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Evaluation Methods for Assembly Work and Product Design in Radically Different Production Systems: Results from Case Studies and Action Research in the Swedish Industry

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ABSTRACT:

This contribution reports on evaluation methods for assembly work and product design in radically different production systems manufacturing automobiles, trucks and sailing yachts.

Our results are based on extended case studies from automobile, truck and sailing yacht manufacturing during the last ten to fifteen years. The paper reports on:
- Results from empirical research evaluating production systems focusing on assembly work and product design.
- Theoretical frames of reference, containing methods for evaluating losses in a production system based on a pre-defined product.
- Evaluation of production systems using a hypothetical production system as reference ("zero system") and discusses the feasibility of this approach.

The so-called "zero-system" calculation is an evaluation method that takes into account both the time and capital losses induced by the production system. The analysis approach enabled us, through its raised scale level compared to conventional studies, to compare how well different production systems made use of resources. The results of the evaluation give indications as to whether it is the product or the manufacturing process that is most viable to reform.

Finally we draw some general conclusions about our productivity evaluation method concerning material supply and the use of available information on the product`s design.

KEYWORDS:

Assembly work, evaluation of productivity, long cycle time assembly work, material flow patterns, motor vehicle manufacturing, parallelized flow, sailing yacht manufacturing.

EMPIRICAL RESEARCH EVALUATING PRODUCTION SYSTEMS FOCUSING ON ASSEMBLY WORK AND PRODUCT DESIGN - SOME FINDINGS FROM RESEARCH WORK DURING THE 1970 - 80'S

Technology combined with work sociology proved a powerful technique when seeking alternative production systems to the traditional assembly line during the 1970's in Sweden, Karlsson (1979), Engström and Karlsson (1982).

Our research used a sociotechnical approach, with the result that researchers and practitioners initially formulated the hypothesis; - "Flow parallelization is the most attractive alternative production system for final assembly of large products such as automobiles, buses and trucks". However, parallelization in final assembly leads to material supply restrictions. The question emerged of how to find appropriate material feeding techniques.

In theory, partly based on a number of case studies, it proved to be both practical and economically viable to supply material for this type of production. These studies were based on the product being analysed by means of the so-called "design analysis", a method of assessing the manufacturability of a product (how difficult the product is to assemble) and how resource-consuming the assembly of a product is, Engström (1983).

After having concentrated on analysis of products, our attention turned to evaluating different production systems.

The analysis of the productivity of different production systems was made with the help of a so-called "loss analysis", a method of calculation developed by Wild (1975). The method was adapted to include a reference system in the form of a utopian loss-free system which introduced a reference point that is only dependent on the product. This so-called "zero system" calculation, Engström and Karlsson (1981) takes into account both the time and capital losses induced by the production system. The analysis approach enabled us, through its raised scale level as compared to conventional studies, to compare how well different production systems made use of resources.

The research was financed by the Swedish National Board for Industrial and Technological Development and resulted in several practical changes in the industry, Engström and Karlsson (1982).

A detailed "zero system" calculation was performed at the beginning of the 1980's for two separate yacht builders, Najadvarvet Corporation on the island of Orust and Comfortbåtar Corporation in Arvika. The sailing yachts were thus subjected to the most extensive analysis so far, the reason being that here the researcher could grasp the small production systems, Engström, Karlsson, Lundberg and Medbo (1984).

Assembly of automobiles and trucks were at this time too difficult to obtain an overview of. This, we realise after our last five years' research work within the Swedish vehicle industry, was caused partly by the lack of an assembly oriented product structure, Engström and Medbo (1991) and partly by the constantly changing work content (for reasons of balancing) on the work stations along the assembly line. Though comprehensive data was available, no one was able to describe the assembly of complete vehicles. Vehicles were, for this reason assumed to be, far too complex to understand because of too many components and an excessive number of variants.

The production systems we report on here are from companies with whom we have collaborated closely for at least five to ten years and participated in their development work.

