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- Manuscript for chapter in book to be published within the GERPISA-network (Permanent Group for the Study of Automobile Industry and its Employees, France).

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IMPLICATIONS FOR IMPROVING THE FLEXIBILITY OF THE EXTERNAL MATERIAL FLOW SYSTEM BASED ON THEORIES AND EXPERIENCES FROM TRANSFORMING THE ASSEMBLY LINE

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Abstract:

This paper presents some earlier known facts and theories as well as newly developed knowledge concerning alternatives to the assembly line. This knowledge is the result of action research performed in the Swedish automotive industry involving two of the present authors during the last decade.

The paper initially describes vital facts and theories which were relevant to this specific problem area two decades ago, constituting a platform for understanding the research and development work performed later in the Swedish automotive industry, as well as the performance and human effects of different assembly system designs. The case studies and plant designs referred to are primarily the Volvo final assembly plant in Kalmar, the Saab Scania body shop in Trollhättan and the Volvo final assembly plant in Uddevalla. These plants started manufacturing in 1974, 1976 and 1986 respectively.

The aims of the paper are as follows:

1 Explaining why and how efficiency and humanisation can be combined. This requires an understanding of the interrelation between the design of product flow structures and operator autonomy.

2 Illustrating this by reference to Volvo's Kalmar and Uddevalla final assembly plants. These plants have attracted international interest due to their design and Volvo's closing down decision in 1992.

3 Summary of the experiences from the Uddevalla plant concerning product flow structure and production scheduling system based on our experiences from the last decade of parallel flow production system design.

4 Identification of two different trajectories with regard to the development of interrelations between infra-structure and assembly systems: one traditional trajectory and one non-traditional. The latter takes advantage of the option of flexibility in parallel flow assembly systems.

We find the last point especially important since the ongoing reformation of the structures between and around automotive plants, particularly with respect to supplier relationships and administrative systems for handling information and materials in final assembly plants, a though suited for the further development of traditional assembly lines, might introduce severe restrictions for assembly system designs in general. This was to a large extent the case in the Uddevalla plant, which suffered from being different with regard to production flow structure and systems for administration of information and materials. This negatively influenced the design, running-in and full-pace production. On the other hand, it is possible to use the experiences from the Uddevalla plant for the articulation of important aspects of "the factory of the future".

1 Background

Two lines of development

In the light of recent developments in the international automotive industry, as well as experiences from alternatives to the assembly line featuring so-called autonomous work groups in the Swedish automotive industry during the last 20 years, two lines of development with regard to assembly system design have crystallised;

(1) refining repetitive, short cycle time work, in serial flow assembly systems (assembly lines), drawing inspiration from Japanese success cases;

(2) developing unorthodox long cycle time work in parallel flow assembly systems, which might be recognised as a new manufacturing paradigm, drawing inspiration from Swedish experiences.

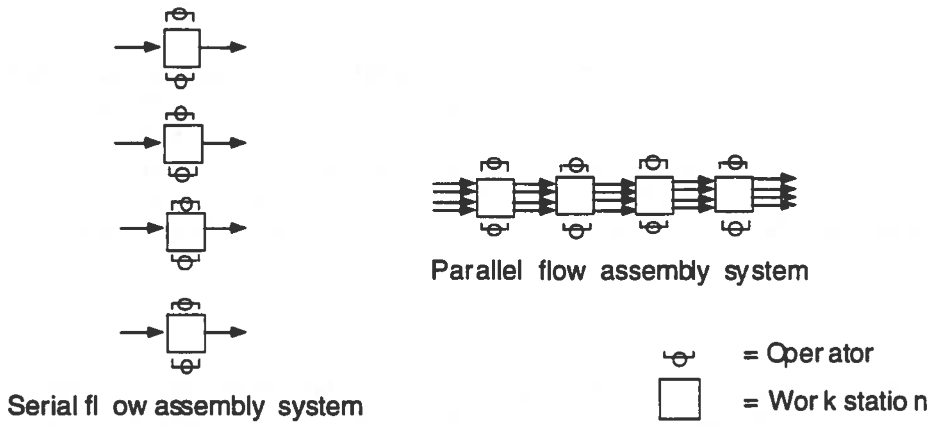

Figure 1. Schematisation of serial and parallel flow production principles. In a serial flow system, the product being assembled passes all work stations along the flow. The cycle time is short. In a parallel flow system, on the other hand, the product passes only one work station, and the work is less repetitive due to the increased cycle time. The work station design varies between assembly systems. In particular, work stations may accommodate a varying number of products and operators (in the cases shown one product and two operators). If operators co-operate on one or more products collectively we have a special type of working denoted collective working in a defined sub-system of work stations and workers, i.e. work station systems.

The parallel flow alternative has been assumed to be contradictory to traditional production engineering practice, striving for reduced manufacturing costs and using mechanisation and standardized work as important means towards this goal. Instead, this new alternative has been supported by the argument that, due to humanisation, sick-leave and turn-over would decrease, and this would compensate, for increased manufacturing cost in non-traditional assembly systems. This might earlier have been an efficient argument, but in today's recession, and considering the Japanese automotive manufacturers´ well-published international market successes, this argument for parallel flow production principles has lost much of its appeal.

The fact is, however, that parallel flow production does, correctly designed, simultaneously achieve increased efficiency and a more humane work compared to the assembly line. Admittedly, most of the Swedish efforts to replace the assembly line during the 1970 – 80s were not entirely successful, although some delimited exceptional examples exist. The explanation for the varying success of non-traditional assembly systems, discussed in this paper, generates important insights into man-machine interaction in complex production systems.

The international debate versus the contents of this paper

The Volvo Kalmar plant (1974 – 1994) was the most internationally renowned example of an assembly system adapted to work groups. Whether these groups were autonomous or not is a question treated below. The Kalmar plant used a serial flow and intermediate buffers between work groups. This plant was in fact quite similar to Toyota's new Kyushu plant.

It is worth noting that in some cases Japanese manufacturers have recently introduced assembly systems similar to the Volvo Kalmar plant built twenty-two years ago, thus reverting to some of the production principles introduced two decades ago in Sweden. In addition, this appears to have happened for the same reasons as in Sweden, namely the increased need for rework at the end of the assembly line, changing worker attitudes, etc. Ironically, after two decades of experience of non-traditional assembly systems, the Swedish automotive industry has in some cases recently introduced a European translation of a Japanese production system based on principles similar to those used in Sweden before the Kalmar plant was designed.

The Volvo Uddevalla plant (1987 – 1993), unlike the Kalmar plant, used parallel flow production which called for new materials supply systems and learning aids not fully developed or introduced on an industrial scale until the birth of this plant. This plant underlined the merits of the parallel flow production principles, as well as the difficulties experienced in the mixing of design, running-in and full-scale production during the same period resulting in a complex process full of contradictions (se Ellegård 1988).

The international debate about this specific plant has so far focused on (1) the effects on productivity and human aspects of applying parallel flow production principles and (2) the closing down decision in 1992. This debate has often relied on secondary data emanating from the Volvo management, and much of the debate seems to have been based on the implicit assumption that if something is good enough it is bound to survive on the industrial scene. In fact, information about the true performance and potentials of the Uddevalla plant was not even available to Volvo's top management when the closing down decision was made, although it is an open question whether this information would have affected this decision.

The international debate has thus not been based on knowledge about true effects in the form of efficiency and human aspects. In addition, the debate has largely neglected important aspects like what were the design assumptions behind this plant, what was already established knowledge before the initiation of the design phase and what was learnt during the design and running-in phases based on previous experiences of assembly system designs. We believe that the anachronistic developments sketched above are due to a lack of understanding of man-machine interaction – an understanding needed for the design of efficient assembly systems.

The authors and our data

Since two of the authors of this paper were involved in, and therefore partly responsible for, materials feeding techniques, layout work structuring, etc., i.e. the design of critical features in the Volvo Uddevalla plant during the start of the design phase, we also had the possibility to collect data during the plant's total life. This included, among other things, a closing down survey using a questionnaire covering ergonomics, psychosocial aspects and worker competence as well as personal data concerning age, education, time of employment, gender, etc., video recordings, structured as well as unstructured interviews and storing of all relevant documentation within the plant in an archive including 2 500 binders and personnel statistics.

The results from a partial analysis of this vast amount of materials have been published in e.g. Engström, Jonsson and Medbo (1996a). This publication summarises earlier analyses published complemented with e.g. analyses of questionnaires distributed during the closing down period. Below, we will illuminate some delimited aspects, using some of our information from the Volvo Uddevalla plant, to illustrate the topics chosen in this paper.

2 The Volvo Uddevalla plant versus the Volvo Kalmar final assembly plant

In this section, we briefly describe the Volvo Uddevalla plant and, as a background, the Volvo Kalmar plant.

The Kalmar plant 1974 – 1994

The Kalmar plant gained an international reputation. The design was heavily influenced by a top manager, who personally intervened in the design process, as was also the case in Uddevalla. His involvement inspired the entire Volvo Corporation to look for new production principles and a new work organisation.

The Kalmar plant was extensively used by Volvo for public relations purposes, but in most respects it did not fully match the image which the company promoted publicly. To overstate the case slightly, the design of the Kalmar plant enabled the assembly workers to "stand by the window and perform traditional assembly work" using an expensive AGV (Automatically Guided Vehicles) system to carry the automobile bodies. The AGV-system was originally intended to enable the operators to vary their work-pace, but in practice this did not happen. The interaction between buffer volumes and group work discussed below was not known at the time.

During the first few years, there was some difficulty in reaching the same productivity as on conventional assembly lines. After an extensive reformation of basic production techniques, the information system that supported the assembly work and the salary system, as well as a decrease in the number of employees, the man-hour costs in this plant were however reduced to 25 per cent below those in the Volvo Torslanda plant with its traditional assembly system (Agurén et al. 1985).

The assembly system in the Kalmar plant was manned by 27 work station systems, separated by intermediate buffers. The intermediate buffers were initially not intended to be used for assembly work, but were in practice used in this way (Agurén, Hansson and Karlsson 1976).

Originally, an internally parallellized production flow was an option in some work station systems. This working method was, however, abandoned due to the materials feeding techniques used and the lack of technical autonomy implied by the fact that the first-in first-out rule applied to the automobiles entering and leaving a work station system.

