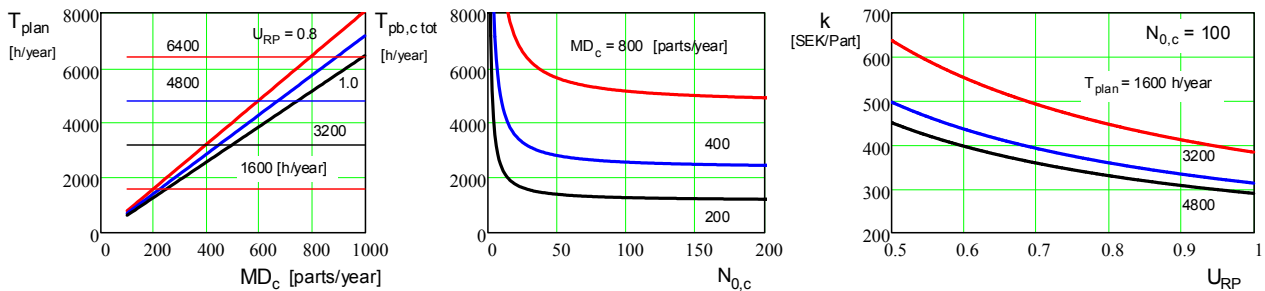

Fig.5 *Illustrations of the relationships found between the lowest value possible for the planned production time T_{plan} and the demand MD_c for the part or product in question, for a degree of utilization of the manufacturing facilities of U_{RP} = 0.8, 0.9 and 1.0, respectively (left); as well as of the shortest production time $T_{pb,ctot}$ required for a given product or part, as a function of the batch size $N_{0,c}$ used in manufacturing it, in the case of a demand for it of MD_c = 200, 400 and 800 products or parts per year, respectively (center); and of the costs per product or part as a function of the*

degree of utilization U_{RP} of the manufacturing facilities, the planned production time T_{plan} serving as a parameter (right), [12].

In the case of strictly *customer-steered manufacturing*, the batch size N_0 is determined mainly by the level of demand and the times at which orders are taken and delivery takes place. When many of the orders during a given year are of contractual character, however, one may well decide to combine several batches and, in connection with this, to manufacture products that are to be kept in stock. Doing so is a contradiction of the well-established principle of Lean Production (based on a Just-in-Time approach), in terms of which one aims at achieving highly secure delivery of products by use of robust production technology and not by way of retaining products in stock. The *optimization of product storage size* (EOQ, Economic Order Quantity) has been dealt with in considerable detail in research [16, 17]. The majority of studies in the area that have been reported on are based on comprehensive macroeconomic models. These models, however, do not take account of measures of production losses such as rejection rates q_Q, downtime rates q_S, and the like. None of the models studied are concerned with the balance between batch size and the size of the lots that are delivered to the consumer. There are many factors that are a function of batch size N_0 which affect part costs. The most important factors affecting part costs k are shown in Table 1. The table indicates the effects that an increase in batch size N_0 has on part costs.

Table 1 *Examples of important factors that affect batch size N_0 in relation to costs per detail k.*

Parameter		Designation	− k	+ k	Comments	Model
Setup time per part	-	T_{su}/part		x	Reduction in downtime duration per part	$k_{su} = k_{su}(N_0, T_{su})$
Storage costs	+		x		Increase in administrative, rent and utility costs	$k_{SH} = k_{SH}(N_0, T_{su})$
Bound capital	+	p	x		Increased costs for bound capital	$k_{Cap} = k_{Cap}(N_0,)$
Downtime rate	-	q_S		x	General decrease in downtimes as N_0 increases	$k_{qS} = k_{qS}(N_0)$
Rejection rate	-	q_Q		x	General reduction in rejections as N_0 increases	$k_{qQ} = k_{qQ}(N_0)$

