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# Integrated time-functions and cost-functions as a basis for analysis of complex production systems

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## Abstract

In practice as well as in literature there is a strong emphasis on developing techniques for the control of production systems. Without attention for the production chain in which such a production system is embedded, this can easily lead to local suboptimization. This paper introduces two analysis tools (the integrated time-function and the integrated cost-function) aimed at preventing such suboptimization.

## 1. Introduction

In recent years, a lot of effort has been put into the analysis and improvement of production systems. Technical, as well as control aspects have been treated extensively; terms like FMS, CIM, JIT and MRP are now part of the vocabulary of any self-respecting operations manager.

These tools and techniques mostly focus on the operations within factory walls, or at best between a supplier and customers. Increased international and often global competition however, makes it more and more important to find tools for the improvement of the performance of the total production system, consisting of several production chains, which together make up a network, from raw material up to and including the final product.

Recent research indicates that, by using cost- and time-functions of this total (integrated) production chain, insight into the most critical parts of the production chain, in terms of time and costs, can be obtained. These parts of the production chain are most interesting for a further analysis and hence possible improvements of the performance [1].

The improvements may consist of a better logistic control of the existing factory network or of a restructuring of the manufacturing facilities.

In this paper the background and research method are described first, then a case study is presented.

## 2. Background

As a framework for our approach we use the so-called product cycle (Fig. 1). A represents the stock of exhaustible and non-exhaustible raw materials. These raw materials are the starting point of a series of transformation processes which result in *final products*. Final products are defined as: "products which do not require further processing by industry before they are of use to consumers" [2]. (Consumers in this context

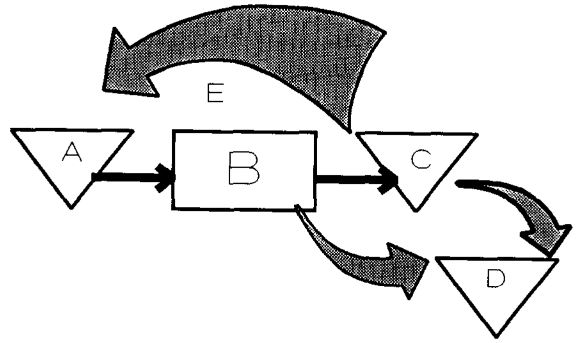


Fig. 1. Product cycle.

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can also be professionals). The series of transformation processes B is called the *production chain*. In practice this network will often be a combination of chains of factories forming either diverging or converging material flows. Waste of the production processes is represented by D. The customer, or the market, can be seen as a final product inventory, (C), with a turn-over rate equal to the reciproke of the final products' service life. At the end of it's service life, a final product, or part of it, will either be transferred to a stock of permanent waste (D), or will be recycled into new products (E).

Companies often control only a part of one of the production chains within this total product cycle. And for a long time, the ability to realise the largest throughput through this particular part of the production chain, given production means, was sufficient for success in business. This was the situation in many countries in the western world as long as a sellers market existed and, generally speaking, still is the situation in eastern european and third-world countries.

Nowadays, however, most producers in the western world have to do more than just delivering large volumes of cheap products. Growing international competition forces producers to offer an increasing diversity of high quality products in a more efficient way [6]. On the other hand governments and the public itself, show a growing consciousness of the negative environment effects of production and products, and hence set a growing number of bounds to producers.

These two developments force producers to look not only at their own part of the production chain, but to have a clear view of the total product cycle in which they take part. Decisions on product development, production capacity, location etc. should be made within that context, because success in the long run is determined by tuning production to final product demand within the constraints as given by society and competition. This statement can be illustrated by the following example.

A producer of PVC (poly-vinyl-chloride), a plastic used as basis for different final products like plastic containers, operates at the beginning of a production chain. Producing as much PVC as possible for a low price would certainly be a bad strategy nowadays. Consumers ask for plastic products in different and changing colours, so adaption of production to these demand fluctuations is important. On top of that the damage to the environment by PVC is an issue attracting growing attention. Facilitating recycling, or a change in product design, will thus be a major competitive weapon, or even a condition for survival in the near future.