In 1987, assembly of the new Volvo 760 model started in the Kalmar plant. This model had a substantially longer total assembly time than the previous model assembled. To accommodate this new model, the plant was enlarged and the intermediate buffers were largely eliminated, since most AGVs in the buffers had to be converted to work station use. Space restrictions due to the building design and the size of the AGVs meant that the number of AGVs in the plant could not be expanded. Thus, the longer assembly time required by the new product and the restriction with respect to the number of AGVs forced buffer volumes to be reduced.

This modification more or less turned the Kalmar plant into an assembly line having the special feature of allowing the production sequence to be revised during the course of production to absorb variations in required assembly time. If required, it was possible to temporarily remove an automobile from the production flow without introducing waiting times. This was because the automobile on each AGV could be individually identified in the central computer system and also because the product specifications for each specific automobile were printed out and used as work instructions when an automobile arrived at the work station system.

In 1989, parallel flow assembly was introduced in those work groups where engine and gearbox sub-assembly was performed and these sub-assemblies and the rear axle were fitted to the automobile body. This change was initiated in order to improve the ergonomic situation in these work groups, but a predictable substantial increase in productivity was also achieved. The revitalization of the Kalmar plant is described by Sandberg (1995).

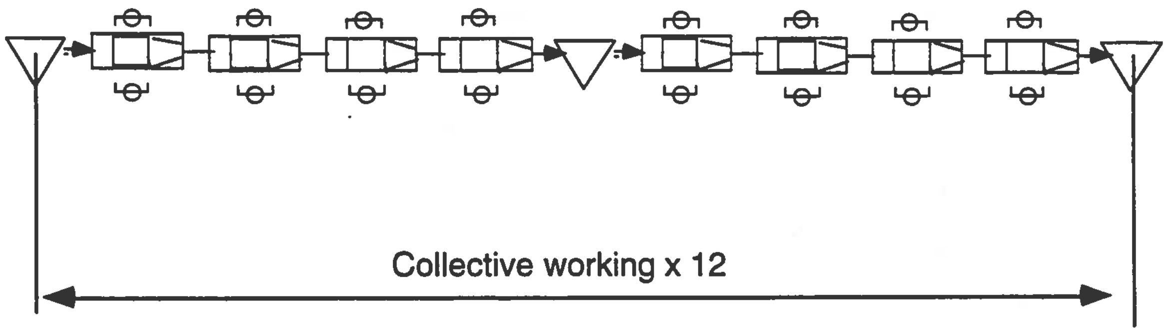

Figure 2. Shematisation of product flow structure and collective working at the defunct Volvo Kalmar plant, i.e. in this case work station systems. Note that, for reasons of simplification, this schematisation has omitted the subassembly stations sometimes integrated in the work groups performing final assembly work. During the final stage of evolution the work groups in some cases consisted of even larger work station systems with no intermediate buffers in between, i.e. the buffers in the middle of the figure above were eliminated.

The Uddevalla plant 1986 – 1993

This plant had six parallel workshops for assembly work with parallel work station systems. The product flow structure was similar to a so-called organic flow pattern, as illustrated in Figure 10. The flow of automobile bodies first diverged into a number of work station systems and later converged. At the start of this flow is e.g. the automated robot fitting of the windshield, while at the end of the flow there was the roller testing of the complete vehicle. Therefore, the assembly workshops were grouped around two parallel test workshops, where media (petrol, freon, etc.) were added and the automobiles were test driven. A separate material workshop prepared kitting fixtures. These fixtures, which contained the components needed to assemble complete vehicles, were transferred to the assembly workshops by means of AGVs.

The workshops for assembly work in the Uddevalla plant normally contained eight work station systems using one of two main layouts (Figure 4). In one layout, used in the three assembly workshops first started, the automobile was assembled in two stages with one sideways transfer within the work group. Each automobile was normally assembled by seven operators, and the normal cycle time was about 100 minutes.

In the revised layout used in the remaining three workshops, the automobile was not moved at all within the work station system during the assembly work. At the end of the final period of full production (i.e. in 1992), normally nine operators alternated between four automobiles. The normal cycle time was about 80 minutes. Of these workshops, only workshops 4 and 5 were used for production purposes, while the sixth workshop was used for training purposes.

In both types of workshop, there were buffer volumes within the work group available in the form of extra automobile bodies representing non-occupied working positions along the body as well as non-occupied working positions at the work stations for subassembly, i.e. doors, engine and dashboard. These subassemblies were therefore integrated into the work group. There was a slight but important difference between the workshops in that specific work group members performed engine and dashboard subassemblies in workshops 4 – 5, while all operators performed work on bodies as well as subassemblies in workshops 1 – 3, allowing otherwise idle operators to temporarily perform subassembly work.

It should be noted that a large variation in work methods and work group sizes existed in the Uddevalla plant. In one extreme case, two female operators regularly assembled complete automobiles by themselves.

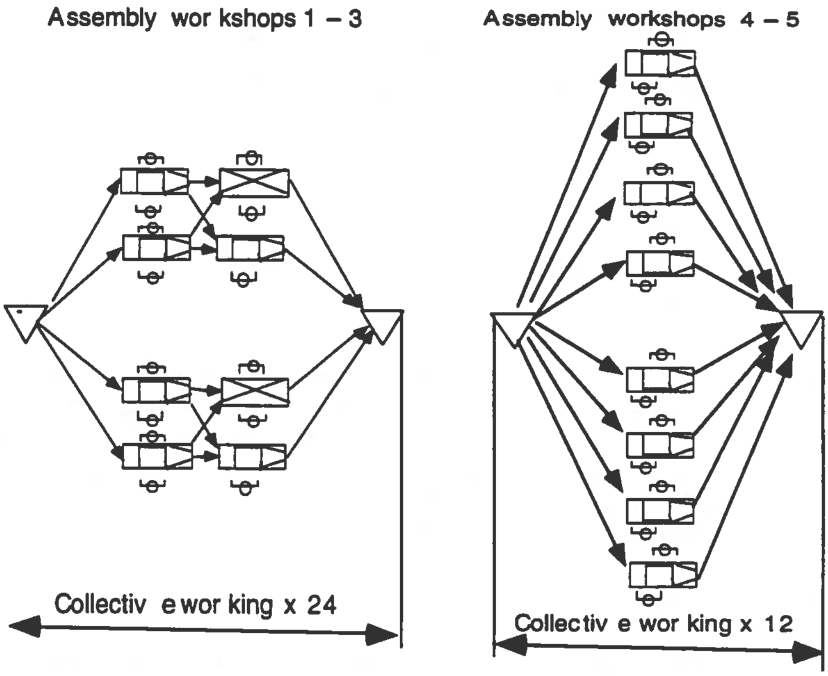

Figure 3. Shematisation of product flow structures in the different assembly workshops at the defunct Volvo Uddevalla plant. Note that, for reasons of simplification, this schematisation has omitted the subassembly stations integrated in the work groups performing final assembly work. The two work station systems to the left contain one extra product, in this case marked with an X. This product represents an invisible buffer, since the work corresponding to an extra automobile is floating around inside the system of maximum four products. Therefore any product inside the system is available for work but the worker concentration, i.e. the number of operators per product, is not maximised.

Example 1:

- In the Volvo Uddevalla plant, automobile components were fed to the assembly work stations in the form of materials kits loaded on kitting fixtures. Three pairs of kitting fixtures (the three interconnected squares in Figure 4) contained almost all components required for a specific automobile. An AGV-system connected the materials workshop with the assembly workshops. A number of stands for the kitting fixtures ran along the length of the building and were used by the materials workshop. The configuration of stands had to be identical in all final assembly workshops, because the common AGV-system and the same kitting fixtures were used to feed materials to all assembly workshops, as was the case with the automobile bodies.

The AGV-system contained a number of stands in each assembly workshop for each type of kitting fixture, corresponding to the components needed for approximately 1/3 of an automobile, while the materials workshop was divided into three separate subshops, one for each pair of kitting fixture. For reasons of costs, the AGV-system used a computerised control system which was not fully integrated. The aisles and roundabouts were divided into sectors, each sector corresponding to a decentralised computer. Thus an AGV only received messages to go from one sector to another in the vicinity, resulting in no possibility for the AGV-system to automatically prioritise between different individual transport assignments and AGV queues. That is, a specific AGV did not recognise what product it carried. Nor was it possible to have detailed control over all transports and give priority to the most important transport assignments according to the status of the assembly work. Hereby, assignments from e.g. one assembly shop impaired the transport capacity available for other assembly workshops. The AGV-system could not deliver materials kits with a guaranteed degree of precision. This precision was much more important than fast transports, because if a work group started building an automobile they had to be sure to have the subsequent kitting fixtures at hand when needed. This AGV-system later had to be supplemented by a manual control station, which was installed in 1990, allowing the computerized AGV control system to be manually overridden.

The AGV-system proved to be a severe restriction for the running in of, as well as the full production in, the Uddevalla plant. The new Autonova plant, opened in the same building facilities as Uddevalla also used parallel flow assembly but omitted the use of AGVs.

