The development of NEXT STEP beyond Lean Production - The link between technology and economics with focus on sustainable developments

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Abstract. The paper provides a brief presentation of different production philosophies and their characteristics. How the one builds upon the other, and how those characteristics considered to be positive and of strong current interest are taken advantage of by developments underway in any given period are examined. Developmental trends that are evolving (NEXT STEP) or that can serve to complement the Lean production philosophy which is dominant today, are taken up. A detailed cost model that can be used to assess different technological production development scenarios is also introduced.

INTRODUCTION

During the last 200 years, industrial production has developed parallel to the development of society in general. A close relationship exists between technological developments and the development both of new patterns of living and of industrial structure and organization. Industrial organization is often viewed, in fact, as a kind of mirror image of society [1]. The tact at which production technology has developed has varied in different parts of the world and in different periods in history. The speed of its development today is accelerating, particularly in such developing countries as China and Brazil. This is closely linked with the rapid spread and development of information technology. As Tseng [2] has pointed out, much speaks for the speed of expansion of industrial production in the world soon becoming as great as it was during the industrial revolution, i.e. before about 1850; see Figure 1.

At the end of the 1800s, industrial activity began increasing appreciably compared to what it had been. The first automobiles were developed and produced by skillful craftsmen in different parts of Europe and the US. Producing them by hand in this way required considerable resources in terms of personnel, making the costs per manufactured vehicle rather high.

The majority of the leading automobile producers today, such as Daimler-Benz and Ford, had their start during these early years. The first large industrial step taken came about in connection with the birth of mass production in the US during the first decade of the 20th Century. The exact start of it is said to have been when Henry Ford began manufacturing his Model-T Fords at the Highland Park factory in Detroit in 1910. According to Womack, Jons and Roos [3], technological and social changes contributed very much to the development of this new industrial concept.

At the beginning of the 30s, Kiichiro Toyoda founded *Toyota Motor Company* and began manufacturing cars for the Japanese market. Societal demands there forced Mr. Toyoda to develop his mass production ideas further so as to satisfy demands for flexibility and resource effectiveness. According to Ohno [4], the changes in the conception of mass production this adjustment in the approach adopted brought about were very consciously undertaken in view of conditions there in Japan. A highly important step was taken in 1937 when Toyoda created the "Just in Time" concept. A major developmental project was undertaken then, at the same time as a new production approach was born, one that 50 years later was to be called Lean Production (Womack [2]).

An interesting discussion pursued throughout the world today concerns how the production concept to be adopted after that will look, i.e. the NEXT STEP. Many of the changes to be involved can very likely be subsumed under the concept of Lean Production. Clearly, considerable emphasis will come to be placed on the increased use of retrieved raw materials. This is something which is already underway and will surely increase in the future. In a later developmental step there will undoubtedly be an increased use of renewable raw materials, the use of organic materials being developed further and increasing in importance. The driving force behind this will very likely be the increase that can be expected in the cost of materials, together with various taxes and fees that can be expected to be levied as well. Considerable efforts are being made, within industry, academic disciplines and research, to achieve the goals of Sustainable Manufacturing [5]. This includes consideration of matters of competitiveness that can be related to questions within the areas of economics, sociology and ecology. Developments in this direction can be furthered by bilateral agreements, legislation and a general increase in knowledge and understanding concerning the questions that are involved. An early and important contribution to this is a Report of the World Commission on Environment and Development in 1987 (Brundtland [6]).

In developmental work in this area in the future, various important aspects of earlier developmental steps will in part remain, in part be adjusted to changes that have occurred, and in part be supplemented by new ways of looking at things and by new technologies that have been developed, all of this being in part the result of research carried out within this area.

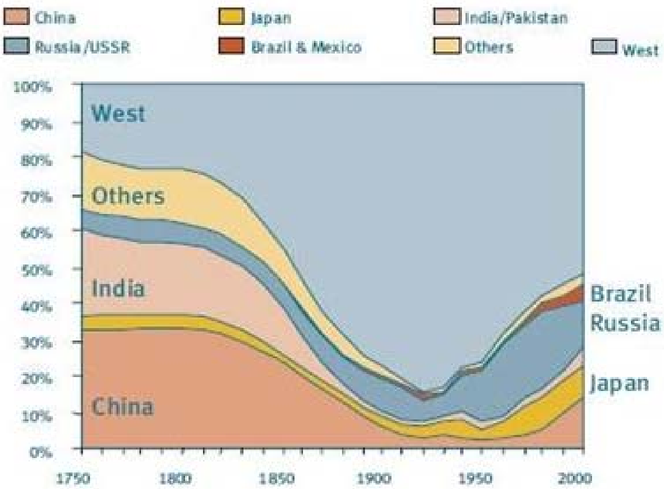

Fig. 1 Distribution of industrial production in the world 1750 – 2000 according to Tseng [2].

Developmental steps in production technology

As was just indicated, many developmental steps or industrial transformations (such as those stemming from new production philosophies), based upon one another in terms both of knowledge and of experience, can be identified.

Manual and work-intensive manufacturing. Before the concept of ”mass production” was established in the US and in Europe, work consisted to a very great extent of craftsmanship and manual labor. Orders from individual customers were often the basis for undertaking the manufacture of a particular product. The product then was very much adapted to the customer’s wishes. The product specifications in the form of drawings, the dimensions that were to apply, together with tolerances, material specifications and work instructions, were made use of but did not provide the total answer to things.

Mass production. In order to make mass production of vehicles and other products possible, a standardization of measurement specifications and work instructions was introduced. This was entirely necessary for enabling production line assembly to take place. The fact that the personnel involved often lacked specialized training led to the tasks they were given being simple and well-defined and being divided up into planning, execution and inspection elements. Such dividing up of work into separate elements later became an integral part of the concept of *Taylorism*, named after F. W. Taylor. The predictability of the task such a work element involved was important for planning of the work as a whole. The craftsmanship that had had been called for earlier was eliminated by use of both machining fixtures and special machines that did not need to be adjusted to the manufacture of a particular product. A production system became so designed that anyone could learn to carry out the tasks involved without the need of any particular professional training or linguistic skills.

Lean production. Discussions of Lean Production and accounts of how it works have been provided by many researchers and production scientists, including Womack et.al. [2], Voss and Clutterbuck [7], Hay [8] and Monden [9]. Their presentations differ in various respects. Common to all of them is the idea that a production flow should be established, and such conceptions as the Just In Time principle, the maintaining of only limited materials or parts in stock, steady production without the materials or parts needed running out, keeping adjustment times to a minimum, freedom from losses in quality (error-free), continual improvement, close collaboration with suppliers, production-appropriate constructions, and visualization of production results and of losses. Ericsson [1] has provided a comprehensive account of the production philosophy behind Lean Production. It is visualized in Figure 2, where various elements and conceptions, partly of industrial and partly of academic character, are taken account of so as to create a comprehensive overview of it all.

The Lean Production Model as presented in Figure 2 is divided into two main parts: an *administrative part* and a *developmental part*. Ericsson [1] notes that the best performance is achieved by a manufacturing system when the same persons both administer and develop it. The model contains various subsystems. Within the administrative part there are person-related functions, including those of the training of personnel, hiring procedures, the salary system, and matters both of safety and of the work environment. An additional function of the administrative part is to maintain the level of productivity and quality that has been achieved. Still a further task of the administrative part is to visualize the production results (including the production rate and the occurrence of rejections and of downtimes) and to give priority to measures that can serve to eliminate or reduce problems that arise (of the latter two types or any others). The developmental part, in turn, has various *tools* or *measures* at its disposal that can be used to deal with problems that have been identified. Measures that require considerable resources and possibly further developments within the organization can be dealt with by means of a proposal system.