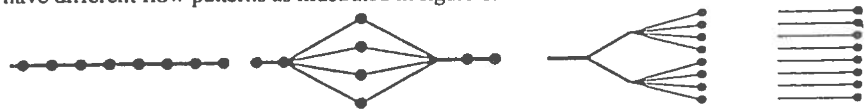
EVALUATION OF LOSSES IN A PRODUCTIONS SYSTEM BASED ON A PRE-DEFINED PRODUCT

Our "loss analyses" were based, as mentioned above, on Wild (1975). This method divides resource consumption into 18 different quantifiable factors, of which five are so-called "inefficiencies" which we here call "work inefficiencies" and the other 13 "system costs". The five "work inefficiencies" are balance, division of labour, system, learning and set-up losses.

The most significant losses relevant to assembly in traditional assembly line production are balance, division of labour and system loss.

The size of each loss is expressed as a percentage of the "necessary work" to perform the assembly. In the analyses this means the assembly time that is considered necessary and only dependent on the product. "Necessary work", in manual assembly, thus means the work time required for one ideal operator to carry out all the work, with the components materializing in his hand.

There is a strong connection between the choice of flow pattern for the product during the manufacturing process and the "work inefficiencies". The production systems we have studied have different flow patterns as illustrated in figure 1.



Serial flow pattern (vehicles)	Mechanistic flow pattern (vehicles)	Organic flow pattern (vehicles and sailing yachts)	Highly parallelized flow pattern (vehicles and sailing yachts)

Figure 1. Different flow patterns for production systems for final assembly discussed in this paper.

Results from evaluation of serial production systems manufacturing vehicles

We have in table 1 compared three production systems for final assembly of vehicles with different flow patterns, since these are the flow patterns used today for high volume serial production:

1 A serial flow pattern, traditional mass production system with paced line.

2 A semi-parallel flow hybrid production system. This system is characterized by a mechanistic flow pattern with centralized, mechanized functions and large differences in the degree of mechanization and parallelization in the process.

3 A parallel flow production system. This system is characterized by an organic flow pattern with successively decreasing mechanization, increased parallelization and maintained or expanded sorting capacity from the beginning of the process to the finished product.

	Serial flow pattern	Mechanistic flow pattern	Organic flow pattern
Balance loss (%)	30	15	5
Division of labour loss (%)	25	20	15
System loss (%)	80	30	20
"Work inefficiency" (%)	135	65	40

Table 1. Comparison, based on empirical data, of "loss analysis" between three production systems for automobile assembly with different material flows. The manufacturability of the products are approximately the same. Note that the organic flow pattern has considerably less "work inefficiencies" than the serial flow pattern, Ellegård et al (1991).

In the table 2 we show a comparison between Japanese and Swedish automobile assembly using serial flow. The figures were obtained from the "loss analyses" where rough estimates, based on official information and data from dismantling of automobiles, which we carried out in the 1970's. This comparison between Japanese and Swedish automobile manufacturing, using serial flow, shows that work pace was not a relevant reason for differences in productivity, Engström and Karlsson (1982).

We have assumed that a Japanese worker worked approx 40% more than a Swedish worker, owing to longer working hours, more overtime and shorter holidays. The Japanese manufacturer had only about half the "necessary work" on the automobile compared to the Swedish counterpart due to higher manufacturability. This enabled the Japanese manufacturer to produce approximately five times more automobiles per employee and year with the same work pace. These facts were not fully appreciated in Sweden in the 1970's.

	Japanese automobile serial flow pattern	Swedish automobile serial flow pattern
Balance loss (%)	12	12[1]
Division of labour loss (%)	8	8
System loss (%)	16	27 + 73[2]
"Work inefficiency" (%)	36	120

Table 2. Comparison between Japanese and Swedish automobile assembly with serial flow. Note that the manufacturability of the products are not the same, i.e. the "necessary work" is not equal, Engström and Karlsson (1982).

EVALUATION OF PRODUCTION SYSTEMS USING A HYPOTHETICAL PRODUCTION SYSTEM AS A REFERENCE

Analyses we have made of assembly work in some cases include not only "work inefficiencies", but also direct, production-related cost factors such as tied-up capital, indirect personnel, machine and tool requirements which we call "system inefficiencies". The term "system inefficiencies" as we use it here is not synonymous with "system costs" as defined by Wild (1975). Whereas Wild is using an ideal factory where, for example, costs for necessary machinery, tools, handling equipment, inventory and space are taken into account as necessary, we have taken another approach.