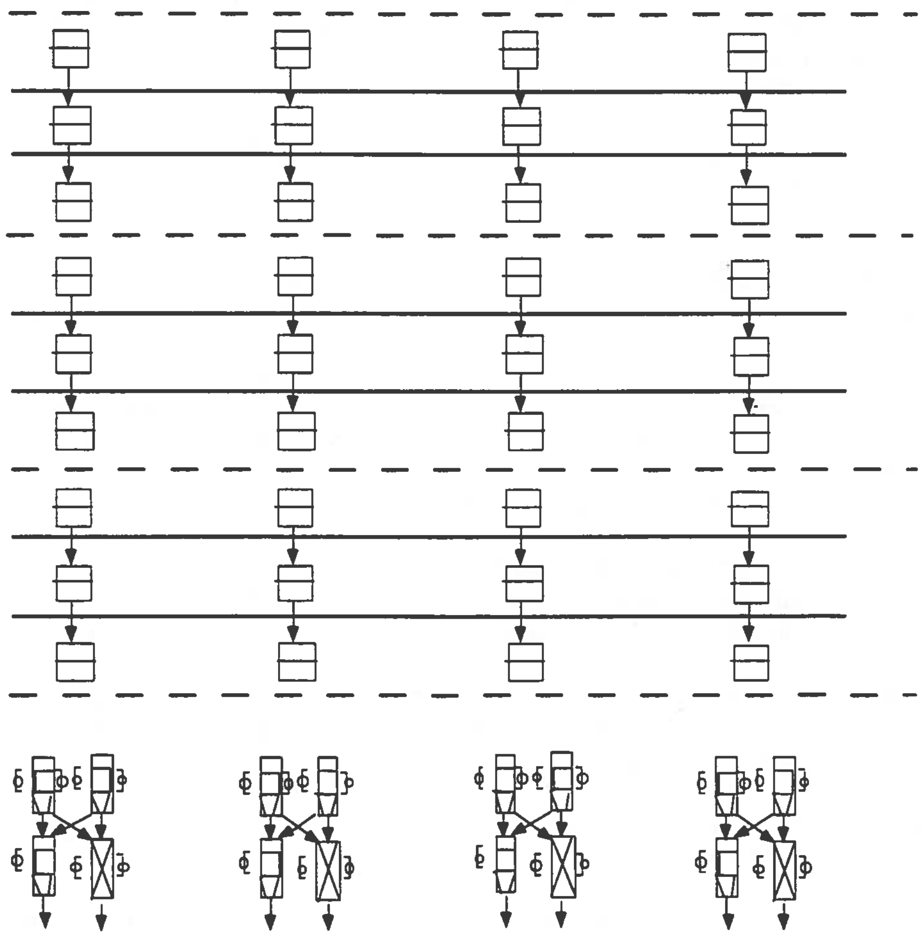

Figure 4. Schematisation of four work station systems in the Volvo Uddevalla plant and the deliveries of materials kits by kitting fixtures. Each automobile required three pairs of kitting fixtures delivered by the AGV-system to the work station systems in the assembly workshop (one AGV for each pair). The materials workshop was therefore divided into three separate subshops, one for each pair of kitting fixture. The queues of materials fixtures were derived from a common queue for the total plant. Three pairs of kitting fixtures contained almost all components required for a specific automobile, i.e. the three interconnected squares in the figure.

3 Production time losses and methods of avoiding these losses

Traditionally, production engineers use mean operation times based on time-and-motion studies when determining cycle times. Accordingly, they have concentrated on dividing the assembly work evenly between the work stations, neglecting the effects of individual variation, i.e. the fact that operators have an inherent variation in pace and efficiency in the performance of repetitive work. Such variation occurs both as inter-operator variation and as intra-operator variation, i.e. variation between operators on the same assembly line as well as variation between successive work cycles for a particular operator. Furthermore, the amount of work to be performed at each work station varies between work cycles and work stations due to product variation. There will also be process variation due to tools and mechanised equipment etc.

On the (machine) paced assembly line, the product is moved along the assembly line at a constant speed, making it available for work during equal time periods at the work stations. This leads to time losses due to the forms of variation mentioned above.

If the time the product is available at a work station is equal to the mean time needed to complete the work tasks assigned to that work station – meaning that inter-operator and intra-operator variation as well as other sources of variation in required assembly time are neglected – idle operator time will occur in some cases, while unfinished work will result in other cases. If the production pace is increased, idle time will decrease but unfinished work will increase; if the production pace is decreased, unfinished work will decrease but idle time will increase. In practice, the allocation of work tasks to work stations is often based on the product variant requiring the greatest amount of work, i.e. the most time consuming product variant will pace the flow.

On the unpaced (i.e. non-machined paced) assembly line, on the other hand, all time losses are in principle due to idle operator time. Each operator constitutes a potential bottleneck in the assembly system, so time losses tend to increase with the number of operators along the flow.

To summarise, assembly systems consisting of a number of work stations in sequence may fail to accommodate inter-operator and intra-operator variation, product variation etc. thus generating idle operator time and/or need for re-work. In both cases, extra manpower is needed (Wild 1975).

There are several approaches/methods of avoiding these time losses. Four main approaches will be considered for reforming the assembly line, namely:

1 To reduce intra-operators variation through standardisation of product and work, e.g. through reducing product variation, enforcing standardised work methods, improving component quality, selective recruitment of assembly workers, etc.

2 To introduce collective working with a flexible division of labour between operators, so that operators can use otherwise idle time to help other operators.

3 To introduce intermediate buffers between workers or work station systems of partly completed products that absorb inter- and intra-operator variation in required assembly time.

4 To break up an assembly line into many, short, parallel unpaced flows. As mentioned above, production time losses in an unpaced flow tend to increase with the number of operators along the flow, so time losses can be decreased by decreasing the number of operators along each flow.

Note that these four approaches/methods do not rule each other out, so two or more approaches may be combined. On the other hand, when time losses have been reduced through the application of one method, there is less need to use another. For example, when variation in required assembly time is reduced by standardisation in a specific assembly system, it might not be worthwhile to reduce time losses further through the use of buffers, group work or parallellization, since this requires extensive re-engineering, although these arrangements may serve other important functions. It should be noted, though, that some of the production time losses are generated by human variation which can never be eliminated.

Conversely, in completely parallellized assembly systems (with only one work station in each flow) variation in required assembly time does not generate time losses, so there is no need to try to reduce that variation in order to reduce time losses.

The three last approaches listed here will be discussed in some more detail in the next three sections.

Example 2:

- We have compared assembly times at the Uddevalla plant with corresponding assembly times at the main Volvo Torslanda plant, where the same model, the Volvo 940, was assembled on two assembly lines during the same period (1993). This kind of comparison is much more meaningful than comparisons between the Uddevalla plant and Japanese assembly plants, which are distorted by differences in manufacturability and extent of external subassembly work. For example, Adler and Cole (1995) compare 9,1 hours per automobile for Japanese luxury producers with 25.9 hours for the Uddevalla plant. On the other hand, Berggren (1992) reports that the standard assembly time for a door to a Saab has been found to be about four times as long as that for a Honda door. If this ratio applies to the entire automobile, a Japanese plant might have required 36.4 (9.1 x 4) hours to assemble a Volvo. Conversely, under the same assumption the Uddevalla plant might have required only 6.5 (25.9 / 4) hours to assemble a Japanese luxury automobile. Of course, neither these nor Adler's figures prove anything regarding productivity, since there is insufficient information about standard assembly times, and which is exactly the point (see also Berggren 1994 or Hancke 1994 concerning the international debate about the Uddevalla productivity).

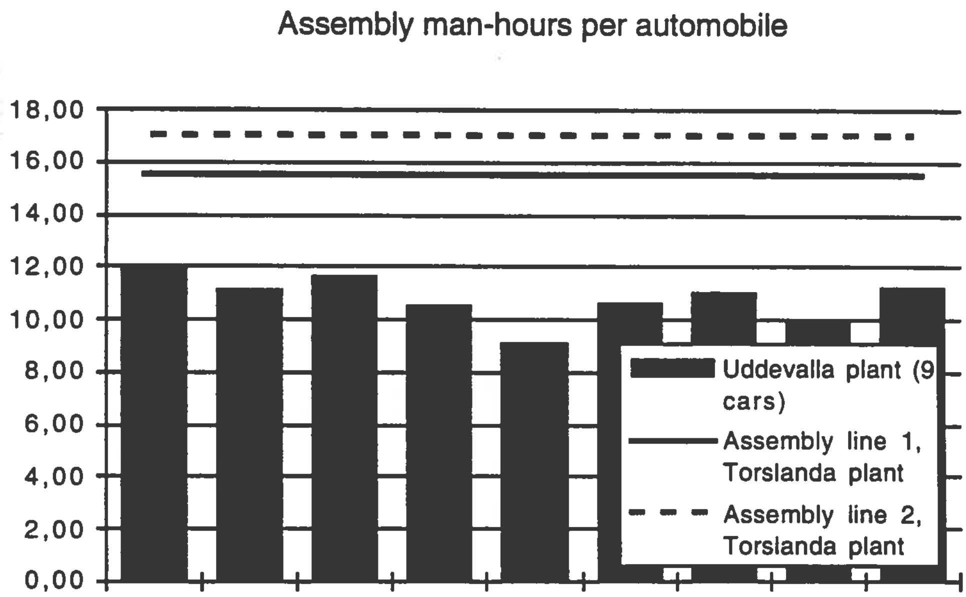

Figure 5. Observed assembly times for the nine video recorded automobiles in Uddevalla compared with the corresponding times for two assembly lines in the Volvo Torslanda plant 1992 – 1993 based on budget figures (Engström, Jonsson and Medbo 1995a). Note that the budget figures include production time losses. Source of data: the authors´ video recordings, Volvo data and The Volvo Uddevalla archive.

The comparison between the Uddevalla plant and the Torslanda plant in Figure 5 shows that for the same automobile model and the same operations, the Uddevalla plant required on average 10.8 hours per automobile for the nine automobiles we video recorded, while the two assembly lines at Torslanda required 15.5 and 17.0 hours per automobile, respectively. The comparison takes into account the assembly and materials handling at the individual work stations. The Torslanda data are derived from budget figures which have been normalised with respect to subassembly work, control and adjustment, roller testing, final adjustment and filling of media in order to make them comparable with the Uddevalla plant, thus obtaining a rough estimate of corresponding assembly man-hours.

The parallel flow assembly system in the Uddevalla plant thus required 4 – 8 assembly man-hours less per automobile than the serial flow assembly systems in the Torslanda plant. In percentage terms, 30% to 90% more man-hours per automobile were required in the serial flow systems.

4 Autonomous groups and collective working

The quest for useful design criterias seen in the two last decades for the purpose of reforming the repetitive work along an assembly line has crystallised the term autonomy (and thereby the term autonomous work groups) as well as and highlighted the fact that autonomy constitutes a relevant incentive for forming true autonomous group work on the shop floor.

This was in fact one of the main insights gained through the evaluation of the Saab Scania body shop in Trollhättan. This evaluation was performed by Karlsson and reported in his doctoral thesis of Karlsson (1979). Karlsson had worked on the shop floor in this plant for four years to collect data for his thesis. His experiences emphasised the importance of understanding the interrelation between technical and social dimensions in the form of possibilities of gaining self-determination of the work. The thesis of Karlsson is not very well-known internationally. It still contains results which are very valid for today's researchers and practitioners. In fact this thesis forms an embryo for a socio-technical design paradigm quite distinct from e.g. work participation and humanisation approaches, due to its implicit engineering point of view, focusing the design of the product flow structures including buffer volumes/positions and materials feeding techniques.