An increase in batch size N_0 results in the value-creating setup times T_{su} being distributed over a larger number of parts. The costs per part of keeping parts in stock can be expected to increase linearly with an increase in storage space (or volume) and with the duration of keeping a part in stock. A certain set cost per detail in this respect is difficult to avoid. In the example presented below, costs for bound capital are assumed to be linear in character, as based on an annual interest factor p. A factor, the effect of which on the selection of a particular batch size is often underestimated, is that of the *dynamic effects* that develop in interactions between batch size N_0, on the one hand, and both downtimes q_S and rejections q_Q, on the other. In more complex and automated manufacturing systems the first period of time after start of production can be considerable, at the same time as a large part of the rejections take place during that period, a tendency of this sort being particularly accentuated in the case of new parts. Figure 6 exemplifies how the running average for downtime rates q_S develops, in accordance with the number of parts N produced thus far, in each of 4 different batches. The continuous curve (black) is a mathematically adjusted one pertaining to the 4 batches involved. The finding that has been reported of the downtime rate's decreasing as the number of parts produced increases is representative for an entire product family, i.e. for all products being manufactured in the production line in question. Certain parts for which the downtime rate q_S increases after about 6000 of them have been produced (cf. Fig. 6) represent an exception to this [13]. Behavior of this sort can be explained primarily in terms of the inadequate functioning of various tools and the need of maintenance.
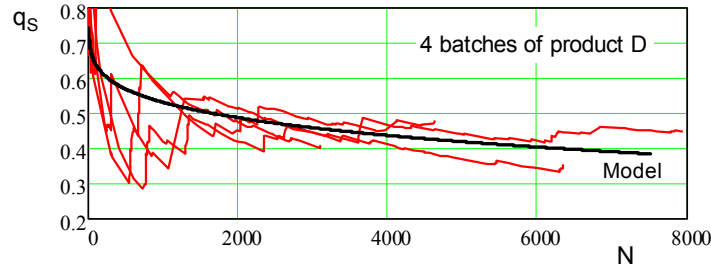
Fig. 6 *Examples of how the downtime rate q_S develops over time in the case of 4 batches of Product D and the mathematically adjusted curve obtained, $q_S = q_S(N)$, [13].*

An *optimal batch size N_{0M}* with respect to part costs can be obtained by complementing the model for part costs by use of Equation 1. The costs per part k_{N0} associated with the batch size that is manufactured, $N_{0M}=N_0 \cdot f_{N0}$, can be computed approximately by use of Equation 10, as exemplified in Figure 7 (left). Figure 7 is based on Equations 10-14 below.

$$k_{N0}(N_{0M}) = k_{su}(N_{0M}) + k_{qS}(N_{0M}) + k_{SH}(N_{0M}) + k_{cap}(N_{0M}), \quad N_{0M} = N_0 \cdot f_{N0} \tag{Eq. (10)}$$

$$k_{su} = \frac{(k_{CS} + k_D) \cdot T_{su}}{N_0 \cdot f_{N0}} \tag{Eq. (11)}$$

$$k_{qS} = \frac{k_{CS} + k_D}{N_0 \cdot f_{N0}} \left[\frac{t_0 \cdot N_0 \cdot f_{N0}}{(1 - q_Q)} \cdot \frac{q_S}{(1 - q_S)} \right] \qquad q_S(N_0 \cdot f_{N0}) = q_{S0} - q_{S1}(N_0 \cdot f_{N0})^{qS2} \tag{Eq. (12)}$$

$$k_{SH} = \frac{k_{SH0} \cdot \dfrac{MD}{N_0 \cdot f_{N0}} + k_{SH1} \cdot N_0 \cdot (f_{N0} - 1)}{MD} \tag{Eq. (13)}$$

$$k_{cap} = k \cdot p \cdot \frac{N_0 \cdot (f_{N0} - 1)}{2 \cdot MD} \tag{Eq. (14)}$$

N_0 is the number of parts sought by the customer in each order that is placed. The model employed here is based on N_0 parts being delivered to the customer and $N_0 \cdot (f_{N0}-1)/2$ parts remaining in stock for the year as a whole. The costs of the bound capital involved are based on the interest costs that apply, which can be said to represent the risk of the non-salability of the product or the failure of the order amount expected to materialize.