Given this background, there is a growing need for methods which enable management to monitor the performance of the production-chain of which their company is a part. This has to lead to either a better coordination over the factories of a multinational company, or better agreements between private factories with their suppliers and/or costumers.

Generally, performance can be seen as consisting of the three elements cost, quality and delivery [3], within certain constraints. Product quality and environmental constraints on product waste are not treated any further here. We consider those aspects as a "conditio sine qua non". If products do not satisfy quality- and environmental standards, they will not be sold at all (in the long run).

In this article we will look at the cost build-up and the throughput time build-up over a production chain. The former is of course directly related to the performance aspects "costs". The latter is related to the performance aspect "delivery". Throughput time through the entire chain determines the time needed for the different chain elements to react to changes in demand both of production volume and of production mix. Insight into the throughput time of the different elements of the chain therefore is an essential basis for decision making on delivery improvement. Recycled products are assumed to be included in the material input of our production-model.

## 3. Research method

### *3.1 The model*

As said, we start from an integral manufacturing system approach. That is to say, from the raw materials via the transformation processes and

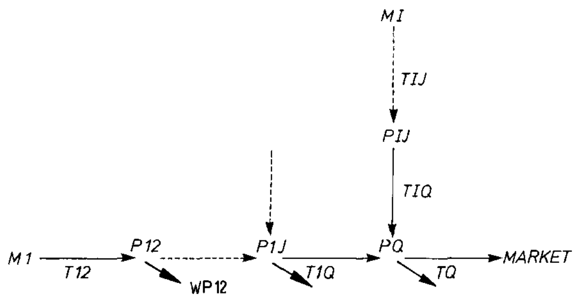


Fig. 2. A production chain. (TIJ = transport of raw material or semi product $i$ to manufacturing process $j$; PIJ = manufacturing process $j$ of (semi) product $i$; PQ = final assembling process; TQ = transport of the total quantity ($Q$) of end products to final users; WPIJ = waste of process $j$ on (semi) product $i$; and MI = raw material $i$)

transports up to and including the delivery of the final product. (See Fig. 2.)

For this purpose, products, parts etc. have to be defined at a certain aggregation level. Since our analysis should give insight into the build-up of costs and throughput time along the chain, products should be defined at the level of a certain group which can be expected to have more or less equal build-ups of parts and components. In practice such a group will often be called a product "family" (e.g. all P.C.'s of a certain type and size).

#### 3.1.1 Production function

For a production chain, a production function can be constructed: $Q+W=F(M,T,P)$; a quantity of products ($Q$) is the result of a number of processes ($P$) and transports ($T$) executed on a certain quantity of raw material ($M$). $W$ stands for the quantity of waste.

#### 3.1.2 Production process

Basically each production process is a transformation of material ($M$) through energy ($E$), labour ($L$) and capital ($C$), resulting in an output of ($Q$) (semi) products and ($W$) waste. Waste is defined as the emission of thermic energy, polluting and non-polluting material. (See Fig. 3.)

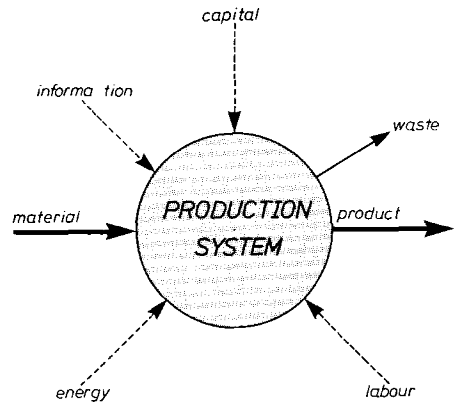


Fig. 3. A production process.