Karlsson distinguishes between technical and administrative autonomy. Technical autonomy, i.e. the possibility to "work up" (saving time by e.g. accumulating pauses due to unbalance, increased work speed, more efficient work methods), is in fact an important precondition for administrative autonomy. Thus, the transformation of the individual, short cycle time, repetitive assembly work into a more professional skill requires, among other things, firstly technical and administrative preconditions for working-up and secondly an integration of non-assembly tasks in the form of maintenance, quality control, production planning, as well as a conscious design in assembly work aimed at maintaining a relationship between work, work descriptions, product descriptions and materials display. Thus, by prestructuring information on material and product/materials, implicitly constituting "mental maps" of the assembly work (e.g. Engström, Jonsson and Medbo 1994a). In practice this entails reformation of materials feeding techniques in the form of e.g. kitting of materials, an assembly oriented product structure, parallel flow assembly using long cycle time work on a stationary product calling for unorthodox layout, etc. All changes call for revised, modern information systems support, since the information systems used in the Swedish automotive industry do not promote aspects important for an understanding of product and work.

Below we have very briefly summarised some of the general aspects concerning autonomous work groups based on the insights gained by the research connected to Karlsson (1979). These aspects have proved to be fundamental for the understanding of e.g. assembly work in the Swedish automotive industries of the 1970s, emanating from (1) Turner and Lawrence (1965), concerning how to realise/operationalise the sociotechnical school by the criteria autonomy, responsibility, feed-back, and variation and (2) Huse (1975) concerning the influence of motoric variation, since to achieve true autonomous group work in technically complex environments calls for integration of social and technical engineering. Thus, aspects like steering, responsibility, education, etc. certainly need to be considered in some way or other.

Some aspects and experiences from autonomous work groups

The rationale for using autonomous work groups is to create as flexible a work organisation as possible, as an alternative to more traditional forms of organising. This flexibility is assumed to make the autonomous work group more suited for a constantly changing environment. Relying on autonomous work groups is seen as an alternative to centralisation and rigidity, on the one hand, and decentralisation and chaos, on the other hand. This organization form is sometimes denoted multi-structured organisation. The group work pattern is derived from defined tasks, preferably by using a number of standardised set-ups. Different competencies are required in order make the group flexible enough, e.g. by using different group work patterns.

The possibility of organising autonomous work groups in complex production systems called, in the early 1970s, for some theoretical approach to operationalising human aspects from an engineering point of view in order to integrate both human and technical aspects in the design of assembly systems.

This need for integrating of technical aspects was not obvious during the 1970s since the public debate, as well as extensive research activities, focused on participation, including mostly social scientists. These activities were supported by political efforts in Sweden to improve work by legislation, e.g. Hörte (1981) and (1983) summarised by Dahlström (1983) focusing on power and participation. A general, vaguely formulated assumption that work groups were something to strive for existed within the Swedish automotive industry giving rise to e.g. the Volvo Kalmar plant, but the impact on the shop floor work in the complex assembly systems was not very deep partly due to the lack of engineering aspects.

However, one vital insight during this period concerned the distinction between goal-steering and direct steering, where the latter could emanate either from technical conditions on the shop floor (e.g. the assembly line) or from organisational conditions (e.g. the superior gives direct orders). Direct-steering hardly generates any commitment or positive attitude towards the work, since it implies involuntarily paced steering.

To transform direct administrative steering of individuals to administrative group-steering is relatively simple, but to transform technical-steering of individuals to technical group-steering is extremely difficult, since it calls for a change in the technical structures, in the form of e.g. machines, layouts, materials feeding, etc.

Goal-steering could imply a high degree of autonomy, but at the same time the self-determination through freedom and the feed-back of information on performance and quality output require responsibility, and to have responsibility entails strain. The strain is the price the individual pays for the extended freedom (i.e. technical autonomy). Thus the need to distinguish between technical and administrative autonomy, where the technical autonomy is a precondition for the administrative autonomy needed is assembly system to amalgamate efficiency and humanisation of the work.

To achieve a favourable development towards increased responsibility within a work group the goal of the group must be precisely defined. Clear rules for the interrelation with other functions, as well as clear demarcations are a precondition for increased responsibility of the group. Partly for this reason, group sizes of 5 – 10 operators are desirable. If larger groups are necessary, sub-group must be defined using rotating liaison men.

Rules regulating the behaviour within the group must also be developed in order to prevent the development of dysfunctional norms within the group. This means that it is necessary to include certain bureaucratic rules in the goal-steering of collective working. Experiences in Sweden indicate that it is important to regularly check up on group responsibility.

Therefore, when introducing autonomous work groups, the work in the production system must be regulated. One reason for this is that the work group must experience a sense of achievement when fulfilling the set targets, but also in order to allow the management to ask the right questions in respect of fulfilment of the rules. The rules are a precondition for good co-operation between group members and management. If the rules are omitted, conflicts will break out putting union representatives as well as managers in a difficult position.

The rules must be few, otherwise the work might be over-bureaucratized. They ought to be specified by written commitments between management and unions. If the rules do not work, the operators should in co-operation with the foreman etc., specify the changes as a suggestion to be discussed by unions and management.

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The multistructured organisation on the shop floor calls for the members to have sufficient education to perform many different work tasks. The education presupposes that the group members' overlapping competence is defined. The education of work group members is therefore in practice important. This education must be started early and include all the tasks of the work group. The education presupposes that the responsibility of the work group for indirect tasks such as quality control, transportation and adjustment is defined. The specific work group must also have the interconnection with other functions perfectly clear. The introduction of work groups thus calls for careful "engineering" of both technical and social preconditions. This engineering is quite dissimilar to traditional production engineering knowledge as it is taught or practised in the automotive industry.

The lack of careful "engineering" has in some Swedish experiences from reforming the work at the assembly line put extra strain on the production engineers, since their work becomes totally different from traditional work in untraditional assembly plants in which traditional engineers are employed. So even though the work organisation in the shop floor might be correct in principle, the functions around the groups sometimes have quite different, unexpected work tasks.

Example 3:

- A question discussed with regard to the Uddevalla plant is the relationship between the quantitative work content, on the one hand, and competence requirements and learning times, on the other hand. It has been argued that the learning times required, and thereby the costs for learning, would be excessive in the Uddevalla plant. This argument is based on the assumption that the relationship between quantitative work content and learning times is quasi-exponential in accordance with curve (i) in Figure 6.

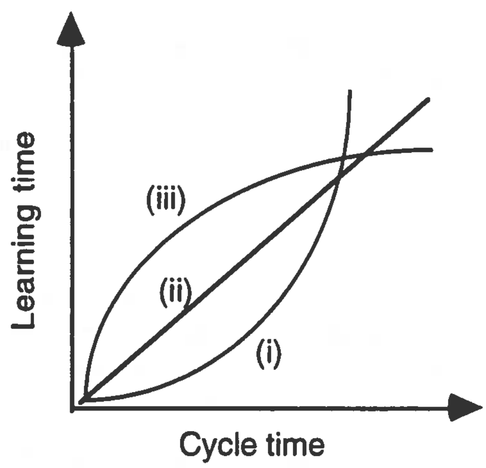

Figure 6. Three different types of relationships between cycle time (quantitative work content) and learning time (competence requirements).

Our data, by contrast, provide support for the hypothesis that the relationship between cycle time and learning time is quasi-logaritmical, in accordance with curve (iii) in Figure 6. The assembly work was not perceived as extremely demanding either manually or intellectually, and assembly work with longer cycle times was not perceived as more demanding manually or intellectually (Figure 7).

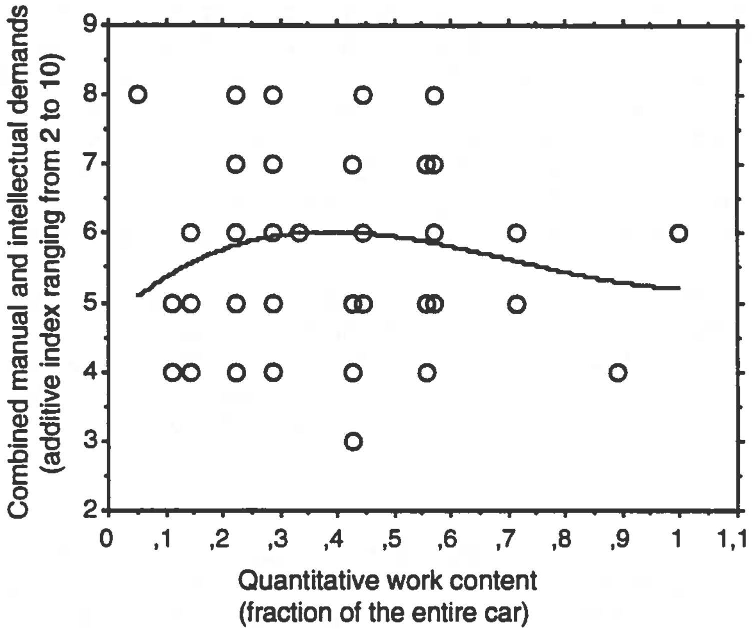

Figure 7. Observed relationship between quantitative work content and self-estimated manual and intellectual competence requirements. Non-linear regression (third degree polynomial). Assembly workers, n=68. Source of data: the closing-down survey (Engström Jonsson and Medbo 1996a).

> These findings are in agreement with our previous argument that short cycle time assembly is learnt by an "atomistic" learning process, following curve (i), whereas long cycle time assembly is learnt through a qualitatively different learning process, "holistic" learning, following curve (i). Further proof of the correctness of the holistic learning hypothesis was gained in a learning experience involving a trainee who assembled 1/4 of an automobile in the special experimental workshop that we used during our co-operation with Volvo (Engström, Jonsson and Medbo 1994a).

Collective working

Work in autonomous work groups is in this paper denoted collective working to emphasise the fact that workers work together on one or more products, having common responsibility for production output. Note that efficient "collective working" requires that the product is of sufficient size, or available in sufficient quantity, so that the workers do not block each other during the assembly work.

The efficiency of collective working with regard to idle time, amount of work in progress and production output (or conversely space required) has been demonstrated by research and simulation research (Wild 1975). Wild originally formulated and established the theoretical frames of references for what is sometimes referred to as analysis of production losses, or loss analysis.