Dynamic effects that can come about through interaction between the administrative and the developmental parts represent a central characteristic of the model. The tools available in the developmental part of the model can be used not simply for solving specific problems or lack of various things, but also for helping to create the motivation needed by the personnel in order to function effectively, motivation that is increased through participation and through the possibility of actively changing and affecting the production system.

NEXT STEP. A variety of developmental routes that can be taken based in one way or another on earlier developmental steps (and the philosophies behind them) can be identified. Only the future can show then whether a new approach that has been taken represents a full step ahead or, although in the right direction, represents simply a certain complement to the form of Lean Production that is already underway. The Lean Production philosophy has been complemented successively by the introduction of new tools and new methods of carrying out the work to be done. One aim involved in various developments that are in progress has been to *highlight the link between the technology employed and economic considerations.*

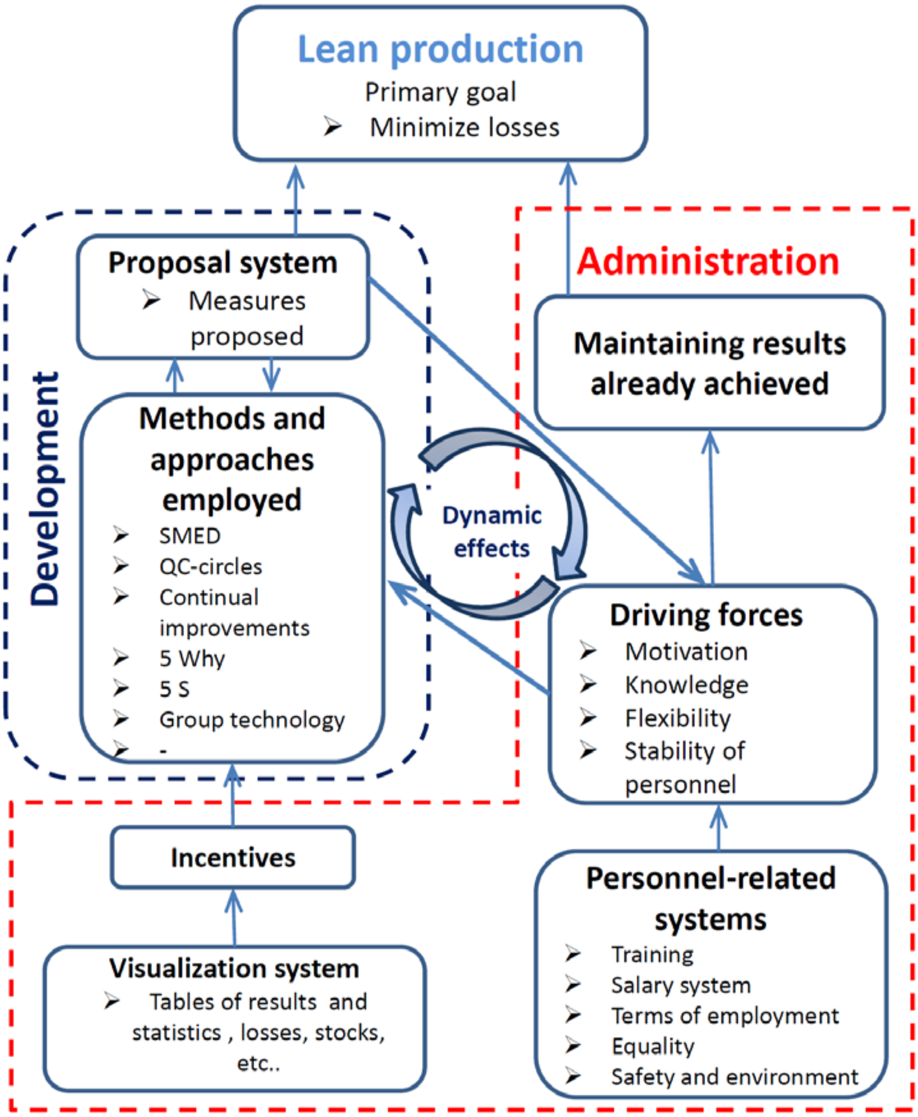

Fig. 2 *The dynamic interactions within the framework of Lean Production that serve to generate continual improvement, as described by Ericsson [1].*

Obtaining a complete breakdown of the costs of manufacturing a product or a part is essential for being able to give adequate priority to the measures needed and to solve the problems that are of greatest importance. In line with this, it is important to know, for example, whether it is the costs for rejects, downtimes, slowdowns, waste of materials, adjustment times, or costs connected with some other parameter or variable, that are most cost-consuming, and how in a more detailed way these various cost sources compare with one another. It is important in this connection to set manufacturing goals, such as those of reducing manufacturing costs by say 20 %, the number of downtimes by 10 %, material losses by 5 % and the number of rejects by 2 %. Computations and a strategy of this sort are practicable if one has a detailed cost model. Use of such a model requires that one have an advanced system for collecting and analyzing the relevant data. An important element of such work is that of being adequately prepared for carrying out *systematic production analyses* in which the relationships between *controlling factors* and *production results* (result parameters) can be identified. A complete cost model and a well-functioning system for obtaining the indata of the model enable economically based key performance indicators to be used as a basis for decisions regarding product development.

Principles and methods obtained from different developmental steps. As already indicated, different production philosophies have been developed on the basis of knowledge and experience gradually built up in connection with production and product development.

Tab. 1 Principles and methods from different developmental steps used within the production area.

Developmental steps or philosophies	Positive characteristics
NEXT STEP	➢ Production analysis concerning costs per cell ➢ Developmental goals ➢ Economically based key performance indicators ➢ Economic basis for decisions ➢ Clear link between technology and economic considerations
Lean production	➢ Insight into problems through visualization and use of key performance indicators ➢ Involvement, participation and motivation ➢ Formalized tools and working approaches ➢ Administration and development within one and the same organization ➢ Effective use of resources
Mass production	➢ Scientifically sound methods ➢ Standardization ➢ Standardized working methods
Manual and work-intensive manufacturing	➢ Adaptation to the wishes of the individual customer ➢ Flexibility

Production performance analysis

All processing and production results can be described in terms of three basic result parameters: rejection rate, downtimes and production or processing rate. The first two of these can likewise be expressed – in more neutral terms – as quality level and production continuity, respectively. As Fig. 3 implies, an increase in the rate of a given process or processing step can require technical improvements or an increase in the competence level of the personnel involved if an increase in production disturbances (rejections and downtimes) is to be avoided. There is thus a balance between production rate, fulfillment of demands placed on the production equipment and possibly on the personnel as well, and production disturbances. This is a balance that applies to basically all types of processing methods.

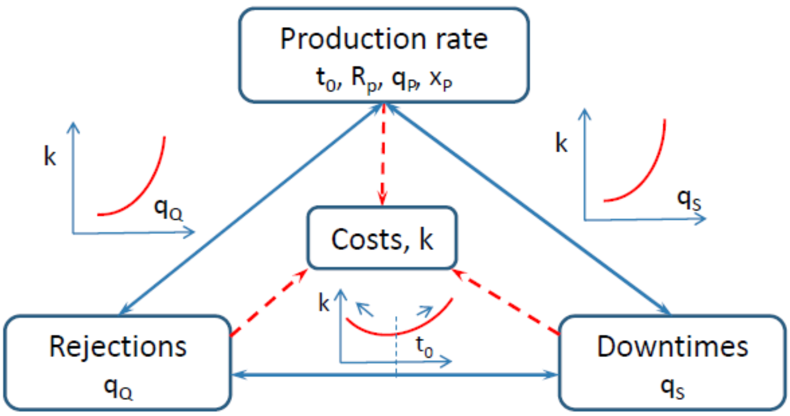

Fig. 3 Major relationships between production rate, quality disturbances, downtimes and production costs, see Tab. 2.