### 3.2 Cost function

Once all inputs of the different processes and all transports, necessary for a production quantity, are known, a cost function can be constructed by multiplying the input, waste- and transport quantities by their local prices. Equation (1) gives the mathematical expression for a cost function:

$$\mathrm{PS}_Q=\sum_{i=1}^{k}\{(M_i m_i)+\sum_{j=1}^{n(i)}(P_{ij}+W_{ij}w_{ij}+T_{ij})\}$$
$$+\sum_{i=1}^{k}T_{n(i)Q}+P_Q+T_Q \qquad (1)$$

where

- $\mathrm{PS}_Q$ yearly integrated production system costs for quantity $Q$;
- $M_i$ quantity of raw material type $i$ (including recycled products);
- $m_i$ price per unit of material;
- $k$ number of necessary material types;
- $n(i)$ number of manufacturing processes for raw material $i$;
- $P_{ij}$ process costs of process $j$ on (raw) material $i$;
- $W_{ij}$ quantity of environmental waste at process $j$ on (raw) material $i$;
- $w$ price for prevention or destruction of one unit of waste $W_{ij}$;
- $T_{ij}$ transport price of (raw) material $i$ to process $j$;
- $T_{n(i)Q}$ transport price from process $P_{n(i)}$ to process $P_Q$;

$P_Q$ assembly costs of process $P_Q$;
$T_Q$ total transport costs of production $Q$ to final consumer markets

By filling in the inputs (see Fig. 2) per process and their respective prices the following formula is found:

$$\mathrm{PS}_Q = \sum_{i=1}^{k} \{ (M_i m_i) + \sum_{j=1}^{n(i)} (C_{ij}c + W_{ij}w_{ij} + E_{ij}e + L_{ij}l + T_{ij}) \} + \sum_{i=1}^{k} T_{n(i)Q} + P_Q + T_Q \quad (2)^{a}$$

where

$L_{ij}$ number of man years in process $j$ on (raw) material $i$;
$l$ labour costs/year;
$C_{ij}$ liabilities invested in process $j$ on (raw) material $i$;
$c$ capital costs (interest rate and depreciation);
$E_{ij}$ quantity of energy used in process $j$ on (raw) material $i$;
$e$ costs per unit of energy (heat or electricity).

### *3.2.1 Analysis*

Having mapped the costs as described, the analysis can be carried out most easily when these results are presented graphically. Principally two approaches can be distinguished:
(1) per cost category over the chain; e.g. labour, energy, transport, over the whole chain. A bar graph is suited for depicting this (see Fig. 4) [7].
(2) per step in the entire chain; this makes clear where along the process flow the contribution to total costs is largest.
When we combine these two dimensions in one graph, the result will be like in Fig. 5. In order to make such a combined graph out of Fig. 4, additional information (a split-up of cost factors to location) is needed.

Cumulative costs per type (the dotted line represents the cumulative labour expenses along the production chain as an example) along the production chain ($X$-axis) can be read from this graph. So 100 here means the final price of the product in the market.

Figure 5 shows that labour represents about 30% of the total costs and that most labour costs stem from the extraction of raw material and the assembling phase. Not only the build-up of real costs of a delivered final product, but also the point along the chain where a fist analysis of the costs seems most interesting for further analysis, can be derived from such a graph.

### *3.2.2 Location dependent cost functions*

In the foregoing chapter the main focus was on the analysis of existing chains and networks. For international production strategy, a comparison has to be made with production systems on other locations producing comparable products. In that situation, location dependent cost function can be constructed. The location of a production system influences the distance to the raw material sources, to the suppliers and to the market and thus the transport costs and transport times. On top of that, different locations will have different prices and quality of the inputs and thus give a difference in manufacturing costs of the production processes in the chain. So the optimum location is defined as there where the sum of the transport costs and manufacturing costs is minimal, within the quality and delivery time constraints of the production system (given market demand).