The design principles for collective working advocated by this frame of reference are to:

1 Have a larger amount of technical autonomy on group level, i.e. the possible gain in technical autonomy by collective working ought to be larger than the gain on individual level. The assembly system should be designed so as to allow a speed up of approximately 25% in order to allow sufficient technical autonomy according to experiences from Saab Scania in the 1970s (Engström and Karlsson 1978 and 1982).

2 Avoid large work groups and place group members closely together, preferably within eye contact, in order to continuously overview the production and the status of internal work.

3 Introduce references to the planned capacity and quality output which is emphasised by the proximity of products and work. Therefore there is a need for decentralised planning and fast feed-back in order to facilitate a constant shifting of work tasks and strategic choice between individual and collective performance, as well as work methods.

4 Integrate work tasks that are possible to locate freely without affecting the production output. In automobile assembly this might be cleaning, certain maintenance, sub-assembly work, etc.

If these design principles are not used, the individual working-up may be the prevailing incentive, i.e., individual working-up is prioritised at the expense of the collective work. This was in fact the case of the Volvo Kalmar final assembly plant where the individual workers were using the buffers between the work group for assembly work. The feed-back on production results was monitored by a red and green light providing digitalised information of the performance (before or after the planned production; see Augrén, Hansson and Karlsson 1976). Due to the assembly system design (Figure 2) it was therefore impossible for the individuals to judge the amount of collective autonomy in order to make strategic decisions within the work group – the individual working-up was the only individual option available.

Example 4:

- As an example of analysis of these data, we have in Figure 8 illustrated the assembly competence in the different product workshops. The diagram is based on wage-related personnel statistics, which divided the assembly work into four steps 29 – 40%, 40 – 60%, 60 – 80% and 80 – 100% of an automobile. To summarise this data, 64% of the assembly workers learnt to assemble at least 60% of an automobile at full pace, and 4% were even able to assemble complete automobiles single-handedly at full pace, which they proved by performing a special test.

Note that in this case, we only report on the competence according to how the worker mastered the different types of assembly work. We have therefore called it "assembly competence". We do not consider other vital aspects of competence, some of which were included in the wage system, for example social competence in introducing new members to the work groups. The wage system was quite advanced and it was constantly being reviewed and debated during the plant's total life.

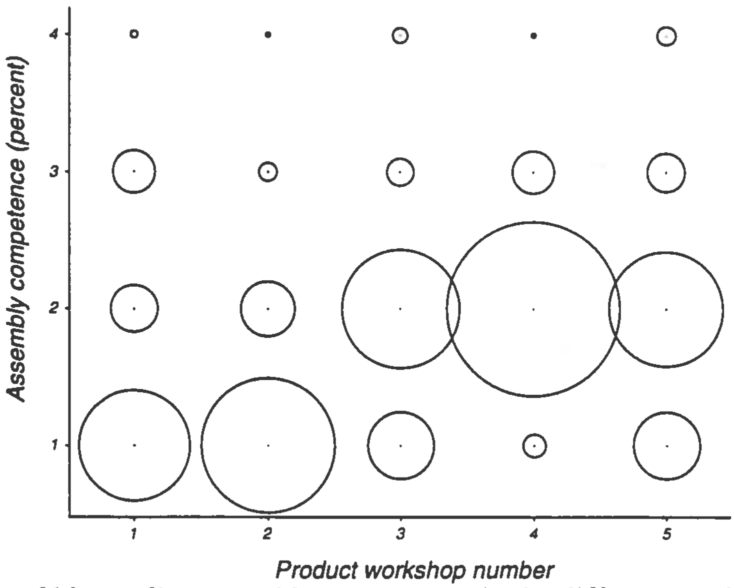

Figure 8. Distribution of blue-collar assembly competence in the different product workshops based on personal statistics. Note that step 4 in the diagram equals the ability to assemble complete

automobiles, i.e. 100% (Engström, Jonsson and Medbo 1994b) (Source of data: Volvo personal files).

The high assembly competence in the plant may to a large extent depend on the prestructuring of the components needed for assembly in kitting fixtures, which formed complete kits of the materials required for one single automobile. The relationship between the vehicles being assembled and the kitting fixtures supported a holistic learning process.

5 Intermediate buffers

Intermediate buffers, i.e. buffers between work station systems, may be characterised according to function, size and position in the production system. Considering the location, we may distinguish (Engström and Karlsson 1978):

1 Buffers between paced work stations
2 Buffers between manual paced work stations
3 Buffers between work group and paced equipment
4 Buffers between work groups
5 Recirculating buffers

It is possible to combine the buffer types mentioned above. General questions in the automotive industry concerning buffers also concern size and function.

Buffers differ according to type of utilisation, i.e. the reasons for which the volume is changed between empty and full. The change in volume is due to social or technical reasons or a combination of both. Note that buffers utilised due to social reasons implies technical effects, as well as the fact that technical buffers give social effects. Let us use the Volvo Kalmar assembly plant as an example of relationship between socially and technically dictated buffer volumes by referring to Augrén et al. (1976), see Figure 2.

> - "In a complex production as is the case in assembly of automobiles there are always different types of disturbances which hinder a smooth production flow. Since the Kalmar plant lacks methods for blocking the intermediate buffers, the buffers are sometimes filled or empty, which prevents the possibility of working up. This means there exists competition between the use of the intermediate buffers either for disturbances or for pauses" (translated from Augrén et al. 1976).

This quotations illuminate the importance of recognising the relationships between the production scheduling system and intermediate buffer volumes. In this case, collective working was supposed to be performed within a serial flow assembly system using intermediate buffers between work station systems (Figure 2). Unfortunately, the disturbances as well as the behaviour of operators belonging to the work station systems located before and after a specific work station system affected the buffer volumes. The information about production pace was monitored by a red and a green light indicating whether a work group was working in advance (i.e. red light) or were delayed (i.e. green light) in compared to the overall expected production output.

The buffer volumes could fluctuate widely, since in some cases the product allowed exceptionally high worker concentration (i.e. the number of workers normally working on a product) due to the product design. It was also difficult for the work groups to overview the collective work – the automobiles were placed in a long row, while in Uddevalla we deliberately condensed the distances between working positions on both the automobile bodies, as well as between the sub-assembly stations integrated in the work station systems in order to promote communication. The only reasonable behaviour for an individual in Kalmar was individual working up. Therefore, the automobiles in the intermediate buffers, originally not intended as work stations, contained a number of operators working intensively, neglecting collective goals, etc.

The Kalmar experiences underline the need for a large variety of available work methods and group work patterns, in order to gain an increased technical autonomy, since if no defined way of reaching autonomy is stipulated to the work groups, as was the case in Kalmar, reaching autonomy might be too complex and difficult.

To conclude, there is an enormous difference between buffers that are utilised due to individual or collective working up. The buffers may also be invisible or visible (Engström and Karlsson 1982), i.e. the invisible buffer is a buffer not consisting of a number of specific products. It could be constituted by the possibility to either increase the worker concentration or to move workers between products.

If non-assembly tasks are collectively possible to locate freely, independent of the pure assembly work, these tasks are valuable since they increase work group autonomy by acting as an "invisible buffer", i.e. a worker or a work group does not need to accumulate extra products in order to e.g. smoothen the product flow or to have some extra freedom. There is also a technical reason for integrating non-assembly tasks; they absorb disturbances and increase the production output.

In the extreme case of long cycle time assembly in a parallel flow assembly system, buffer products before and after the collective work station are not needed, since the speed variation in itself represents a buffer. Since buffers are not needed, space requirements are substantially reduced. In fact, one of the merits of parallel flow assembly systems is better space utilisation.

Note that:

- Invisible buffers are difficult to explain to the operators since nothing physical represents the accumulated working up.

- Social buffers collectively utilised may serve as a co-ordinator of work group members. This is both an advantage and a disadvantage.

- Visible buffers might serve as a direct planning instrument for the work group, i.e. the physical product waiting before or being left unfinished after a specific work group conveys a message.

- Increased technical buffer volumes reduce the need for social buffer volumes since the operator or operators do not need to add extra buffer volumes in order to guard against e.g. some types of disturbances.

6 Parallel unpaced flows

Parallellized flow

It should be noted that it is not the fact that there are several parallel flows but the fact that each flow is short and unpaced that reduces the time losses in parallel flow assembly systems. To attain sufficient production capacity the short flows usually have to be multiplied. However, but as far as the assembly work is concerned there is no economies of scale favouring assembly systems with a large number of parallel, short flows over systems with a small number of parallel, short flows.

To provide a quantitative illustration of efficiency losses as a function of the number of work stations in sequence, we have performed simulations of unpaced assembly lines of moderate lengths with different amounts of relative intra-station variation in assembly time. It should be noted that the efficiency losses according to Figure 9 are due to intra-station variation in required assembly time and do not include losses due to inter-station variation in required assembly time.

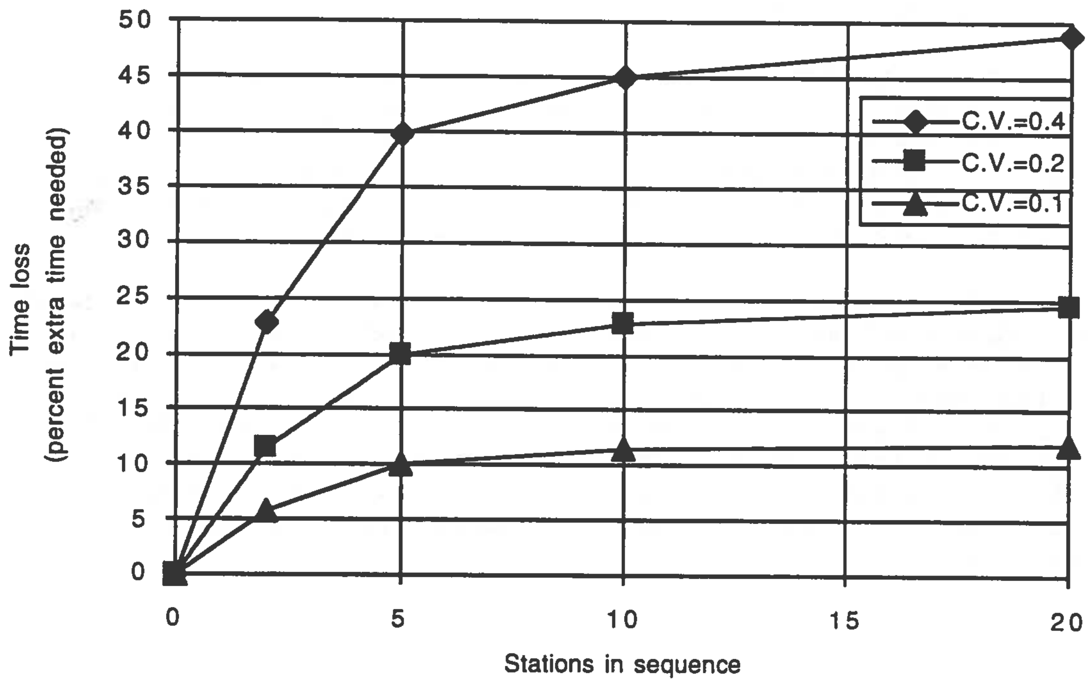

Figure 9. Efficiency losses due to intra-station variation in assembly time according to the length of the assembly line and Coefficient of Variation (C.V.) for the assembly time at each work station (Engström, Jonsson and Medbo 1996b).