The minimum cost level k_{N0} can be determined by setting the derivative for the batch size manufactured ($N_{0M}=N_0 \cdot f_{N0}$) equal to 0. An example of obtaining the part costs is presented in Figure 7 (right). An example of the part costs, shown as a function of f_{N0} (where $N_0=400$), and of the size of the series produced, $N_{0M}=N_0 \cdot f_{N0}$, can be seen in Figure 8.
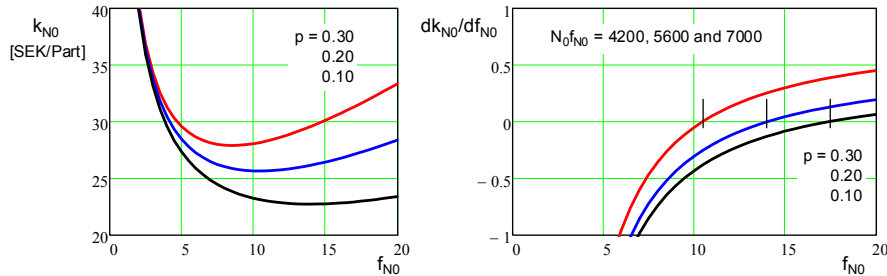

Fig. 7 *The portion of the part costs k_{N0} associated with the batch size being manufactured $N_0 f_{N0}$ (left) and its derivative with respect to f_{N0} for interest factors of 0.10, 0.20 and 0.30 (right), for a batch size by the customer of $N_0 = 400$ parts and a total number of parts purchased per year of $MD = 8000$.*
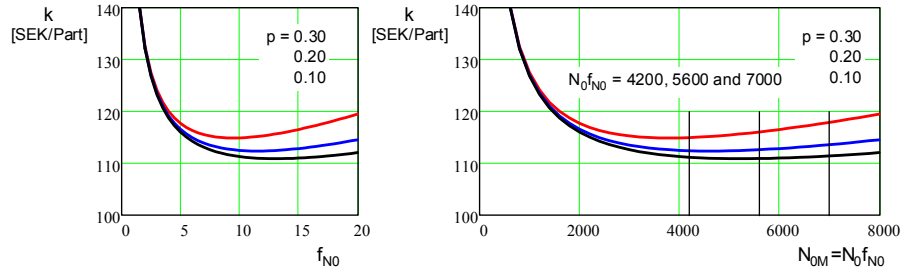
Fig. 8 *Examples of part costs k shown as a function of f_{N0} (N_0=400) and of part costs shown as a function of the size of the series manufactured, N_{0M}=$N_0 \cdot f_{N0}$, the optimal values being indicated.*

The cost model shown in Equation 1 can also be used to determine the *optimal number of operators* for a given production step in terms of part costs [14]. The minimum part cost level can be obtained by expressing the cycle time t_0 as a function of the number of operators n_{op} and inserting into the equation the total salary costs involved, $K_D = n_{op} \cdot k_D$. The assembly costs $k(n_{op})$ can be obtained, by use of the equation, as a function of the number of operators n_{op}, batch size N_0 serving as a parameter, as exemplified in Figure 9. The lowest level of assembly costs for the number of operators involved and for the batch size selected is obtained when $dk/dn_{op} = 0$, as can be seen in Figure 9 (right).
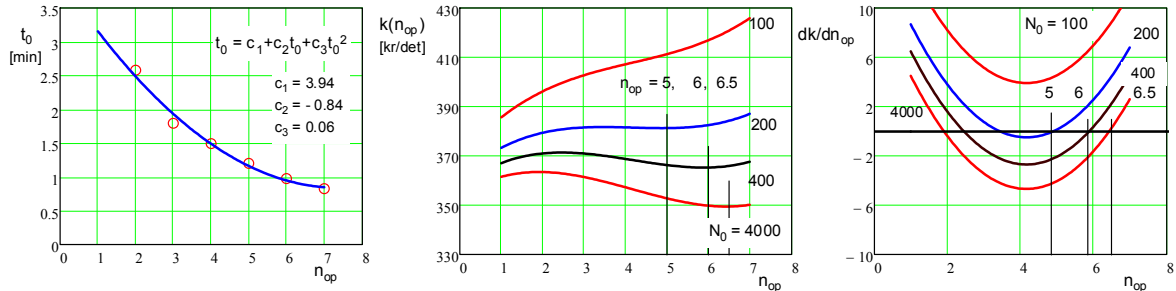