Fig. 3 shows how an increase in the production rate can lead to an increase in costs due to disturbances that lead to downtimes or shutdowns, and to disturbances in quality that increase the rejection rate.

The results at any given processing point or for any given segment of the processing chain can be described in terms of a number of different *result parameters*. Production efficiency can be regarded as the central term here, summarizing the overall effect of the different result parameters. The result parameters can usually be expressed in absolute numerical terms and can for the most part be assigned to the following three groups:

- *Quality parameters* concerning dimensional requirements, surface-characteristic requirements and any requirements regarding additional characteristics, together with possible requirements concerning functionality and performance: $Q_1, Q_2, \dots Q_n$.
- *Downtime parameters* concerning downtimes caused by process-related events: $S_1, S_2, \dots S_n$.
- *Production or processing rate parameters* expressed in such terms as the number of products or product components produced during a given period of time: $P_1, P_2, \dots P_n$.

Increasing attention is being directed at environmental issues and matters of recycling concerned with maintaining a *sustainable development* and use of natural resources. In assessing the environmental burden that production and use of a given product involves, it is important to take the entire life cycle of the product into account. Regarding manufacturing of the product, attention needs to be directed not only at the material or combination of materials the product is composed of, but also at the tools, equipment and additional substances employed in its manufacture. In line with this, the result parameters traditionally employed have been complemented by use of various environmental and recycling parameters aimed at providing a picture of the results that manufacturing of a particular product can have in a broader sense.

- *Environmental and recycling parameters* that take account of such factors as the tools, equipment and processing substances employed, the energy requirements involved, the waste to be disposed of, and the *scrap recycling* that can be achieved: $ER_1, ER_2, \dots ER_n$.

Losses in quality can be described in terms of the rejection ratio q_Q (see Tab.1), specific instances of loss in quality being designated as q_{Qi}. For any given product or product component, there can be a large number of quality requirements that need to be met, and there can be functional requirements too. The latter requirements are rather usual when product components are to be assembled or to be attached to one another. In such cases it does not suffice simply for each component to be correct in itself, but the components must also be put together properly for the functional requirements to be fulfilled. For cutting process, losses in quality can occur in connection with quality requirements of all types.

Downtimes can come about as a result of either external or internal disturbances that lead to a production stop. Scheduled and unscheduled downtimes can be distinguished. Scheduled downtimes, such as due to maintenance work, usually have less serious consequences than unscheduled ones, such as caused by machine failures. Examples of external disturbances that result in a downtime are electric power failure or a subcontractor failing to deliver in time. The extent to which downtimes occur in a production system, a production line or an individual machine can be described in terms of the downtime ratio q_S (see Tab.2). Downtimes occurring in specific processing situations, in turn, can be denoted as q_{Si}. Downtimes in metal cutting processes can come about in many different ways, such as through tool failure or problems connected with chip formation.

Production or processing rate parameters are usually expressed either directly in terms of rate (number of either product or product-component units, or of processing operations of a particular type, completed within a given period of time: Rp) or in terms of the length of time that processing of a particular type requires: tp. Changes in rate (it is usually a reduction in rate that is of primary concern) can be expressed either as the extent of the decrease or increase in rate (q_P, see Tab.2) or in terms of process development factors (x_p and x_{su}, see Tab.2). The rate change or process development results obtained are dependent upon the cycle time and the nominal setup time. The term "nominal" means that a reference time is involved; one determined either in advance or in the current situation. If a nominal time of this sort of changes, as it frequently does while production is underway, the rate change or process development values obtained change as well, making comparisons between various points in time or different parts of the production process difficult, unless the basis for comparison is made completely clear. Rate variations in metal cutting processes are often caused by variations in the machinability of the workpiece material. A marked decrease in machinability readily leads to the machine speed (and the corresponding values for the cutting data) needing to be reduced.

A number of different *factor groups* (A-G below) applying to the different processing methods employed can be identified. The many factors (designated as A_1, A_2, A_n, B_1, B_n, etc.) contained in these groups can each readily affect, either singly or in combination, the production efficiency and the result parameters of the production processes carried out. For metal-cutting processes, it is not at all unusual for 50 - 70 individual factors of this sort to each be seen as having an appreciable effect on the production result obtained.

Systematizing the many different factors of this type that can be identified is thus necessary for developing an approach able to affect production results in as effective and optimal a way as possible.

The major factor groups considered here are the following, ways in which these could be divided up further into subgroups also being indicated:

A. Tools and tooling systems. Geometrically-related factors (macro- and microgeometry). Surface-related factors (surface characteristics, coatings, etc.). Material-related factors (hardness, toughness, etc.).
B. Workpiece materials. Geometrically-related factors (stiffness, heat capacity, etc.). Surface-related factors (topography, chemical composition, structure, hardness, etc.). Material-related and structural factors (machinability, formability, castability, weldability, etc.).
C. Processes and process data. Equipment-related factors (stiffness, damping effects, etc.). Process-data-related factors (cutting data, stamping force, casting temperature, etc.). Process-related substances added (lubricants, protective gases, nucleating agents, additional materials added, etc.). Procedural factors (operational sequence, tool changes, etc.).
D. Personnel and organization. Standard operating procedures, managerial functions, measures to take in case of process failures, etc. Work structure, responsibilities, opportunities for personal initiative, etc.
E. Maintenance and service. Tool-related factors. Process- and equipment-related factors. Planned and emergency repair and maintenance.
F. Special factors. Every processing method has its own unique characteristics, such as the forming of built-up edges, galling, the appearance of scratches on the surface in connection with forming processes, welding spatter, and specific defects such as scabs produced in the casting process.
G. Peripheral equipment. Material-handling equipment, gripping tools, conveyor belts, and the like.

Factor groups A-D as well as G can be seen as representing indata for the production system, whereas groups E and F concern consequences and needs that can arise in the course of production. The classification on which these factor groups are based is a very general one that can be applied to manufacturing processes of basically all types, though manufacturing methods can differ somewhat in the meaning various of the concepts here have.

Factor group D, which can also be termed *human factors*, is more important than one might initially think. It is particularly important in the case of knowledge-intensive firms, which often concentrate on continual development of the competence of their employees; see Fig. 2. The success of such firms is highly dependent upon two factors, both of which are linked with factor group D: the *average competence* of their employees and the presence of persons of *top-level competence*.

Through combining the different result parameters taken up earlier with the factor groups just considered, one can obtain a matrix of the type shown in Fig. 5, in which the factors are listed in the column at the left and the result parameters are listed at the top from left to right. This matrix will be referred to as the *Production Performance Matrix* or *PPM*.

Relationships between a particular result parameter and a given factor group can be either quantitative or qualitative. PPM's primary areas of application are the following:

- *Following the production* which is underway with the aim of discovering critical segments of the production process that are in need of improvement and assessing how improvement can best be achieved.
- *Obtaining insight* into how the current production system functions and using this as a help in developing new production systems.
- *Providing help in assessing* the probable effects of various measures that could be taken for improving the production system, such as in selecting the types of tools, the processing methods and the workpiece material(s) to be employed and the specifications that the processing data are to meet.
- *Providing the basis for the documentation* and assessment both of the experience gained in studying the production carried out, and of the competence of persons involved in the production process.

PPM has had the strongest impact thus far in the first of the areas just referred to, i.e. in providing a basis for determining how improvements can be made in critical segments of the production system.