Also note that a short paced assembly line is less efficient than a short unpaced assembly line of the same length, since, as noted above, the cycle time in a paced assembly line must in practice exceed the mean required cycle time due to the human natural variation in working speed while performing repetitive work. This applies to paced assembly lines of any length. In this case, there is strong pressure on keeping up with the pace of the assembly line. This does not mean that efficiency losses are eliminated, though; working "too fast" as well as working "too slow" leads to adverse effects in efficiency terms. For example, working "too fast" may generate re-work at the end of the assembly line.

Earlier research concerning repetitive work is certainly of importance for the understanding of non-traditional assembly systems of today. This research illuminates the importance of the impact man-machine interaction on performance. Conrad (1954, 1955) executed a number of experiments where he varied the degree of pacing, i.e. how paced the work was, and studied the effect on production output. One result was that the available time span for the operator had a critical influence on the production output. Optimising available time for work along an assembly line also increased output. If, on the other hand, the operator was heavily paced, the number of products manufactured decreased. Conrad concluded that production systems regulated by the operator were more efficient, thereby underlining the need for intermediate buffers in a serial flow (i.e. queues of products between work stations). This was later confirmed by Davies (1965) using computer simulation . Experimental studies by Buffa (1961) confirm Conrad´s conclusions about the importance of optimising the time available for work since that the pace of the product flow only has importance for output this is due to the fact that the product may become unfinished since the operators did not have time enough to carry out all necessary work tasks to complete it..

Dudley (1958) showed that an unpaced, trained operator has a skewed distribution of a repetitive work task, i.e. there are more short than long work cycles. Similarly, Murell (1963) indicates that the average performance of an unpaced operator is considerably higher. Note that a worker on a subassembly station with a buffer before and after that station could have an extreme technical autonomy due to the buffers before and after the station, even though the main assembly work in itself may be paced. This is one of the reasons for the popularity of subassembly work compared to work on the assembly line in some plants.

To some extent, it is possible to reduce intra-station variation in assembly time by reducing product variation, e.g. by including all "options" in all automobiles or by combining options into a few "packages". This means, however, that customers have to buy what the manufacturing system is good at producing rather than the manufacturing system being good at producing what customers want. The resulting "invisible cost" in the form of lost revenue is not evident from calculations of assembly man-hours per automobile, but may nevertheless be considerable.

While parallel flow systems need less man-hours than the assembly line, due to reduced time losses, and, in addition, working conditions are improved due to, e.g., increased technical autonomy, it should be noted that the design of such parallel flow systems is intricate. Such systems require an advanced material feeding technique, since the components to be fitted can not be supplied en masse in material containers (e.g. Engström 1983; Johansson and Johansson 1990; Brynzér 1995). They also require holistic learning to facilitate the learning of long cycle time assembly work, etc. (e.g. Nilsson 1981; Marton 1986; Marton, Hounsell and Entwistle 1986). And as discussed below, a parallel flow assembly system also calls for another type of mechanisation and automation than a traditional assembly line.

7 Mechanisation of assembly in parallel flow assembly systems

Mechanisation or automation of assembly work might seem to contradict the parallel flow production principle. Superficially, the numerous parallel work stations may be assumed to call for more assembly tools than required on the assembly line as well as multiplication of expensive automated production equipment, thereby making the cost of tools and automated equipment a severe restriction for parallel flow assembly. Automation and parallellisation would thus be two contradictory production principles. Note that automation of the assembly work requires a product design suitable for automation, which calls for engineering in the design department. This is not always economically feasible for small-scale manufacturers. Taking the product design of the 700/900-model manufactured in Uddevalla as an example, automation is not viable nor possible due to the product design, i.e. these automobiles have an extremely low manufacturability compared to some Japanese or German automobiles manufactured by volumes exceeding those of Volvo.

For example, the substantially extended cycle time, which in the extreme case is synonymous with the manufacturing of complete automobiles by a few individuals, may be assumed to require all the tools used along the assembly line to be available in each parallel work-station system. This would imply an enormous number of tools at the parallel flow work station systems. For example, 48 parallel work station systems, such as were to be found in the Uddevalla plant at full-scale production, might be expected to require 48 times as many tools as needed at an assembly line with the same production capacity. Thus, space restrictions at the work stations affecting tools and fixtures would render the parallel flow production principle unrealisable for this reason alone, not to mention cost considerations.

Also, the fixed, highly automated equipment needed on the assembly line somewhere during the assembly process can for reasons of cost not be directly multiplied due to parallellisation. This precludes that for example work station system using its own roller test facility.

Though plausible, this argumentation is questionable and to some extent false. Paradoxically, fewer tools may be required in a parallel flow assembly system than in a serial flow system (Engström and Sjöstedt 1984). As discussed further below, the fixed, highly automated, equipment ought to be redesigned and located at specific positions in the assembly system's product flow structure. This sometimes calls for splitting up the functions of the tools and the mechanised/automated equipment used on the assembly line.

The point is that the implicit assumption that the hardware should be transferred unchanged from the assembly line to the parallel flow assembly system leads to erroneous conclusions. For example, at the closing down moment of the Uddevalla plant, a large number of unused tools were sent back to the other Volvo plants since the engineers at Uddevalla did in many cases multiply the number of hand tools required at the assembly line by the number of parallel work station systems, to a large extent disregarding our calculations.

The interaction between parallellisation and mechanisation or automation is explained by the impact of the task frequency on the type of mechanisation, since the task frequency is decreased through increased parallellisation, long cycle time or group work.

If the task frequency is increased, i.e. if a specific work task is performed more frequently, automation may be necessary due to ergonomic aspects, since the human being is not fully suited for repetitive work exceeding certain frequencies and loads. On the other hand, if the task frequency is decreased, the load could be increased. This may be illustrated by e.g. the difference between lifting and fitting an automobile seat weighing 18 kg every two minutes on an assembly line versus fitting the same seat four times a day suggesting that at specific values of load and frequency the work transforms into a "healthy exercise". If the task frequency is increased it also becomes more economically feasible or desirable to automate, though in the case of assembly this also requires reformation of the product design (Engström and Karlsson 1982).

If, on the other hand, the task frequency is decreased, the assembly work will require less specialised tools, since fragmented, repetitive work will be transformed into coherent aggregates of delimited work tasks. Instead of fitting just the components available at the work position along the product possible to fit during a short work cycle, the operator fits interrelated parts requiring many different tools (e.g. fitting the data box for the fuel injection which requires box, console and screws, as well as fitting and connecting the cables).

Expensive pneumatic tools could in some cases be replaced by inexpensive, electrically driven tools provided that the cycle time is long enough (i.e., that the task frequencies low are enough). In the extreme case the operator fixes a number of fittings using the electric tools. Thereafter he torques down these fittings to correct torque using a torque wrench. The fact that the electric tool is slower than the pneumatic one is compensated by the lightness, the lack of air tubes and the fact that the worker could fit many components at the same time working in more "favourable" positions. Also, at long cycle time assembly work on automobiles, the pneumatic tools may force the operator to leave and re-enter the automobile body to shift the sockets in order to achieve correct torque, since in some cases equipment used contains a number of sockets and one or two air tools, where the choice of socket automatically monitors the correct torque.

Some of the tools used on the assembly line could be excluded or reduced. This specifically concerns tools with a fixture function since the operators in the work-group command the whole tolerance chain and are capable of fixing the component, adjusting its position and finally completing this specific assembly work by securing the prefitted components with the torque required. The fixture needed on the assembly line for the front and headlight details was thus not required in the Uddevalla plant. Also, fixtures used for gluing components could be substituted by small fixtures with low pressure (by springs or threads) to be applied for a long period. This was the case in Uddevalla for some rubber mouldings. Short cycle work and products that move from work station to work station, by contrast, imply gluing that requires high pressure and a short application period.

The argument for the reduction of the number of tools in parallel flow assembly system is supported by figures we extracted from Volvo data in 1990, also confirmed by our physical inventory in Uddevalla. The normalised figures for the Torslanda assembly lines and Uddevalla plant were 1.6 hand tools and mechanised equipment respectively 0.6 hand tools and mechanised equipment per assembly minute.

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Of course there are some work tasks which must be automated which use other kinds of expensive equipment. For example, the gluing of the windshield usually calls for a robot, a fixed highly automated equipment, due to tolerance requirements and the dangerous isocyanate vapours. If this type of equipment can not be redesigned to take advantage of the lowered task frequency, thus allowing the work task performed to be divided between several more general tools, the expensive equipment ought to (a) be positioned at the high frequency part of an organic flow pattern, i.e. where the flow diverges or converges or (b) be designed mobile and shared among workers or work station systems. Our conclusions are:

(a) A parallel flow assembly system needs less tools than a serial flow system and expensive automated equipment could be positioned at the high task frequency parts of the flow pattern, while the low frequency implies a larger proportion of manual work (a so-called organic flow pattern (Figure 10).

(b) Expensive mechanised or automated equipment could be designed mobile and utilised jointly by several work-groups or workers. This was the case in Uddevalla for e.g. the pneumatic tool needed to simultaneously fit the four bolts of the front engine beam (which was shared within a work station system) to the correct torque and the press for the front windshield gluing (which was shared between two work station systems). Other types of equipment handled the same way were the electrical test equipment and equipment used for checking if the air conditioner leaked freon.