The sensitivity for international competition of the specific product concerning costs can be simulated by making location specific cost functions. By comparing the various cost functions on the different locations one gets insight in the sensitivity for international competition or the best location to produce the specific products. Figure 4 can be seen as an example of a location dependent cost function.

### *3.3 The time function*

The total manufacturing time necessary for the delivery of products to the customer, starting at

[a] If $\mathrm{PS}_Q$ is expressed as a function of $Q$, the production quantity, and the different inputs are expressed technology dependent coefficients of $Q$, a similar cost function can be used for technology choices.

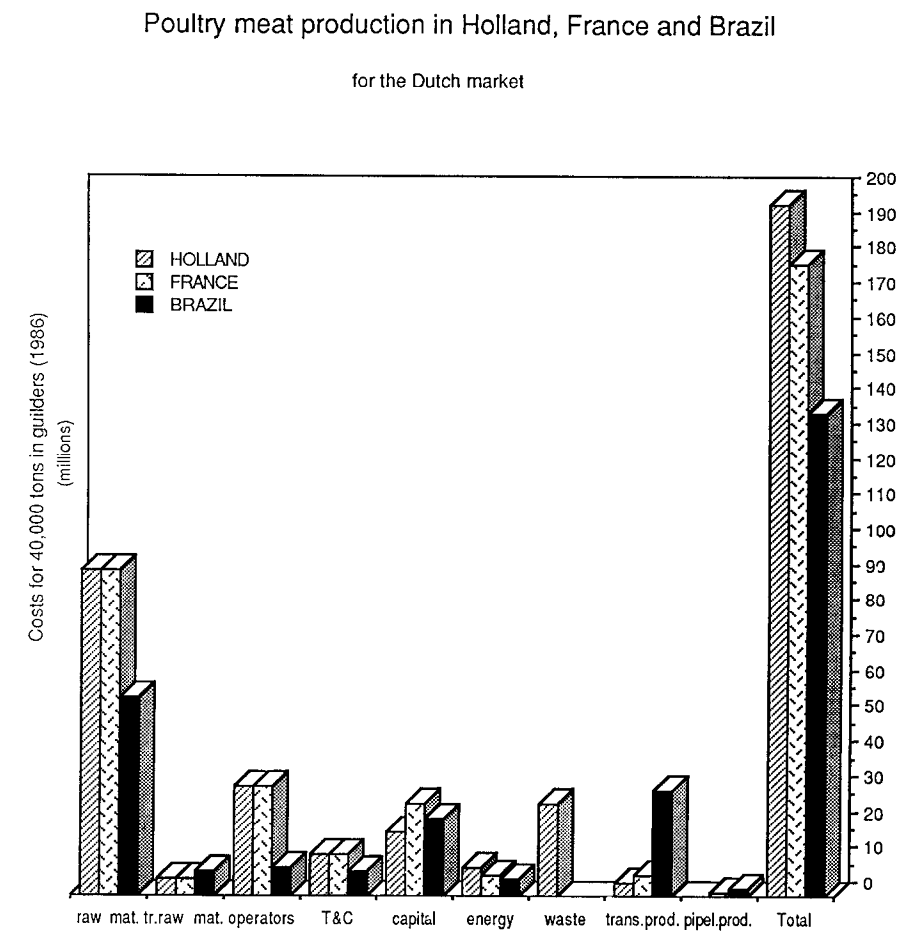


Fig. 4. Cost function of type (2)[b]. (raw. mat = raw material; tr = transport; T&C = technology and control labour; tran. prod = transport final product; pipel. prod = pipeline costs)