Fig. 9 *At the left an example of the assembly time t_0 for a given product, shown as a function of the number of operators n_{op}, in the middle the assembly costs being shown as a function of the number of operators, and at the right the assembly cost derivative as a function of the number of operators.*

The cost model presented in Equation 1 can also be used to determine the *optimal automation level* (x_{af}) in a given production step in terms of part costs. The term "Level of Automation" can be defined and described in a number of ways [15]. It can be described indirectly in terms of the relationship between the equipment costs per hour and the salary costs per hour, as shown in Equation 15.

$$x_{af} = \frac{k_{CP}}{k_{CP} + K_D} = \frac{k_{CP}}{k_{CP} + k_D \cdot n_{op}}$$

Eq. (15)

The ratio x_{af} is termed the automation factor. It varies in value between 0 och 1.0. Production when $x_{af} = 0$ is entirely manual, the equipment costs being negligible, whereas when $x_{af} = 1.0$, it is salary costs which are negligible, production being completely unmanned. The automation factor x_{af} can be used to characterize different production systems in terms of cost. Introducing the automation factor x_{af} in Equation 1 as a help variable allows different production systems and how viable they are to be compared.
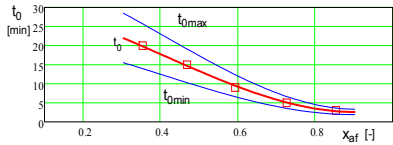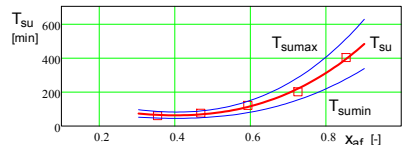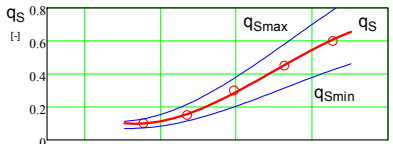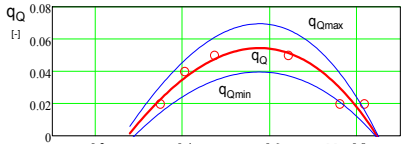
In order to be able to compare different production systems, it is necessary that the performance of each of them be known, unless reasonable assumptions regarding this based on experience or on observations can be made. The following formalized steps can be taken as a basis for inserting the automation facto xaf into computations:

1. Configure a variety of different alternative production systems and compute for each of these the total salary costs per hour K_D and the total equipment cost per hour k_{CP}, together with the automation factor x_{af} in question.

2. For each of these production systems, compute or determine in some other way the numerical value and the variance of each of the production parameters of interest contained in Equation 1.

3. Plot the numerical relationship between these production parameters and the automation factor x_{af} in the manner exemplified in Table 2.

4. Determine the analytical relationships of relevance found between these production parameters and the automation factor x_{af}.

5. Insert the analytical relationships revealed in point 4 into Equation 1, which leads to the part costs being shown as a function of the automation factor x_{af} together with such factors as the batch size N_0, all paid production time per year that is planned T_{plan}, the technical lifetime of the system n, and capital costs p per year.

6. Determine the minimum of the part costs through derivation on the basis of the automation factor x_{af}, using the modified Equation 1.

Analyze the different production systems by varying the parameters involved and studying the results in each case.

Table 2 *Examples of different parameters (cycle time t_0, downtimes T_{su}, downtime rate q_S and rejection rate q_Q) shown as a function of the automation factor x_{af}, the circles and the red lines representing the data and the mathematically adjusted results, respectively, the blue lines representing the assumed variance of the data.*

Parameters	Data and adjusted functions	Parameters	Data and adjusted functions
Nominal cycle time, t_0 $t_0(x_{af}) = m_0 + m_1 \cdot x_{af}$ $+ m_2 \cdot x_{af}^2 + m_3 \cdot x_{af}^3$		Setup time, T_{su} $T_{su}(x_{af}) = p_0 + p_1 \cdot x_{af}$ $+ p_2 \cdot x_{af}^2 + p_3 \cdot x_{af}^3$	
Downtime ratio, q_S $q_S(x_{af}) = r_0 + r_1 \cdot x_{af}$ $+ r_2 \cdot x_{af}^2 + r_3 \cdot x_{af}^3$		Rejection ratio, q_Q $q_Q(x_{af}) = s_0 + s_1 \cdot x_{af}$ $+ s_2 \cdot x_{af}^2 + s_3 \cdot x_{af}^3$	