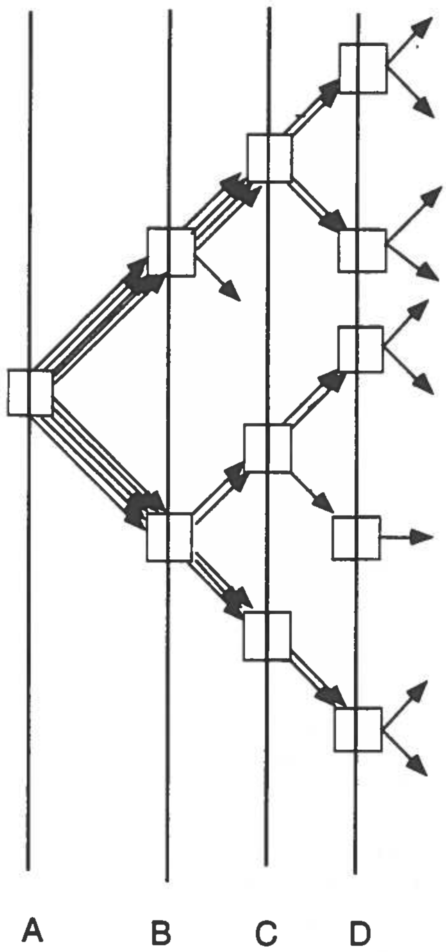


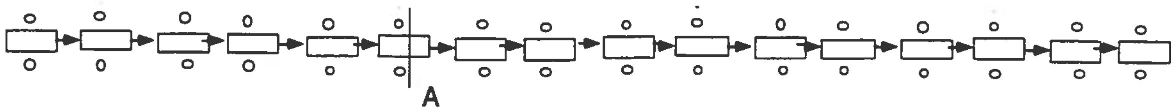
Figure 10. In an organic product flow structure the task frequency varies along the flow as illustrated in the figure above by the A – D arrows. In fact, comparing the frequency between a parallel and a serial flow for the manufacturing of automobiles, the relationship is, in practice, approximately 80:1. Our comparisons of the use of tools on an assembly line versus a parallel flow system clearly show that some mechanised or automatic equipment used at the assembly line could (a) be redesigned due to the lowered task frequency, thus allowing the work task performed to be divided between several more general tools, or (b) be positioned at the high frequency part of an organic flow pattern, i.e. where the flow converges or diverges, or (c) be designed mobile and shared among workers or work station systems (B – D).

Example 5:

- Below two simplified cases are illustrated, a serial flow and a parallel flow assembly system, denoted Case 1 respectively Case 2. We consider the utilisation of a tool used by one worker at the assembly line at one specific work station, e.g. a press for the fitting of the windshield, positioned at or along "A" in the sketches.

Case 1:

individual cycle time: 2 minutes
production rate: 0.5 product/min (cycle time = 1/production rate)
number of work stations: 16
work organisation: individual working



Case 2:

production rate: .0.5 product/min (cycle time = 1/production rate)
minimum individual cycle time: 8 minutes (4 x 1/0.5)
number of work stations: 4 x 4
work organisation: collective working on four work stations

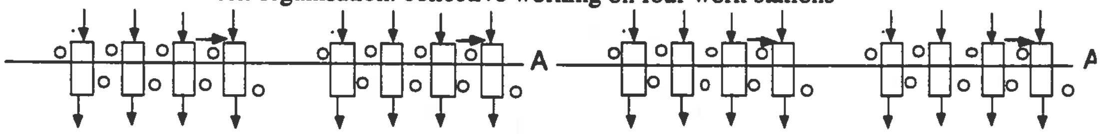


Figure 11. Two cases discussed concerning utilisation of tools comparing parallel and serial flow production.

In both cases, the assembly time required by each object is 64 man-minutes (disregarding, for simplicity, production time losses), and the throughput time is 32 minutes. In Case 1, the station time is 2 minutes, in Case B 32 minutes. In Case 1 the cycle time is also 2 minutes, but in Case 2 it is 8 minutes, since the operators circulate between 4 work stations.

In Case 1 this tool is assumed to be utilised 100% during the 2 minutes cycle time by two operators at a specific work station. In Case B the same tool is designed, mobile transversely along the product flow and commonly utilised by a work group performing work on four work stations (i.e. a work station system). In Case 2, the tool is required 2 minutes out of 32 at each work station, i.e. 6.25% of the time. If the demand for the tool at one work station is independent of the demand for the tool at another work station in the work station system, the tool will not be needed at any work-station in the work-station system approximately $p_0 = (1-0.0625)^4 = 77\%$ of the time. It will be needed at exactly one work-station approximately $p_1 = 4*0.0625*(1-0.0625)^3 = 21\%$ of the time, and it will be simultaneously needed at two or more work-stations approximately $q = 1-p_0-p_1 = 2\%$ of the time.

In this case, where a tool is shared between four work-stations, so that four tools are needed, the multiple utilisation problem is not very serious, as the tool will be simultaneously needed at two or more work-stations during only about 2% of the time if the demand for the tool at one work-station is independent of the demand for the tool at another work-station in the work-station system. If we want to reduce on the number of tools, however, synchronisation of intra-group and inter-group work is called for. This requires methods such as (1) stipulating the production sequence within each work station system, and (2) booking schemes with specific time spans for the use of the tool as preferred at extremely expensive fixed production equipment such as roller test stations which require solid fundaments, as well as other types of installations in the building facilities.

Correctly designed the synchronisation of production sequences may have a humane, as well as a technical merit. It promotes group work since it calls for the workers within a work station system to co-operate and it minimises e.g. the need for resequencing the product specific materials fitted, minimises the queues of products coming and leaving the parallel flow assembly system, etc. (se discussion in Section 8). On the other hand, inter-operator and inter-group synchronisation of assembly work introduces dependencies between operators. Thus decreasing autonomy but promoting co-operation. Unless there is true collective working, these dependencies, like the dependencies inherent in assembly line, will cause production time losses.

Note that the utilisation calculated above is in fact even lower if we include the production time losses in the argument. From a theoretical point of view these losses can not be better than 50% and in practice they have proved to be over 100% (e.g. Engström and Karlsson 1982).

The design of assembly systems with regard to mechanisation and automation of assembly work thus depends on the task frequency. The task frequency, in turn, is a parameter affected by the division of labour. Hence, product flow structure and work station design are related to the need for or the possibility of, mechanising or automating the assembly work.

To conclude, a parallel flow assembly system calls for another type of mechanisation and automation of the work than a traditional assembly line. This mechanisation and automation will vary "organically" according to the different task frequencies in the product flow structure. Thereby a fixed "automation level" is not needed. Depending on both the potential revenues and the technical difficulties in automating the function considered, the degree of automation may vary according to the task frequency and the possibility of moving equipment between or inside different work stations systems or work station systems. At an assembly line the span of feasible mechanised/automated installations is considerably more restricted.

8 The production scheduling system in the Volvo Uddevalla plant and its implications

Some shortcomings of the Uddevalla plant in relation to the production scheduling system

While the Uddevalla plant achieved rather impressive assembly performance (see example 2), it could have been even more impressive. The Uddevalla plant had the opportunity to improve its productivity further, as shown by our video recordings of the assembly work in the workshops. We noted that the work pace in the work groups was superior, by about 15%, to that based on standard assembly times as calculated by production engineers using time-and-motion studies (Engström, Jonsson and Medbo 1995a; Engström, Jonsson and Medbo 1996b). This potential was never fully utilised since there was a general lack of understanding of the production principles applied, as well as a lack of knowledge of the he plant's true performance. Of course the fact that extensive revision of, among other things, the production scheduling system and the materials workshop was required to take full advantage of the potential made it somewhat difficult to argue for an extensive rework of Volvo's most modern plant. These malfunctions are to some extent rectified in the new Autonova plant.

Furthermore, while the psycho-social work environment observed in our survey of assembly workers at the Uddevalla plant (Engström, Johansson, Jonsson and Medbo 1995) was favourable compared with industrial blue-collar work in general, with respect to most psychosocial job factors measured, the psychological work load was rated as less satisfactory in the Uddevalla plant than among blue-collar workers in the engineering industry in general.

The profiles from the measurements of psychosocial job factors among assembly workers, compared with reference data from blue-collar workers in the engineering industry, are shown in Figure 12.

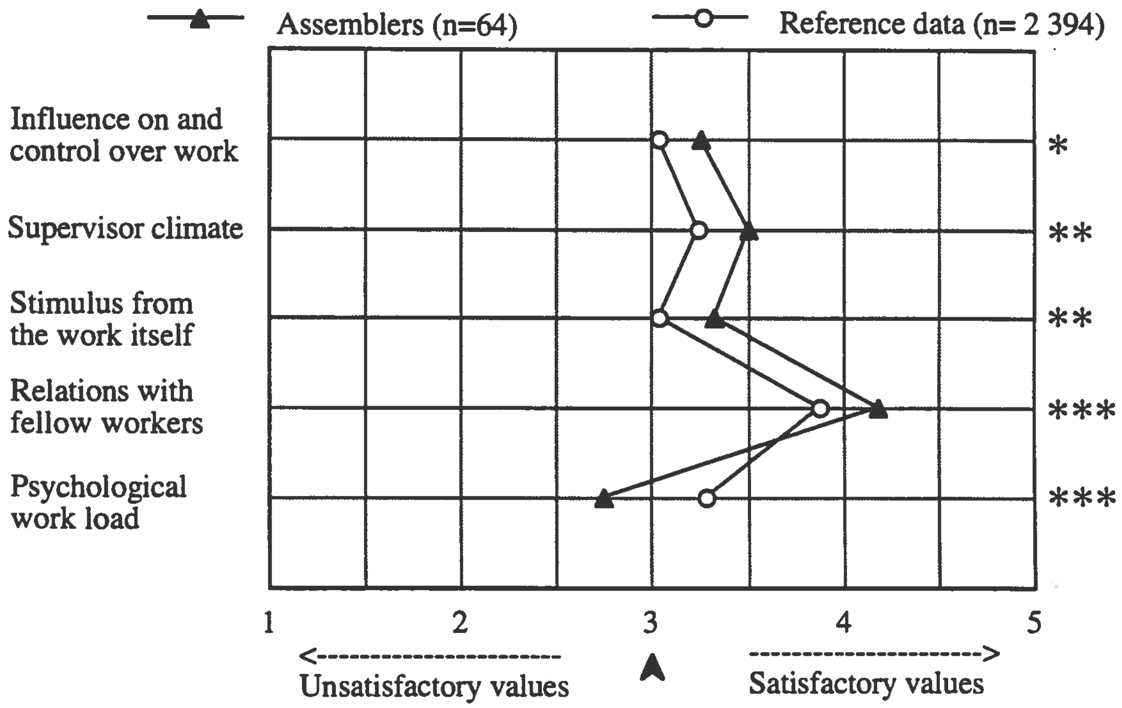


Figure 12. Profile of attitudes to work, showing psychosocial job factors by mean values (Engström, Johansson, Jonsson and Medbo 1995). Note: the significant differences (according to a two-tailed t-test) between the assembly workers and reference data (industrial blue-collar workers) are marked with asterisks (* p<0.05; ** p<0.01; *** p<0.001). Source of data: the closing-down survey.