The reference production system we define as the "zero system" is an ideal production system where only "necessary work" is required and where no tools, machines, equipment, inventory, or premises etc are required. Thus all investments in means of production are considered as "system inefficiencies" and the only costs considered necessary, except for "necessary work", are the capital costs for the "base object" (i.e for automobiles the body, for trucks, the frame and for yachts, the hull) and material assembled, during the ideal throughput time. The "system inefficiencies" are then quantified as a percentage of what we call the "necessary system cost".

In comparisons of the efficiency of different production systems, methods for analysis are normally using correction factors attempting to make production systems and products directly comparable. One of the production systems studied is often used as a reference and the comparisons are made with a "better", higher scale, but in absolute values, i.e. time or cost.

The reliability of the results in this type of analysis is low, since products with different manufacturability and fundamentally different processes and production systems are adjusted using the same set of correction factors. Moreover, even small inaccuracies in a correction factor, e.g. which operations each production system comprises, lead to large errors due to effects of multiplication, for example Krafcik (1988).

The application of "zero system" calculation means that each production system is analysed individually and is assessed in relation to the product it produces with regard to "work inefficiencies" and "system inefficiencies". By means of these relative values (%) assessment

1 True for sequence balancing. If sequence balancing was not performed between variants, balancing loss increased by 10%. The Japanese automobile has been assumed not to have the same variant distribution as the Swedish automobile.

2 Post-production adjustment not carried out on the line. The loss thus comprises 27% attributable to the serial flow while 73% is post-production adjustment carried out after the automobile has left the line.

and comparison of different production systems can simply be made while maintaining the knowledge of each system's specific preconditions.

The normal procedure for determining "work inefficiencies" in production system for assembly is to use time studies to calculate the necessary assembly work. This is possible in vehicle manufacturing where such studies are available. Where time studies have not existed, as was the case for sailing yachts, we have instead counted components, classified their characteristics and correlated against the estimated assembly time requirement (which is one of the steps in the "design analysis"). The results were checked against observations, comparisons and interviews.

In the "zero system" calculation, we conducted for sailing yacht assembly, "work inefficiency" comprises the sum of the balancing, handling and system losses, since it was not possible to identify these individually. "System inefficiency" consisting of those losses not included in "work inefficiencies"[3] were calculated as costs differentiated as follows:

- Fixed assets; machinery, equipment, buildings etc.
- Current assets; interest on store, work in progress and finished goods. Of these costs, the capital cost for "base objects" and 67% [4] of the value of additional material for the ideal throughput time constitute the "necessary system" cost.
- Overheads; tools, maintenance, fuel, supervisors etc.

The ideal throughput time is determined from the "necessary work" in combination with the highest mean number of operators who are able to work simultaneously on the product.

The "zero system" calculation is used:

1 To identify rationalization potential for an existing production system with a given product design and to give priority to loss reducing measures.

2 To make comparisons between existing and/or sketched production systems with the same or different products.

3 To compare production locations in geographically different places with different pre-conditions.

The variation in manufacturability of products will of course also lead to varying resource requirements. Large differences in "work inefficiencies" between two compared production systems manufacturing two different products, with great differences in manufacturability, do not therefore necessarily mean that the system with the greatest "work inefficiencies" has the largest rationalization potential in production since design changes under certain conditions can be the most appropriate method of increasing production efficiency, even if this is not always possible.

When comparing different companies, it is important that the same rate of interest is used in order to be able to obtain comparable "system inefficiencies" and "necessary system" costs.

Results from evaluation of low volume production systems manufacturing sailing yachts (Comfort 32 and Najad 37)

The cycle time for workers or work-teams manufacturing yachts of 9 - 11 meters varied between 20 and 100 hours. For cycle times of more than 40 hours the learning time has proved to be considerable and the workers had difficulty in achieving full pace.