After inserting the relationship obtained into Equation 1, as exemplified in Table 2, one is able to compute the part costs $k(x_{af})$ as a function of the automation factor x_{af}, as well as of other variables. Doing this enables all of the parameters considered to be shown as a function of the automation factor x_{af}. This is shown below in a somewhat simplified cost context with use of the modified Equation 1. The lowest part costs as determined by use of the automation factor x_{af} can be computed by deriving the part costs and finding the value of the automation factor x_{af} for which the cost derivative is found, by use of Equation 16, to be zero. At the same time, one should be clear regarding the fact that the cost equation provides either a maximum or a minimum value.

$$\frac{d}{dx_{af}} k(x_{af}) = 0$$

Eq. (16)

Figure 10 exemplifies how the part costs can vary as a function of the automation factor x_{af} for batches of differing size, here those of $N_0 = 100, 200, 10^3$ and 10^4. The diagram there also illustrates the importance of using the proper indata in the cost model. In the case considered there, the variation in the diagram illustrates the difference between use of the maximal and the minimal level for the indata, in line with the differences shown in Table 2.

In the example reported, 6 different configured production systems, A-F, are included. The automation factor x_{af} varies there from 0.35 to 0.82. In Figure 11, the computed production capacity PC, as obtained for each of the systems in accordance with Eq. 8, is shown in terms of the number of thousands of parts produced per year. In the present case study, the maximal production capacity PC and the lowest part costs are not found at one and the same value for the automation factor x_{af}.
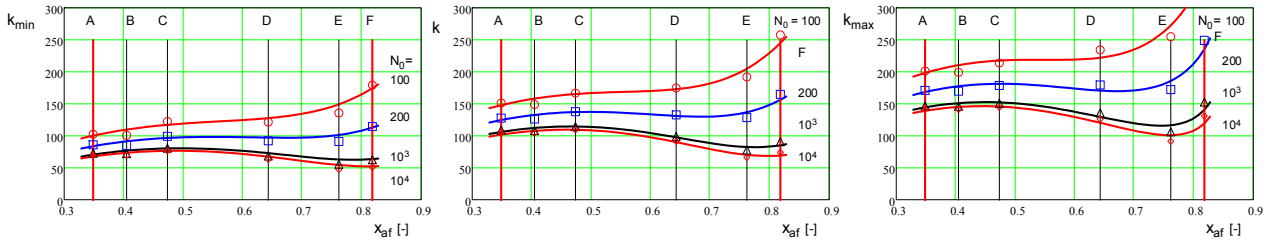
Fig. 10 *Part costs k_{min}, k and k_{max} shown as a function of the automation factor x_{af} for each of the production systems A-F for different batch sizes N_0.*
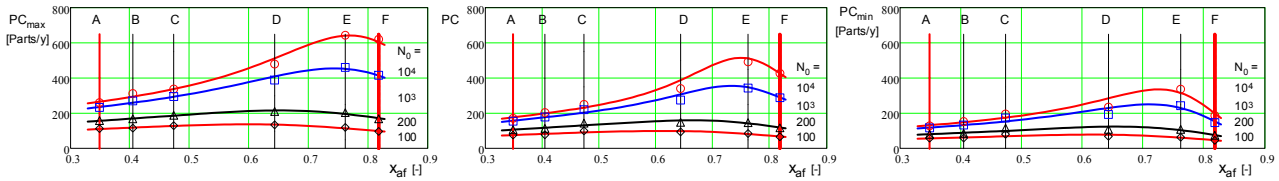

Fig. 11 *The production capacity PC_{max}, PC and PC_{min} in terms of the number of 10^3 parts produced per year, shown as a function of the automation factor x_{af} for different batch sizes for each of the production systems A-F for different batch sizes N_0.*

Discussion

A generic model for describing part costs in discrete product manufacture was presented by the author earlier [6, 7, 11]. It deals in part with how losses of different types, in terms of rejection rates q_Q, downtime rates q_S and cycle times t_0, for example, contribute to part costs as a whole. In the present study, a further development of the model, adapting it to questions of how to optimize the production system and how to select as adequate a production system as possible in light of the needs and conditions at hand, was presented.