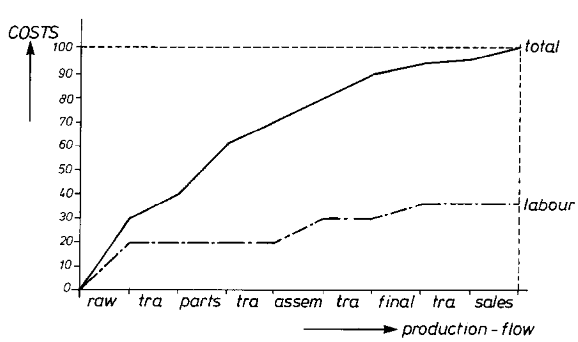


Fig. 5. Integrated cost function (fictive). (raw = raw material production; assem = final assembly; tra = transport; final = finished product inventory; parts = parts production; and sales = inventory in sales traject)

the last manufacturing facility ($P_Q$ in Fig. 2), is illustrated by the production-distribution scheme of Forrester [4], see Fig. 6.

As can be seen, there is a set of time elements; factory lead time, delays and inventories which together form the *planning loop*. This planning loop is the total time span from customer order via production to delivery of goods. If demanded goods are present in one of the inventories then of course the time span order of delivery is much smaller.

[b]In this example from the food-processing industry, a cost function for 40,000 tons of poultry meat was constructed (from egg-laying battery up to and including distribution to retailers). The data were obtained from a Dutch company in 1987 [7].

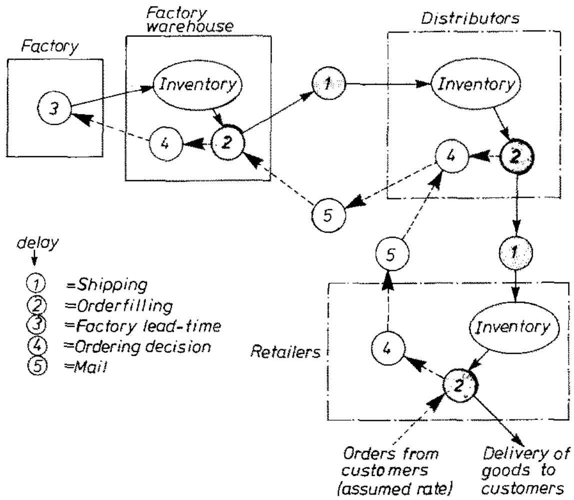


Fig. 6. Production-distribution scheme.

Apart from factory lead times and transport times, over the production chain, the R & D throughput time has become important. It is often stated [5] that the main bottleneck for a fast entrance on the market lies in the R & D phase. The Japanese are supposed to be faster in this respect. In this paper the R & D phase will not be treated further, we concentrate on the throughput-time in the production chain after the R & D process.

By measuring the amount of time spent at each of the composing elements of the planning loop we can get insight in the exact build-up of total throughput time for the production chain. We discern two parts in the planningloop:

- the administrative part: customer order to factory order;
- the physical part: factory lead time to receipt by customer;

(dotted lines respectively full lines in Figure 6). Generally speaking, a manufacturing firm faces the situation that a product has to be delivered with a specified delivery time against minimal costs. A time function can now be constructed by depicting horizontally the elements of the production chain and vertically the normal amount of time spent on each element. Vertical lines in the graph represent stocks.

As said, this throughput time of the material flow is not the whole story. There is also a throughput time of administrative channels. This is the time span between the observation of demand in a certain stage of the production chain, and the start of activities, based on the observed demand, in upstream stages of the chain. This time span includes:

- time-buckets used in the control systems;
- transport-time of messages between control systems;
- time-buckets in production schedules.

This administrative throughput time can be represented by vertical lines on the time function. These vertical lines start from the associated demand point. Their length represents the administrative throughput time from this demand point to its delivery stage upstream.

### *3.3.1 Analysis*

By adding the physical throughput time between the delivery- and demand point (the difference in level on the vertical scale), to the administrative reaction times an indication for the minimum total reaction time between the respective stages is found.

After having made a time function like the one in Fig. 7, conclusions on delivery possibilities can be drawn. The position of the so-called *decouple point*, i.e. the last main inventory point along the chain, can be projected. This can be done by subtracting the desired delivery time (vertical line through A between dots) from the total throughput time plus administrative reaction time in a certain stage (point A; Fig. 7). Going back along the $X$-axis on the level found by subtraction, the most upstream location for the decouple point can be found (point B).