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

Fig. 4 The basic structure of the Production Performance Matrix (PPM).

Most processing methods display special behaviors of some sort. These are subsumed above under factor group F. The specific behaviors involved can be seen as being produced by various of the factors contained in factor groups A – D in particular. In cutting processes, such behavior as the formation of built-up edges, chip hammering, and the occurrence of uncontrolled chip formation have a negative effect on both the processing carried out and the results obtained.

A PPM provides the basis for computing key performance indicators, concerning rejections, downtimes and rate (cycle times), for example. These can serve as indata for a cost model. Determining relationships between different factors and result parameters enables the costs connected with specific result parameters and factors (or factor groups) to be assessed.

Production cost model

Although many different cost models have been described in the literature (see e.g. Jönsson et.al. [9]), 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 specicial interest have been presented in particular by H. Yamashina and T. Kubo [11] and by N. Chiadamrong [12]. The present author [13, 14] has published a cost model based on Eq. 1, one that includes the parameters of central interest along with the variables that affect part costs, these involving loss terms concerning *rejects* (q_Q), *downtimes* (q_S), *rate losses* (q_P) and *material waste* (q_B).

$$
\begin{aligned}
k = {} & \frac{K_A}{N_0}\left[\frac{1}{n_{pA}}\right]_a + \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)\cdot(1-q_B)}\right]_b + \frac{k_{CP}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right]_{c1} + \\
& \frac{k_{CS}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\cdot\frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RB}}{U_{RB}}T_{pb}\right]_{c2} + \\
& \frac{n_{op}\cdot k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RB}}{U_{RB}}T_{pb}\right]_d + \\
& \frac{1}{N_0}(K_{AUH} + K_{CUH} + K_{GUH})_e + \frac{1}{N_0}(K_{HL} + K_{Tno} + K_{RW})_h
\end{aligned}
\qquad \text{Eq. (1)}
$$

Definitions of the parameters and variables included in this cost model are presented in Tab. 2. The parameters k_{CP} and k_{CS} are equipment costs per hour för producftion and for downtimes for a given machine or production line. The product $n_{op}\cdot k_D$ represents salary costs per hour for carrying on production there, where n_{op} is the number of operators involved and k_D is the average cost per hour.

The cost model described in Eq. 1 can be modified by introducing a development factor (x_i) and a cost factor (κ_i). The *development factor* affects both the cycle time $x_p\cdot t_0$ and the setup time $x_{su}\cdot T_{su}$. Setting $x_p = 0.9$, for example, allows the effect that a 10 % reduction in the cycle time would have on the part costs. Similarly, the effect on the part costs of a reduction in the setup time can be studied by varying the development factor x_{su}. This allows the effect on the part costs to be compared with the effects of other changes, such as a reduction in the rejection rate (q_Q) or in the downtime rate (q_S). The cost factors affect both equipment costs, $\kappa_C\cdot k_{CP}$ and $\kappa_C\cdot k_{CS}$, and the salary costs $\kappa_D.k_D$. These factors, which are all numbers greater than 1.0, describe the effect of an increase in the equipment costs or in the salary costs on the part costs. A value of $\kappa_C = 1.1$ represents a 10 % increase in the equipment costs, one that can be due, for example, to a production line being complemented by the addition to it of measuring equipment or handling equipment.

Cost models based on Eq. 1 for different development scenarios involving two different salary levels are exemplified in Fig. 5 and in Tab. 2. Cases 2 and 3 there represent different goals that have been set, or goal functions as they are called, in relation to production in its present state, Case 1.

The examples above show that, by changing the downtime rates $\Delta q_S = -0.10$, $\Delta q_Q = -0.025$, $x_p = -0.10$ and $x_{su} = -0.5$, a company can compete effectively with a company having salary costs of only say ¼ as much. The changes in the rejection rate just referred to can often be achieved without any sizeable investments being needed.

Tab. 2 Definitions of the parameters and variables in the cost model described in Eq.1.

$k_A = \frac{K_A}{N_0}\left[\frac{1}{n_{pA}}\right]$	k_A = Equipment costs per acceptable part K_A = Total costs of the tool employed N_0 = Series size aimed at (average batch) η_{pA} = Number of batches of average size the tool can be used to produce	Eq. (2)
$k_M = \frac{1}{N_0}(K_{AM} + K_{CM} + K_{GM})$	k_M = Maintenance costs per part K_{AM} = Maintenance costs per part for the tool K_{CM} = Mainenance costs per part for the machining equipment K_{GM} = Maintence costs per part for the auxiliary equipment	Eq. (3)
$k_H \frac{1}{N_0}(K_{HL} + K_{Tno} + K_{RW})$	k_H = Complementary costs per part K_{HL} = Costs per batch för stock and buffers K_{Tno} = Costs per batch for non-operational time K_{RW} = Costs per batch for reworkiing	Eq. (4)
$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N}$ $N = \frac{N_0}{1-q_Q} = N_0(1 + \frac{q_Q}{1-q_Q})$	q_Q = Rejection rate N_0 = Series size aimed at N = Total number of parts or material components	Eq. (5)
$q_S = \frac{t_S}{t_p} = \frac{t_p - t_0}{t_p}$ $t_p = \frac{t_0}{1-q_S} = t_0(1 + \frac{q_S}{1-q_S})$	q_S = Downtime ratio t_0 = Nominal cycle time t_S = Downtime per part t_P = Production time per part	Eq. (6)
$q_P = \frac{t_{0v} - t_0}{t_{0v}} = 1 - \frac{t_0}{t_{0v}}$ $t_{0v} = \frac{t_0}{1-q_P}$	q_P = Lengthening of cycles t_0 = Nominal cycle time t_{0v} = True cycle time	Eq. (7)
$T_p = T_{su} + N \cdot t_p =$ $T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)}$	Tp = Batch production time T_{su} = Setup time for a given batch N_0 = Series size needed N = Total number of parts or material components	Eq. (8)
$t_{pb} = \frac{T_p}{N_0}$	t_{pb} = Average production time for a part in a batch containing N_0 acceptable parts	Eq. (9)
$K_B = \frac{N_0 \cdot k_{B0}}{(1-q_B)(1-q_Q)}$ $q_B = \frac{m_{tot} - m_{part}}{m_{tot}}$	K_B = Total material costs of a batch k_{B0} = Material costs of a part q_B = Material loss per manufactured part m_{tot} = total mass of raw material needed for manufacturing a part m_{part} = mass of material in a finished part	Eq. (10)
$U_{RP} = \frac{T_{prod}}{T_{plan}}$; $T_{plan} = T_{prod} + T_{free}$ $T_{free,b} = \frac{1-U_{RP}}{U_{RP}} T_{pb}$	U_{RP} = Reduced degree of utilization T_{prod} = Total production time T_{plan} = All paid time the maximal production time planned requires $T_{free,b}$ = Extra time needed per batch	Eq. (11)