Of the total assembly time for sailing yachts, 10 - 30% was attributable to "necessary work" the higher figure refers to the sailing yacht with the highest manufacturability i.e. Comfort 32. For interior carpentry work, the proportion of loss-free time was often as low as 5 - 10%. The

3 It should be noted that "work inefficiency" and "system inefficiency" are not independent variables. An example of this is that the higher the "work inefficiencies" are the more operators and tools are needed and these require even more space. For this reason the "system inefficiencies" increase when "work inefficiencies" increase.

4 67% due to the effect of compound interest in linear consumption of addition material (all components have the same value and are added at the same rate during the whole assembly).

"work inefficiencies" were caused principally by adjustments and the handling time these involved. A considerable proportion of the worker's time was devoted to pre-adjustment i.e. the worker tested the fitting of components inside the hull and often had to go and make adjustments at a work station or machine outside the hull.

Even if it was not possible for us to individually identify each separate loss in the "work inefficiencies", we can with certainty say that division of labour loss was by far the dominating one.

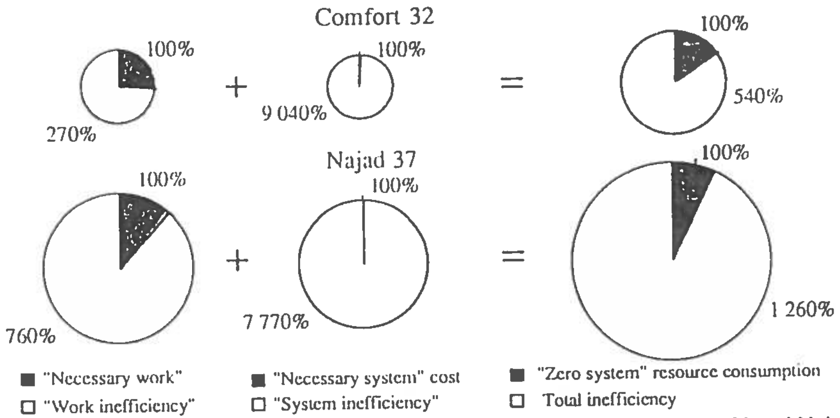


Figure 2. The result from the "zero system" calculation made for the Comfort 32 and Najad 37 sailing yachts. The areas of the circles in the above figure are in direct proportion to resource consumption. Comfort 32 has a greater manufacturability than Najad 37, and "work inefficiencies" are therefore smaller, while investments in means of production have led to greater "system inefficiencies" than for Najad 37. In order to make the "inefficiencies" comparable we have normalized these using costs as a base in the figure above, Lundberg and Medbo (1981).

Comparison of and results from "zero system" calculations in vehicle and yacht manufacturing

Swedish vehicle final assembly has developed from serial flow with high division of labour and efficient production techniques etc, to efficient team work on complete vehicles. Sailing yachts, on the other hand, have always had team work but with considerably less advanced production techniques. Table 3 is a summary of the characteristics of vehicle and yacht final assembly.

In Table 4 we show the results of "zero system" calculations for an automobile of a given manufacturability produced in three different production systems, for a truck manufactured in two different production systems, and for two different yachts, with different manufacturability, manufactured in two different production systems.

Table 4 clearly shows that with regard to "work inefficiency" the new production systems for vehicle manufacturing are considerably more efficient than traditional systems with serial flow pattern. The labour cost for the assembly work itself is however relatively small in relation to the actual production cost of the product.

These new production systems are also more efficient as regards space requirements and utilization , and are not at variance with parallelization (a twenty-fold parallelization of the flow does not demand twenty times as many tools).