This position has some important conse-

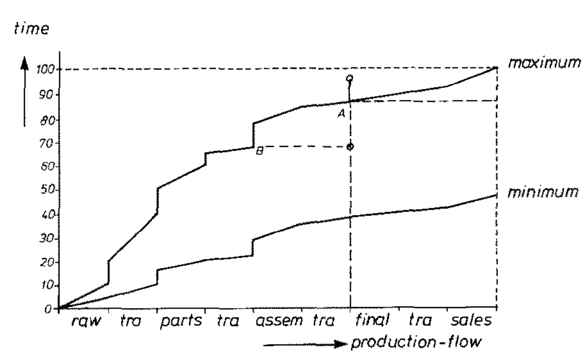


Fig. 7. Integrated time-function (fictive).

quences for the control of the chain, e.g. do you have to produce and sell from inventory of finished goods or can customer orders be satisfied from parts inventory (assemble-to-order). Production of parts or subassemblies in the far East, for example, will be expressed graphically by a sharp rise in the time curve, representing the typical one month transport lead time. Facing the situation of a customer demanding JIT deliveries (short lead time: short distance back on the graph) this means that the decouple point will be in inventory of products close to the market. Relocating production to Europe in this case, means a lower cumulated throughput time and consequently deliveries on "assemblage-to-order" basis, because the relative delivery time increases. Like in the cost-function, we here should concentrate on the part of the curve with the strongest "rise-percentage" too. It is precisely there that measures to reduce the total throughput time are most likely to have the strongest effect.

### *3.4 Application in practice*

In practice one problem sticks to this graphic representation of the cost function. Most products are build up of several parts, together forming the product's bill of material. To bring all parts in the function has two important disadvantages:
- it blurs the picture of the costs splitup over several categories;
- it makes information-gathering much more time- and money consuming.

Until now, however, we tackled the problem by using the simple truth that 20% of parts (grouped on basis of equal supplier specifications) usually represent 80% of costs.

Application of this time function gives a problem analogue to the one mentioned for the costs case. Again a product is typically build up from several parts, each with a different production, not to speak of development or administrative lead time. Here we solved this problem by taking into account parts and sub-assemblies with the longest respectively shortest overall lead-times. Putting these two profiles in the graph results in an area within which the total throughput time lies (see Fig. 7). Of course the more to the right on the $X$-axis (close to the final user) the more parallel both boundaries of the throughput time area run, since all parts go through the same (assembly-) processes there.

In practice, collecting the information necessary to construct the functions can be difficult. Especially when other companies make up a part of the production chain to be analyzed. In the case which is explained in Section 4, the cost and time information for the in-company part of the production chain was found by analyses of cost-price calculations and by means of measurements in production. The cost and time data for the rest of the production chain were based on quotations and even on balance-sheet analysis.

A last item concerning practical application of both cost- and time functions, is the possibility that the most interesting parts of the production chain for throughput time or costs reduction, do not lie in the sphere of influence of the same company that carries out the analysis. In that case, the functions can be a means for supplier or even buyer selection. Application of the functions can stimulate thinking about forward or backward integration.

## 4. Case

### *4.1 Introduction*

In September 1987 we started a research project with a European-based consumer goods manufacturer. The problem was initially formulated as something like: "How can we follow the market better from a manufacturing point-of-view?". Following the market here meant; following trends like:
- annual consumer price erosion of about 5%;
- shortening life cycles of product types;
- increasing number of product types;
- increasing variation in demand per product type.

Confronted with these trends a lot of pressure had been put on factories (assembly plants for the final product), to reduce manufacturing throughput times. The idea was that this would enable a quicker reaction to the market and hence improve profitability of the company.