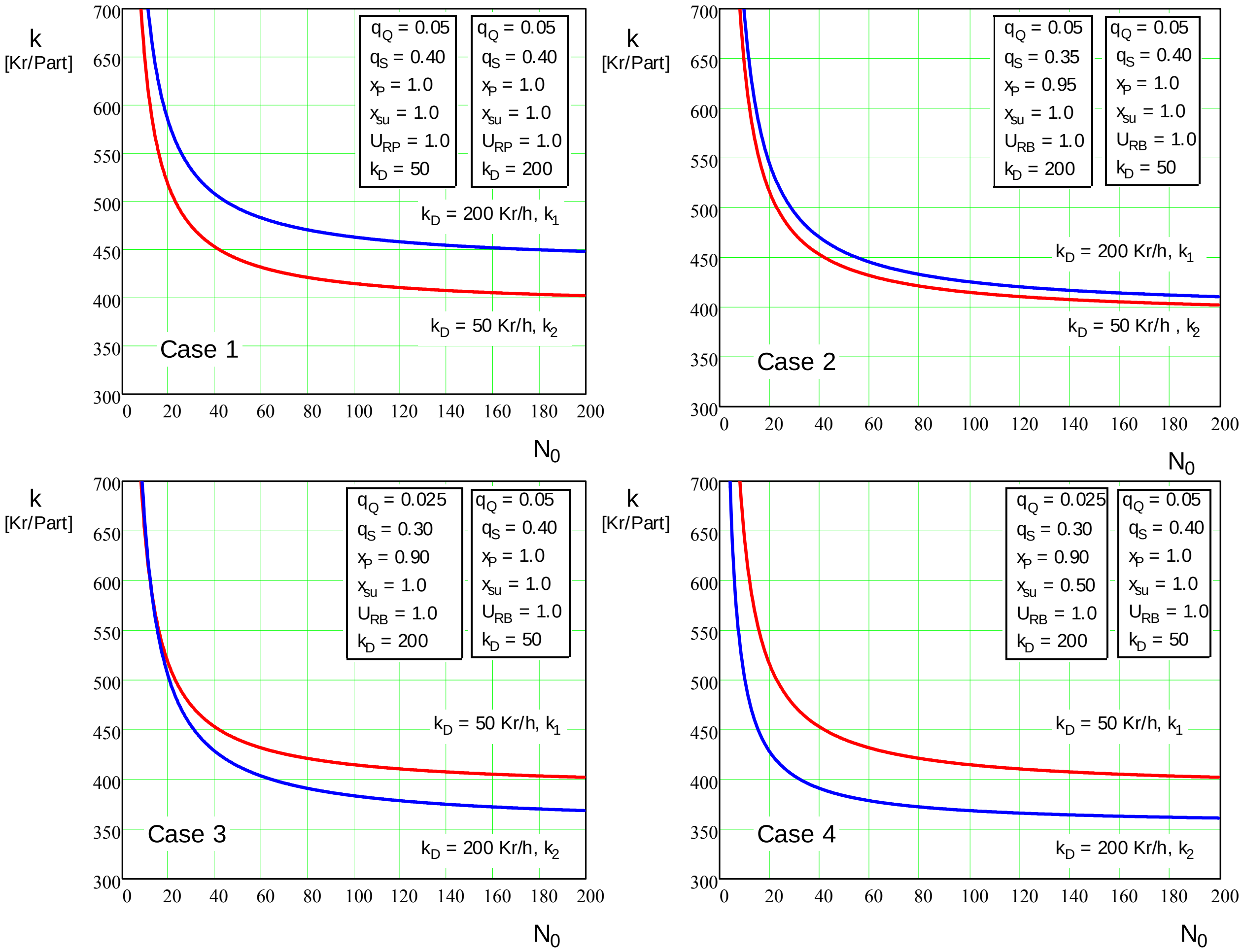

Fig. 5 Part costs shown as a function of series size N_0 for 4 different salary levels, where k_D = 50 Kr/h and k_D = 200 Kr/h.

Tab. 2 Examples of changes in part costs k for batch sizes N_0 = 20 and N_0 = 200 for different development scenarios.

Case	q_S	q_Q	x_p	x_{su}	**k(N₀=20)** [SEK/part]	**k(N₀=200)** [SEK/part]
1. ↓	0.40	0.05	1.0	1.0	575	460
2. ↓	0.35	0.05	1.0	1.0	550 (- 4 %)	425 (- 8 %)
3. ↓	0.30	0.025	0.90	1.0	500 (- 13 %)	415 (- 10 %)
4.	0.30	0.025	0.90	0.5	425 (- 26 %)	412 (- 10 %)

Identification of research areas

A PPM is very suitable for use in identifying development needs. Two important questions concern the priority that development measures of various types should be given and how these should be selected. A PPM often has to do with a specific machine or production line. In the case of flexible manufacturing activity this means that information pertaining to a particular time period can very well concern a variety of products or parts. The statistical variation in the average costs of 5 different products all manufactured in the same production line is exemplified in Fig. 9. Each data point there represents a batch for which N_0, the number of parts involved, varies between 200 and 2000 parts.

It is important to clarify in this context how the losses involved are related to manufacture of the product or products involved and how general the occurrence of such losses is (see Fig. 6). A development project can take account of all parts being manufactured and thus indicate in a general way what effects the losses that have been identified have. The development measures undertaken can also be more specific, directed at solving a problem relating to a specific result parameter, such as a given quality requirement, for example, one which may involve one or more separate factors (or factor groups).

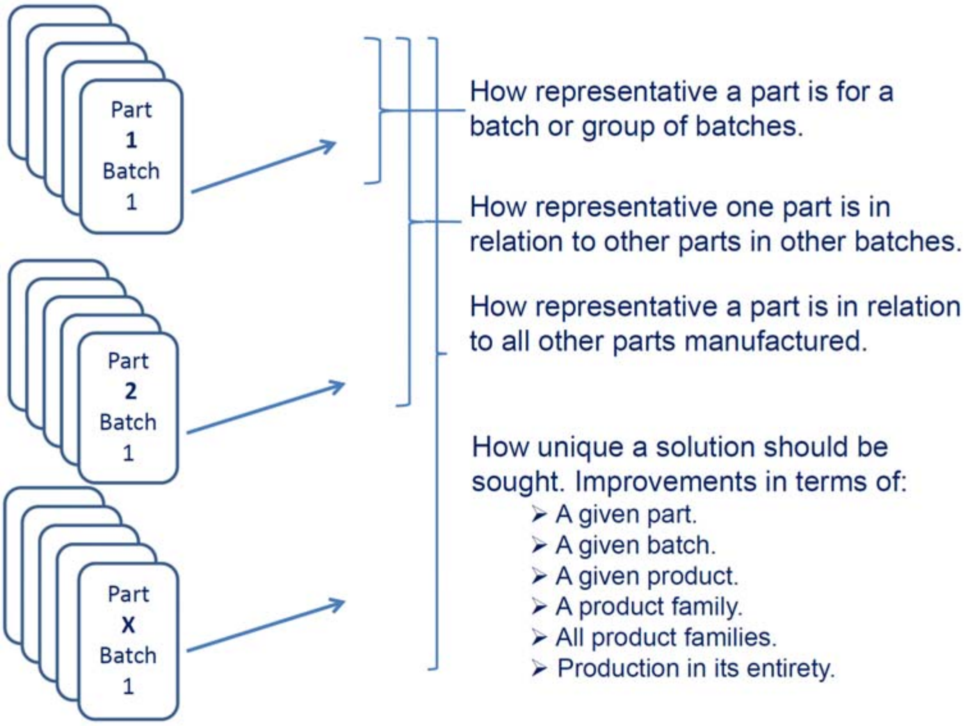

Fig. 6 Different levels of investigation.

Factor groups A-G with the individual factors belonging to them represent a systematic point of departure for production development. The results of a completed analysis resulting in a PPM, as shown in Fig. 7, indicates directly the areas in which developmental measures can be called for.