Automobile (organic flow pattern)	Truck (organic flow pattern)	Sailing yacht (organic and highly parallelized flow pattern)
Differences:		
-Assembly both inside and outside the "base object".	- Good accessibility since assembly is carried out from the outside of the "base object".	- Assembly mainly inside the "base object".
- Extensive production engineering support and material is kitted before assembly begins.	- Very extensive production engineering support, with special attention to the individual product. Material is kitted before assembly begins.	- Little production engineering support and components are manufactured in the own carpentry shop.
- Many special tools, fixtures and labour-aiding equipment.	- Many special tools, fixtures and labour-aiding equipment.	- Not many special tools, fixtures and labour-aiding equipment.
- The product is specified in detail with extensive demands on assembly and components.	- The product is specified in detail with extensive demands on assembly and components.	- The product is not specified in detail and final design of components is often done at the same time as assembly (alignment, adjustment).
- Standard products with some individual customer specification.	- Standard products with individual customer specification. - Considerably more leads and connections than for the automobile.	- Standard product with extensive individual customer specifications.
Similarities:		
- Long cycle assembly work (automobile 100 minutes and more, truck 240 minutes, and sailing yachts 3 000 minutes). - Team work on stationary objects by highly qualified operators (the number of operators per product is; - automobile 7 - 12 operators, - truck 15 operators, - sailing yachts 15 operators). - Blue collar workers have direct access to foremen and supervisors. - Low manufacturability for the product compared to competitors (this does not apply to Comfort 32).		

Table 3. Summary of differences and similarities between some of the studied production systems for automobile, truck and sailing yacht final assembly.

SOME CONCLUSIONS ON EVALUATION OF ASSEMBLY WORK AND PRODUCT DESIGN

We show here estimates that the "zero system" calculation makes possible:

1 If we assume that it was possible to increase manufacturability for Comfort 32 to that of the automobile, it would be possible to assemble yachts approximately 60 times faster (we normalize on the basis of the observed number of components fitted per minute according to table 4). In the case of trucks 25 times more components are fitted per minute than for yachts despite the fact that the sizes of the products are almost comparable. That loss-free assembly time per component is longer in the case of yachts is partly explained by the fact that the components are heavier and require more space. Moreover, yachts contain proportionally more fasteners and these require proportionally more assembly time.

2 The sailing yachts involve more than seven times greater "work inefficiencies" than automobiles. The difference lies mainly in the sailing yachts' manufacturability and only to a small extent in the production system and its flow pattern, which represents a potential in changing the Najad 37 design to the manufacturability of the automobile of 19 times less "work inefficiency", according to table 4. It is possible, therefore, by means of "zero system" calculation, to determine maximum resource potential for product development aimed at increasing manufacturability.

"Inefficiencies"							
	High volume					Low volume	
	Automobile (the same manufacturability)			Truck (the same manufacturability)		Sailing yacht (two different products)	
	Serial flow pattern	Mechanistic flow pattern	Organic flow pattern	Serial flow pattern	Organic flow pattern	Organic flow pattern	Highly parallelized flow pattern
"Work inefficiency" (%)	140	70	40	160	40	270	760
"System inefficiency" (%)	20 000	30 000	20 000	25 000	20 000	9 000	8 000
Key factors							
Proportion of "necessary work"	1			2		4	10
Proportion of components assembled	1			1.8		0.3	1.2
Throughput time (h)	6	16	7	12	9	90	250
Annual production (No. of products)	100 000	50 000	50 000	6 000	4 000	70	40
Assembly speed (components/minute/"necessary work")	2.3	2.3	2.3	1.0	1.0	0.04	0.03
Space requirement (m^2/product/year)	0.6	0.6	0.4	4	2	13	15
Size of repair area (m^2/product/year)	0.2	0.2	0.1	0.1	0	0	0
Hand tools and mechanized equipment (no./assembly minute)	1.6	1.6	0.6	-	-	0.008	0.005

Table 4. Estimated inefficiencies and some representative key factors based on empirical data for some of the production systems studied. Note that the manufacturability of the products is not the same, i.e. the "necessary work" is not equal. Learning losses are not included in the figures for the organic flow pattern used for vehicle manufacturing, these can be significant in this type of system, unless methods described in Engström and Medbo (1991) are being used.

3 "System inefficiencies" in high-volume vehicle production are approximately the same while sailing yachts on the other hand have a considerably lower "system inefficiency". For "work inefficiency" the situation is the reverse. In absolute cost, "system inefficiency" is substantially greater than "work inefficiency", proving that low-volume production can be economically justifiable. This is true because the new, organic, highly parallelized production systems allow smaller production volumes with low "work inefficiencies", but in our opinion the potential has not, however, been fully utilized.