An important factor affecting part costs is how adequately one utilizes a given production system. An increased *degree of utilization* reduces equipment costs per part. For the needs that a given yearly order volume (MD) represents to be met, a certain number of planned hours of production time are required. The cost model in its present version describes the economic consequences of failing to reach the level of planned production time needed in order to satisfy the demand that exist for a given part or family of parts. To facilitate planning in this regard, particularly in connection with the planning involved in creating a new factory unit, the term *characteristic part* was introduced, defined as denoting all of the parts belonging to a particular product family that can be manufactured in a given production line. Use of the characteristic part concept can simplify comprehensive planning needed when pronounced fluctuations in the market occur.

Certain *assembly operations*, for example, are highly suitable for a *flexible volume manufacturing* approach being employed, provided the cycle time can vary with the number of operators involved. The lowest costs possible for the manufacture of some part, with use of a given number of operators and a particular batch size, can be achieved then if account is taken of the relationship between the cycle time and the number of operators engaged in the work at hand. The number of operators that results in the part costs being kept at a minimum can be determined on the basis of results of a standard procedure used for deriving part costs. A matter not taken up in the present article is how costs based on a variety of different factors can best be determined. For any given level of demand, the minimum part costs possible for the number of operators involved and for the production time which is aimed at can be sought. An optimization strategy of this sort is of genuine interest if the losses that develop increase with an increase in the number of operators, at the same time as the set costs for equipment represent the major cost consideration.

In the present study, a simplified economic model for determining the *optimal batch size* is presented. A minimum level is sought for the costs of downtimes, for losses during initial preparations and trials, for costs of keeping in stock parts that have been manufactured, and for the costs of

bound capital. The model has been limited thus far to taking account of either constant or periodic demands for a part, or a characteristic part, having a given yearly volume of production. The batch size demanded by customers (the numbers of the parts in question sold) is denoted as N_0, and the manufactured batch size as $N_0 \cdot f_{N0}$, where N_0 is delivered to customers and $N_0 \cdot (f_{N0}-1)$ represents the parts kept in stock. In terms of the standard approach that is adopted here, a minimum cost for the batch factor f_{N0} is sought. Sensitivity analyses indicate that the manufacture of large batches keeps manufacturing costs at a minimum, its thus often being profitable to manufacture parts that are to be put in stock, even if producing large batches of them makes the level of interest to be paid high. It is important to point out that decisions based on a model of this sort contradict a philosophy of *Lean Production* since they involve the manufacture of parts that are to be kept in stock. The motive in producing parts that are to be kept in stock is not to avoid the high costs of startup times and setup times this can involve, but rather to improve manufacturing technology and profitability. The model reported on here can also be used for determining the profits that a reduction in startup costs and setup costs can provide. In addition, at some stage of development a manufacturing philosophy based on the *just in time* principle should be superseded by the making of pragmatic and realistic decisions that can lead to a more optimal form of production being established, one that can result in an increase in the amounts of different parts being kept in stock. This is done not with the aim, at the same time, of concealing possible problems connected with an increase in the numbers of a given part kept in stock, but rather with the aim of dealing effectively with certain problems in need of being solved that can have marked financial implications.

The question of the production system to be decided upon is a strategic one. For many years the question of what an *optimal level of automation* is has been discussed. In the present study an *automation factor* x_{af} allowing the relationship between equipment costs and personnel costs to be determined is presented. It enables different manufacturing systems to be compared in terms of distribution of costs. Expressing different production parameters of a manufacturing system, such as cycle time and setup time, as a function of the automation factor makes it possible determine the minimum costs involved as a function of batch size and annual demand. Selecting the production system to be employed and estimating the annual demand for the product in question can also provide an indication of where the manufacturing system should best be located. A certain limitation in use of the automation factor is that it can vary in size, depending upon the salary level in the region in question. In many cases, however, the equipment costs are more unvarying in character than salary levels are. The model developed provides the possibility of simulating the part costs under a wide variety of conditions.