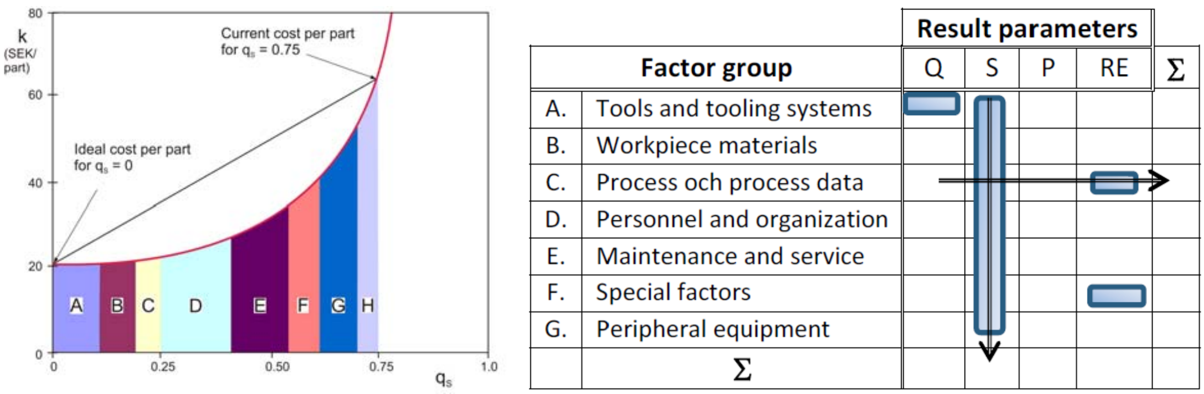

Fig. 7 An example of the distribution of downtime costs in proportion to the share of q_S for each factor related to PPM (left) [17] and an example of the areas in the PPM that are of major concern and can be of particular relevance to production development (right).

A production performance matrix generally indicates that, in order to solve the developmental needs at hand, production improvement efforts need to take account of a variety of different factor groups. This makes production development a complex task, one that results in there generally being few clearly best solutions available. In a mature production system the most obvious and easily identified developmental measures have already been carried out.

The potential of different improvements that can be linked to the different cells that a PPM takes account of is exemplified in Fig. 8. The designations A, C, D and E refer to respective factor groups, where in the case in question no major can be traced to factor groups D, F or G. Computing the proportion of loss cell-by-cell enables the proportion of loss factors as a whole to be determined for each cell. How the downtime periods $t_{S,D9}$ caused by the factor D9 contribute to the total proportion of downtimes qS is exemplified below. The cell-by-cell calculations can be carried out with the help of Eq. 1 and the relationships reported in Tab. 2. The cell-by-cell costs for factor D9 (factor no. 9 in factor group D), for example, can be obtained by use of Eq. 12.

$$
\begin{aligned}
q_S &= \frac{t_S}{t_P} = \frac{T_S}{T_P} \\
\Delta k_i &= k(q_S) - k(q_S = 0) \\
\Delta k_{i,j} &= \Delta k_i \cdot \frac{\Delta q_{S,j}}{q_S} \\
\Delta q_{S,j} &= \Delta q_{S,D9} = \frac{t_{S,D9}}{t_P} = \frac{T_{S,D9}}{T_P}
\end{aligned}
\qquad \text{Eq. (12)}
$$

The principles reported above can also be applied to the remaining loss terms, or variables that can be identified in a PPM, (q_Q, q_P and q_B).

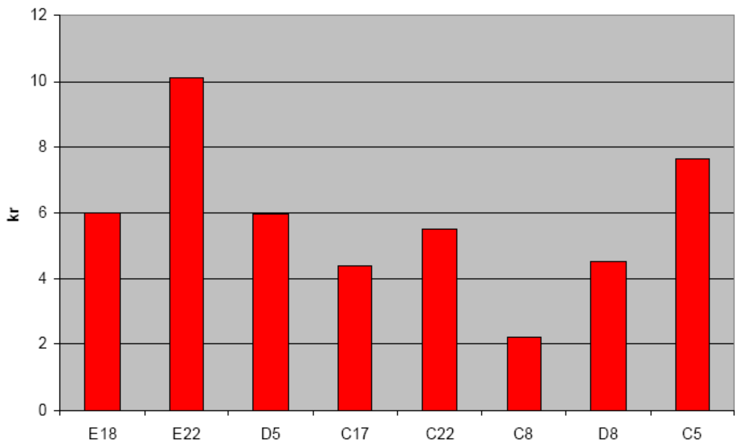

Fig. 8 An example of some of the part costs that can be related to the respective cells in a PPM.

Use of cost derivatives. Another principle that can be used for identifying a development project is to study the derivatives linked to the cost equations based on Eq. 1. The parameters and variables in the cost equations that have the largest differentials also have the strongest effect on the part costs when a change occurs. The principles for computing the cost effects of a change of a variable z that has an initial value of z_0 are contained in Eq. 13. The product of the derivative and the variable value z_0 yields the weighted cost derivative, which indicates the strength of a variable at point z_0. A relative change in the variable is given by the ratio of the change Δz to z_0. A prerequisite for these principles applying is that the change occurring in the loss parameters is less than abt 10 % if the higher derivatives of the differentials are ignored.

$$\Delta k = \frac{\partial k(z_0)}{\partial z} \cdot \Delta z$$

$$\rightarrow$$

$$\Delta z = z_0 \cdot \frac{\Delta z}{z_0} \qquad \text{Eq. (13)}$$

$$\Delta k = \frac{\partial k(z_0)}{\partial z} \cdot z_0 \cdot \frac{\Delta z}{z_0}$$

The values of the cost derivatives in a particular sample are illustrated in Tab. 3. A change in the cycle time (x_p) and in the downtimes (q_S) there has the strongest effect on the part costs under a certain set of conditions.

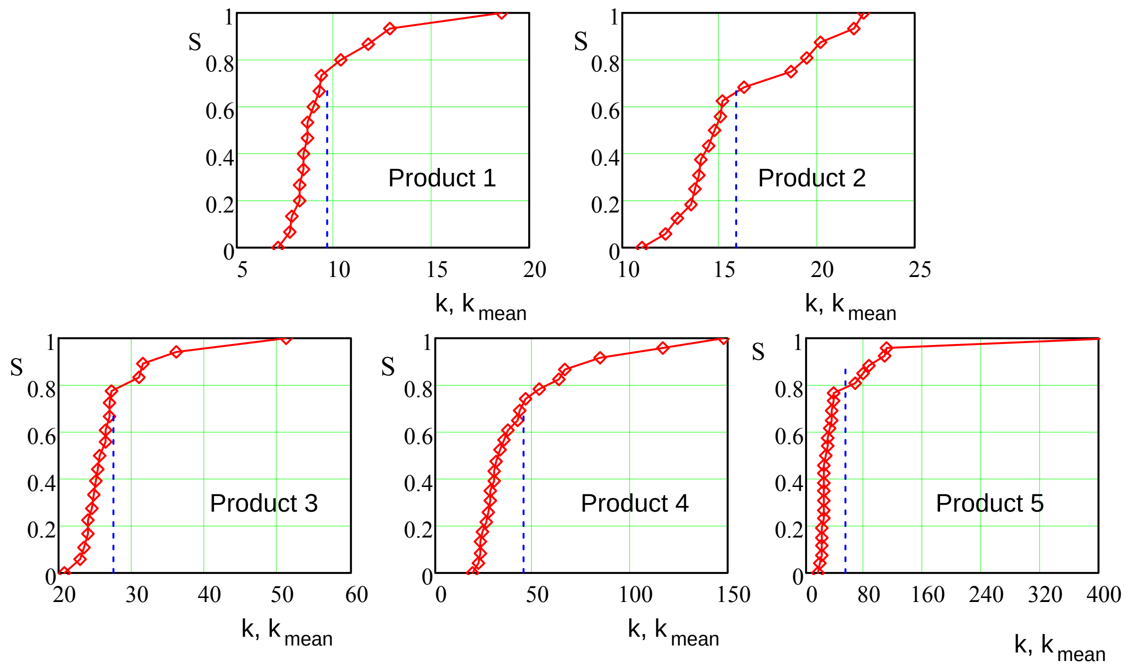

Fig. 9 Distribution of the productions cost and the calculated mean costs of different batches of selected products 1-5, Stål [17].