*4.2 Analysis*

The situation sketched here formed the starting point of our research. As first analysis we used time- and cost functions along the production chain, from component- and subassembly production to distribution of the final product.

Due to the limited time available for the study, a cost function over the entire production chain could not be made. (We had to restrict ourselves to the part of the production chain, that is drawn in the graphs). Nevertheless, the graphs as shown here represent the "IST"-situation, for a part of the chain, quite well (Figs. 8 and 9). From these graphs we can immediately draw some conclusions concerning the bottlenecks in throughput time and -costs.

As far as throughput time is concerned, rapid reaction to market-demand is blocked at point C, Fig. 9, being the inventories of the sales organizations in the different countries.

So the conclusion was that not the factory but the control of the chain from the factory up to the market, is the key to improve the relation to the market. Another remarkable aspect of the time function was the relatively high and variable part of the total throughput time formed by transport to the market. Even relatively short distances turned out to take more than three times the manufacturing throughput time in assembly.

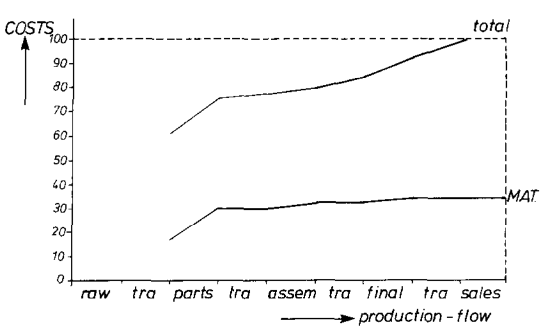


Fig. 8. Cost function.

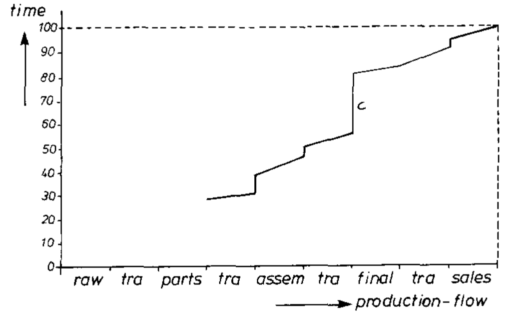


Fig. 9. Time function.

The costs graph indicates the integral costs build-up of the final product. The material content is represented by the lower line in Fig. 8. But the stage in which total costs are influenced most strongly is in the components-production stage, not in assembly.

*4.3 Possible solutions*

Given the existing situation, there seemed to be the biggest promise for structural throughput time reduction in elimination of the after-assembly stocks. This could be achieved by changing the existing control system in this part of the chain, since that was the reason for the extreme stock levels. Basic question in the design of such a system is; where to place the decouple point (the boundary between the order- and the plan-controlled part of the chain). In the existing situation, this point was located between final assembly and customers, a make-to-stock policy. As an alternative the decouple point was placed between component-supplier and final assembly; a make-to-order policy.

In order to find out whether the latter was a realistic option, flexibility in final-assembly was investigated. This seemed to be sufficient to cope with the demand, expected in a make-to-order situation. Depicted in time- and cost-functions, this would show smaller contributions to total costs and throughput time toward the right side of the functions. So on basis of time- and cost-functions of the (part of) the production chain the original problem could be reformulated into a more structural approach to performance improvement.

## 5. Conclusion

In order to measure the real effect of changes in a part of a production chain, we should look over the chain. Only if we use systems like MRP, JIT etc. to give the final customer an additional benefit, we can earn back our investments in these systems.

The integral cost- and time-function we developed turned out to be effective and efficient in practice. The quick and clear insight they give, forms a good basis for improvements in the production chain that really add value. So the conclusion can be drawn that a time- and cost analysis along the entire production flow, i.e. from raw material to finished product, should be at the basis of formulating a production strategy. Decisions on relocation or reallocation can be based on insights thus created. Also improvements in the control of the factory network in terms of total throughput times can be deduced that way.

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