Cost models describing the effects different factors and conditions can have on manufacturing processes can be expected to increase in importance, particularly through their providing *decision support* in connection with developmental work and questions of where best to place various manufacturing facilities. The use of detailed cost models places strong demands on the competence of personnel involved in collecting relevant indata. Limitations in the availability of the indata that use of the present model and of other models in this area limits the industrial application and implementation of them.

References

[1]   J.-E. Ståhl, Metal Cutting – Theories and models. Division of Production and Materials Engineering, Lund University in cooperation with Seco Tools, Textbook, 2012.

[2]   J. Womack, D. Jones, D. Roos, The machine that changed the world, First Harper Perennial, 1990.

[3] C. Voss, D. Clutterbuck, Just-in-time, A Global status report, IFS Publications/ Springer-Verlag, 1989.

[4] E. J. Hay, Just-in-time breakthrough, John Wiley & Sons Inc., 1988.

[5] Y. Monden, Toyota production system, An integrated approach to just-in-time, Second edition, Chapman & Hall, 1989.

[6] J.-E. Ståhl, The development of NEXT STEP beyond Lean Production, Proceedings of ICA3M 2011, Shenzhen, China (2011).

[7] Jönsson M., Andersson C., Ståhl J-E. (2008) Implementation of an Economic Model to Simulate Manufacturing Costs, The 41st CIRP Conference on Manufacturing Systems, Tokyo, Japan.

[8] Jönsson, M., (2012) Cost-conscious manufacturing – Models and methods for analyzing present and future performance from a cost perspective, PhD thesis LUTMDN(TMMV-1063)/1-85(2012), Division of Production and Materials Engineering, Lund University, Lund.

[9] Yamashina H., Kubo T. (2002) Manufacturing cost deployment, Int. Prod. Res. No. 16, pp. 4077-4091.

[10] Chiadamrong N. (2003) The development of an economic quality cost model, TQM & Business excellence, Vol. 14, No. 9 pp. 999-1014.

[11] Ståhl J-E., Andersson C., Jönsson M (2007), A BASIC ECONOMIC MODEL FOR JUDGING PRODUCTION DEVELOPMENT, Proceedings of the 1st International Swedish Production Symposium, Göteborg.

[12] Stål C., Ståhl J.-E., Gabrielson P., Andersson C. Defining a characteristic product in a certain production line, submitted to 5th International Swedish Production Symposium, Linköping 2012.

[13] Stål C., Ståhl J.-E., Gabrielson P., Andersson C. Cost-Based Optimum Bach Size in Discrete Part Manufacturing, submitted to 5th International Swedish Production Symposium, Linköping 2012.

[14] Jönsson, M., Andersson, C., Ståhl, J.E. (2011). Relations between Volume Flexibility and Part Cost in Assembly Lines. In: 20th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM), San Francisco, USA, 2010-07-10. Pergamon-Elsevier.

[15] Fasth Å. Stahre J. Dencker K. (2008) Measuring and analyzing Levels of Automation in an assembly system, Proceedings of CIRP08, Manufacturing Systems and Technologies for the New Frontier, 41st CIRP Conference on Manufacturing Systems, May 26-28, Tokyo, Japan.

[16] Erlenkotter D. Ford Whitman Harris and the Economic Order Quantity Model, Operations Research, Vol. 38, No. 6 (Nov. – Dec. 1990), pp. 937-946.

[17] Cheng T. C. E. An economic order quantity model with demand-dependent unit cost, European Journal of Operational Research 40 (1989) 252-256 North-Holland.

[18] Schultheiss, F., Jönsson, M., Lundqvist, B. & Ståhl, J.E. (2011). Cost Optimization by Incremental Production Improvements of Metal Cutting Operations. In: The 4th International Swedish Production Symposium, Lund, Sweden, 2011-05-03/2011-05-05. Ståhl, J.E. ed. The Swedish Production Academy. 540-547.