The example shows that the degree of utilization can also be a very strong factor here. In the case at hand, the degree of utilization is already 100 % (U_{RP} = 1.0). In many manufacturing tasks, certain changes in many of the variables need to be made in order for a given goal to be achieved, such as that of reducing the part costs by say 20 %. One should note, however, that since many of the parameters involved are dependent upon one another (see Fig. 1), due to the differentials of many of the variables behaving additively. An approximation in which one assumes that the variables are independent of one another is usually adopted, one that leads to the effects of a change being overestimated. For example, a reduction in the cycle time t_0 (x_p) that leads to a nominal reduction in the part costs can in fact result in an increase in the actual part costs due to an increase in both the rejection rate q_Q and the downtimes q_S.

Tab. 3 Computed cost derivatives of a given production case.

	Variable value	Variable	Cost derivative	Units involved	Weighted cost derivative
N_0	200	Batch size	- 0.075	Kr/part	- 15
q_Q	0.05	Rejection ratio	456	Kr	23
q_S	0.40	Downtime rate	487	Kr	**195**
k_D	200	Salary costs	0.31	h/apiece	61
x_p	1.0	Development factor	327	Kr	**327**
x_{su}	1.0	Development factor	15	Kr	15
U_{RP}	1.0	Degree of utilization	- 307	Kr	**- 307**
κ_C	1.0	Investment factor	281	Kr	**281**

Economically based key performance indicators. In principle, all parameters included in the cost equation based on Eq. 1 are considered to represent economically based key performance indicators. An ideal cost for the manufacture of a particular part in a given production line can be computed by setting all loss parameters $q_i = 0$ and all setup times $T_{su} = 0$, and assuming full utilization, i.e. that $U_{RP} = 1.0$. The production-economic efficiency level can be computed on the basis of the ratio of the ideal to the actual part costs, using Eq. 14.

$$\eta_E = \frac{k_{Ideal}(q_Q, q_S, q_P, T_{su} \ldots\ldots = 0,\ \ U_{RP} = 1.0)}{k} \qquad \text{Eq. (14)}$$

The *developmental potential* expressed in Kr per part can be computed using Eq. 15.

$$\Delta k_{pot} = (1 - \eta_E) \cdot k = k - k_{Ideal} \qquad \text{Eq. (15)}$$

OEE (Overall Equipment Efficiency).is a key performance indicator used rather generally in connection with Lean Production. It represents the ratio of value creation time to total time. For a batch, the value creation time is the product $t_0 \cdot N_0$. The remaining time then represents the actual time needed in order to manufacture the batch in question (see Eq. 8 in Tab. 1. The OEE per batch can be computed using Eq. 16.

$$OEE_{Batch} = \frac{t_0 \cdot N_0}{T_{su} + \dfrac{t_0 \cdot N_0}{(1-q_Q)(1-q_S)(1-q_P)} + \dfrac{1-U_{RP}}{U_{RP}} \cdot T_{Batch}} \qquad \text{Eq. (16)}$$

The manufacturing-economic efficiency level η_E is computed in Fig. 10, with OEE being seen as a function of batch size N_0 for 2 different production examples. In the case of ideal production, η_E and OEE each take on a value of 1.0.

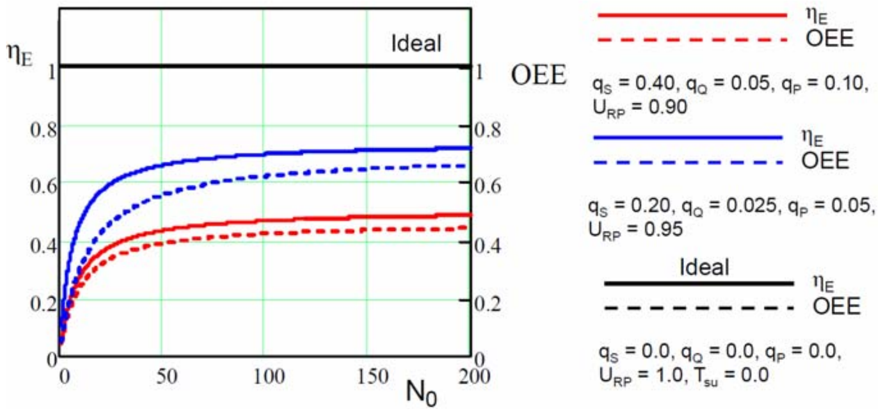

Fig. 10 The manufacturing-economic efficiency level η_E and OEE shown as a function of batch size N_0 for 2 different production examples.

Cost optimization based incremental production improvements. Typically, companies determine the cutting data for a machining process on the basis of their previous experience and of recommendations from the tool manufacturers. This cutting data, specifically the feed f, depth of cut a_p and cutting speed v_c, is often only investigated and determined when a new product is introduced or when a major change in the production process takes place, such as the introduction of a new machine or of new cutting tools. Although the company may succeed in selecting the optimum in terms of cutting data rather early, the probability of this is rather low, due to the high costs both of running the experiments this would require and of the delay in production it would bring about. Accordingly, production is usually initiated before the optimum cutting data employed and attempting to improve the selection of it, while normal production is underway. Large companies often have resources earmarked for efforts to improve the manufacturing process. In small and medium sized enterprises (SMEs), this is frequently not the case, lack of sufficient resources often proving a serious problem there. In efforts to remedy this, a new method was developed for improving the machining process in terms of costs per part, one requiring no expensive equipment or highly educated staff [15]. This method involves varying the cutting data incrementally, and recording meticulously the effects this has on the tool wear, as well on other factors, such as scrap rate (q_Q) and downtimes (q_S), that affect the part costs, allowing the machining costs to be optimized (see also Fig. 3). When this method was implemented in a small Swedish company, it was found to provide good results. It should be noted, however, that this method is best suited for use in the manufacture of products having large batch sizes and where the cutting tool is engaged during most of the production time involved.

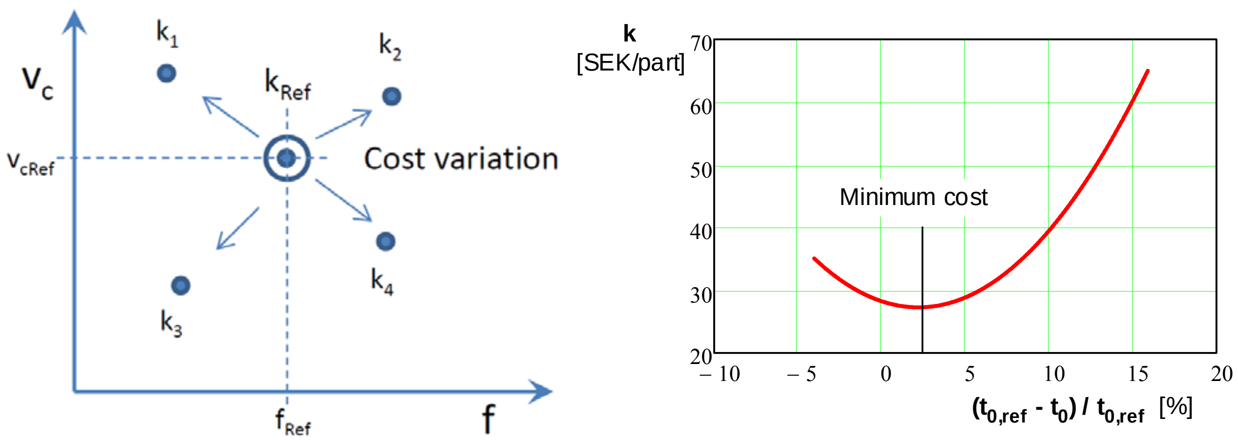

Fig. 11 A general diagram of variations in the cutting data (left) and a graph of the effects of variations in the cycle times t_0 on the part costs (right). The index ref refers to the reference value used initially by the company.