We would like to point out that the relation between "work inefficiency" and "system inefficiency" must be in better balance, which requires a greater resolution of "system inefficiency" than reported here. The ideal production system chosen is so ideal that "system inefficiency" may appear absurd. In some cases it would probably be more suitable to measure "system inefficiency" in absolute values.

We have ascertained that even if it is possible to apply the same evaluation method on such different products as automobiles and sailing yachts, the reasons for "work inefficiencies" are specifically different. As stated above, this is due to differences in the product's manufacturability, but also to the fact that in vehicle manufacturing, there exists a special pre-condition in that detailed information about the product is available from the design and central pre-production departments, before the material arrives in the production system.

If product information emanating from the work of the design departments is used correctly, it is possible to decrease the "inefficiencies". This principle has been used to create advanced

material feeding techniques for production systems using organic flow patterns, where for example, material is kitted for the individual product and supplied to work-teams who assemble complete vehicles (utilising the principle that work and work instructions support each other during the assembly work in order to, for example, speed up the learning time, Engström and Medbo (1991), Johansson and Johansson (1990).

The vehicles' components are carefully specified, with low tolerances ready for fitting. Sailing yachts, on the other hand, have many components which cannot be regarded as finished for fitting when arriving at the work stations. The components require some sort of adjustment, which causes extensive "work inefficiencies".

A practical consequence of our "zero system" calculations for one of the yacht builders was that after having decided that changes in the product design were not viable, the efforts were concentrated on decreasing the "system inefficiencies", since these were high. Although it was not possible to influence these directly, they could be decreased indirectly by changes in the work organisation which resulted in a higher average number of operators per product and thereby an increased production rate in the same premises and without any significant investments, Engström, Karlsson, Lundberg and Medbo (1984).

Some yacht manufacturers have in recent years approached the manufacturability of the trucks Two (examples of sailing yacht producers who are leaders regarding manufacturability are Dehler Yachts in Germany and Mac Gregor in California).

The modern - non-traditional - production systems for final assembly of vehicles with an organic or highly parallelized flow pattern, resemble the production systems used for yachts and can manufacture products with even lower manufacturability. This is due to the fact that the product can be allowed to stay in the work stations until finished.

In the future, however, traditional productivity evaluation concepts must be more varied and must be developed to include flexibility aspects, one reason being the small marginal cost of an additional product manufactured (since it is possible to run production on overtime in a part, or a number of branches, of the flow). Product changes are also carried out faster through increased competence and autonomy on the shop floor.

FUTURE ASPECTS ON REFORMING THE "ZERO SYSTEM" CALCULATION

The new organic flow production systems developed for vehicle manufacturing has made it necessary to place a special focus on material supply. The new demands on the material supply systems emanates from mainly two "sources". One is that the increased parallelization of assembly demands many more addresses to deliver the material to and the other is that long cycle time work demands that the material be presented to the operator in a way that supports his assembly work and decreases learning losses.

The use of just-in-time material flow systems also place high demands on creating order for assembly early in the value-adding chain.

The analyses presented so far in this paper have treated material supply activities as part of the "work inefficiency" or as activities that fall outside the production system proper, thus becoming part of the "system inefficiencies". Today we are concerned with activities involving bringing components to the assembly stations and rearranging them in the order determined by the product being assembled. These types of activities are of course value-adding whether they are being performed by the operators involved in assembly or by workers specially assigned to material supply and should not necessarily be viewed as "inefficiencies".

This creates a need to formalize and generalize experience by means of evaluation methods which simultaneously take into account both internal and external activities and relate these to resource requirements and the product design. Such methods have been developed partly by introducing the concept of "integration-level" as a measure of the ability of a material flow system to create orderly conditions, Engström, Johansson, Lundberg and Sjöstedt (1989).

"Integration-level" is introduced via the use of "entropy" as a theoretical metaphor for the degree of disorder at a position in the material flow system. The concept of entropy has earlier been applied to transport-related problems, Marthur, Satsagini (1985) and Tomlin and Tomlin (1968). Basically, the difference in entropy that a material flow system can achieve is considered as a measure of the value-adding characteristics of the system. We would in the future like to expand this concept to also include information on the product and material. This must be included in future evaluation methods and must also be included in, or complement, the "zero system" calculation method.

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