Challenges with which production development is faced

Different activities that both product and production development involve, and interactions of these, both with one another and with the market, are shown in a schematic way in Fig. 11. In efforts to achieve both successful productions generally and high production values as well, one need to deal as effectively as possible with chains of information that can often be difficult to grasp. There are 5 different feedback loops that can be noted:

1. A feedback loop that serves to maintain a balance between what is important to the customer and what is important from a production standpoint.
2. One aimed at ensuring that any adjustments in the product that are needed be made prior to the start of production (2A) and that the tools and the machining system that are needed are available and installed (2B).
3. A feedback loop for optimizing production while it is underway.
4. One for optimizing the value of already established products from the customers‘ standpoint, and the production values achieved in manufacturing them.

5. A feedback loop aimed at utilizing experience gained in connection with established products for optimizing new products and new production systems.

The loops 1-5 provide the basis for a variety of different challenging production-related research and development projects. A more comprehensive presentation of the different challenges involved has been provided in reference [16].

Tab. 4 Examples of challenges in production and development research.

Loop	**Examples loop-for loop of the different challenges involved**
1.	a. Assessment of the production value achieved through changes in the material and the design of an already established product. b. Assessment of the manufacturing costs in the case of varying production volume (due to difference in demand).
2.	a. Involvement of competing subcontractors in connection with adaptation of a product during manufacturing. b. Use of freed production capacity for the manufacture of newly developed products, and concrete relationships between product development strategies and investment strategies in deciding upon new production equipment to employ. c. Utilizing information and experience concerning current or earlier production in new product and production system development.
3.	a. Maintaining and enhancing strong mutual dynamic effects achieved through interactions between administrative and developmental functions as shown in Fig. 2 earlier (so as to develop and improve competence at all levels in the company). b. Organizing and employing the production data that has been collected so as to provide an adequate basis for environmentally based decisions. c. Optimizing production processes from an environmental standpoint without this being based primarily on economic incentives. d. Obtaining key performance indicators relating directly to the manufacture of a given part.
4.	a. Involving computer subcontractors in the task of optimizing a product or part with the aim of improving its Producibility, i.e. for increasing its production value.
5.	a. Systematizing knowledge and experience gained from production that is already underway (or was carried out earlier) for use of it in product development and in the development of new products.

More concrete technological challenges are those concerned, for example, with use of *lead-free work material* that can make the machining of many components, particularly those of small dimensions, more difficult, and also challenges connected with sustainable development involving machining carried out with reduced amounts of *process additives* such as cutting fluids or oil. Production steps such as those of grinding, for example, which is energy-demanding and environmentally troublesome, can be avoided by increasing the degree of hard machining carried out, i.e. the machining of components consisting of hardened steel.

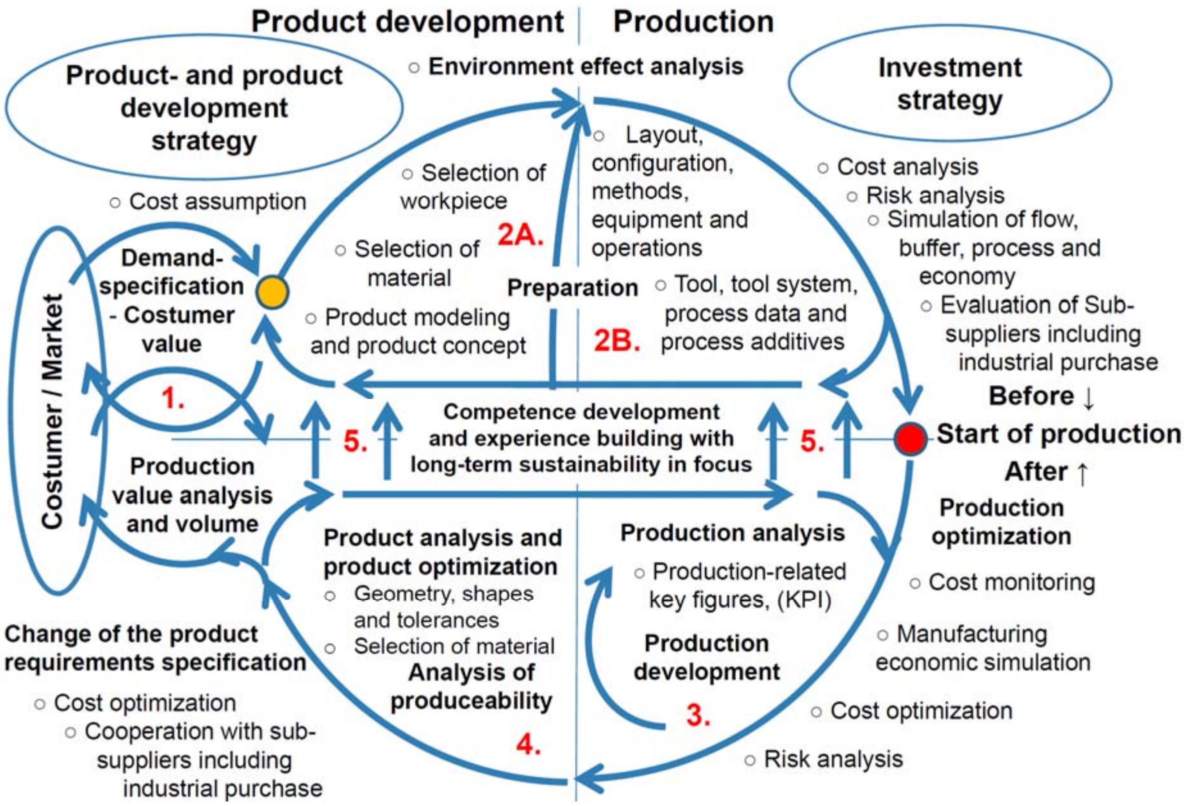

Fig. 11 A diagram of the continual interaction between the market, product development and production, which leads to successive increases in value to the customer and in production value, partly through its resulting in increased producibility and in a lowering of part costs, which can be seen as representing or leading to a NEXT STEP technology.

Summary and conclusions

Such production philosophies as those of mass production (Henry Ford) and of Lean Production were developed parallel besides many developments in society as a whole. Characteristics regarded as being positive and as being oriented to the current or the future state of things are retained in the ongoing developments that take place. An important element in the Lean Production philosophy concerns the dynamic interactions that take place between the administrative and the development functions. Use of formalized tools such as 5S, for example, contributes not only to the direct improvement this brings about, but also to the cooperation, which is very important, between various groups or persons within the company. Increased participation in the work of the company as a whole also contributes to motivation for developing personal competence. Developments within the production area tend to lead to stronger links being established between technological and economic considerations. Decision support in product development can also be expected to be based to an increasing extent on key performance indicators. Economic models that take account of all important variables and parameters, such as those of cycle times and loss terms, which affect the production costs of separate parts, are also needed for maintaining control of different developmental scenarios and analyzing them. Systematic production analysis taking account of data concerning such factors as downtimes, rejections and setup times are of central importance for being able to determine optimal routes for production development. There are many challenges with which both research and development are faced within this area.

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