Examination of the differences between the assembly workers and reference data (Figure 2) showed that there were significantly more satisfactory values in the study sample with regard to the factors "influence on and control over work", "supervisor climate", "stimulus from the work itself" and "relations with fellow workers". In contrast, "psychological work-load" was rated as significantly less satisfactory in the study sample.

The failure to realise its productivity potential as well as the somewhat unsatisfactory psychosocial work-load may be partly explained by the production scheduling system used in the Uddevalla plant, a system whose design was based on the traditional assumption of the merits of detailed control over the production flow.

While the Uddevalla plant was a parallel flow assembly system, it operated somewhat similarly to a system composed of a number of short paced assembly lines, due to the design of the AGV-system and the production scheduling system using fixed starting times, planned weeks beforehand, for all the work station systems derived from a common queue for the total plant. For example, it was not possible to start assembly of a particular automobile ahead of schedule so as to create a safety margin enabling the group to fulfil its production quota even if the assembly work was adversely affected by unexpected disturbances or working-up. So while the flows in the Uddevalla plant were not paced, they may be characterised as "administratively paced", and as noted above, short paced flows are not as efficient as short unpaced flows.

Internal production scheduling and product flow structures

In the Volvo Uddevalla plant the materials kits, each of which was delivered on three pairs of kitting fixtures, were put together in a common materials shop delivering kits of materials to all of the six assembly workshops. The kits as well as the naked automobile body were transported to the assembly workshops by an AGV-system. The production scheduling system was designed so that each particular materials kit was assigned to one of the approximately 40 work station systems and a specific product weeks in advance, long before the actual picking of the components in the materials workshop and the start of the assembly work.

This procedure actually functioned as a number of separate parallel queues of specified, interchangeable products. Interchangeable in the respect which was, according to the planners responsible for the design of the system, not allowed. In practice it turned out the other way around. This was basically due to the scheduling of the production and materials flows being nuanced only in the form of product individuals. Thereby restricting the optional flexibility of a parallel flow assembly system since it was impossible to accumulate the working up between automobiles. In fact the assembly system was working almost like a number of short paced assembly lines on which the work station systems or individuals were never able to work in advance, never given the satisfaction to reach or exceed the production quota.

To make things even worse, the naked body was assigned to a specific product at the Torslanda plant, thereby refraining from the possibility of replacing a defective body by another body of the same type. This option is especially desirable in automobile manufacturing in Sweden due to the somewhat inferior quality of naked bodies too a large extent manufactured by automated production as is common practice. The Kalmar plant had another better planning procedure, partially designed by people with experience from the Uddevalla plant.

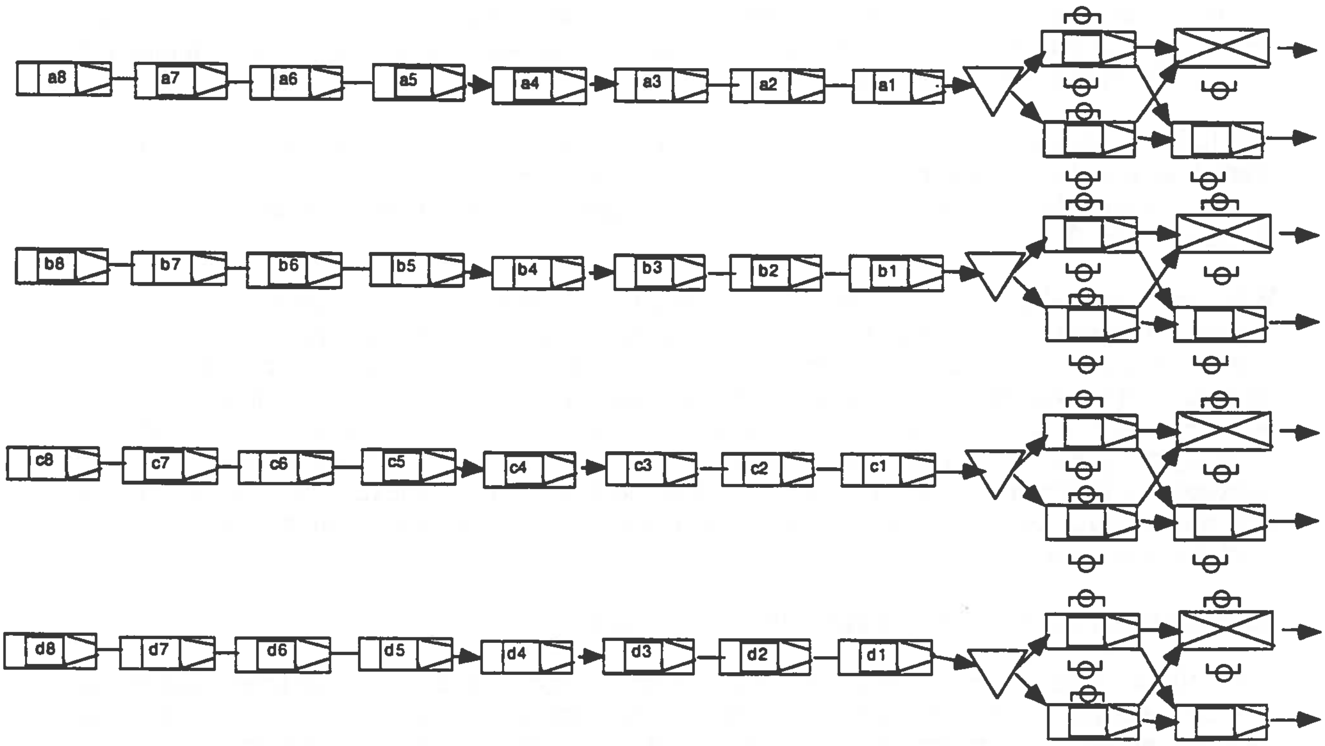


Figure 13. Schematization of a product flow structure as practised at the Volvo Uddevalla plant due to the design of the production scheduling system. The codification of the automobiles above illustrates the requirements due to the three subshops within the materials workshop, i.e. automobiles a1, b1, c1 and d1 require four deliveries of three pairs of kitting fixtures from each subshop, etc. This production scheduling system with its separate queues of automobile bodies and materials kits for each work station system led to a continuous replanning of the overall production sequence constituting the sequence of automobile bodies and kits, a materials workshop coagulating by ready made material kits not immediately needed by the assemblers, as well as severely restricted autonomy, since the working up between products could not be accumulated by the work groups. This since Uddevalla used fixed starting times for all the work station systems, which were planned weeks beforehand and derived from a common queue for the total plant. According to our interview the lack of technical autonomy was in fact the reason for the two female operators´ decision to learn more than half a automobile in order to be able to build complete cars by themselves. This dysfunction was never rectified. Therefore the options of parallel flow assembly system were never fully utilised or even generally recognised in Uddevalla or by Volvo in general. The argument against the planning by a pooled buffer using "assembly variant" were that it might reduce the precision in deliveries of finished cars. This proved to be the other way around, the delivery precision was in fact higher according to our simulations (Engström and Medbo 1992).

An alternative was to instead base the production scheduling on the variant codification of product individuals Uddevalla might have created a common queue of planned products between the materials workshop and the parallel work stations systems in the assembly workshops. This was not immediately possible to achieve since the product variants were not physically substitutable from the assembly point of view. The work groups did not have the competence to build all variants, and some equipment and tools were specific for certain work station systems since some tools were far to expensive to multiply.

This restriction could be remedied by classifying the product variants into clusters with various degrees of characteristics relevant for the assembly process. The production scheduling system would then allow any material kit to be sent to any of the work station systems which had facilities for manufacturing specific product variants, sometimes denoted "assembly variants". The introduction of "assembly variants" required a more developed product description since the original planning procedure did not contain any information concerning assembly characteristics.

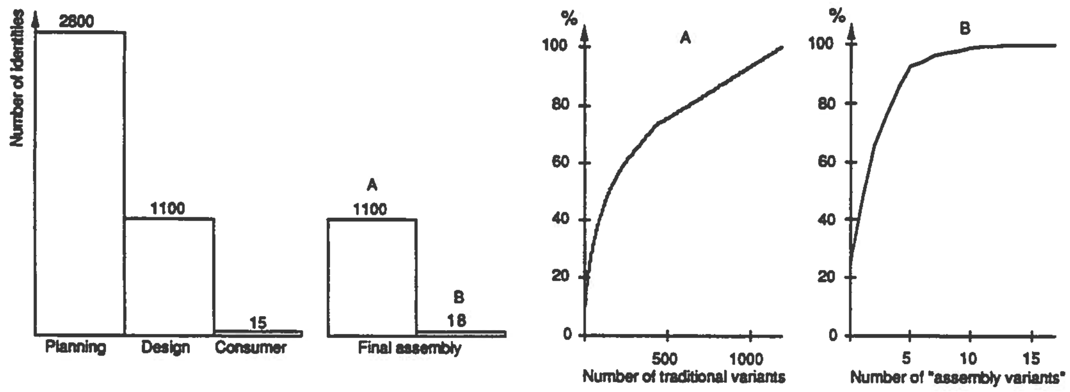


Figure 14. The diagrams in the figure are based on an analysis of 2 800 automobiles manufactured during six weeks within the Volvo Corporation. To the left is the total number of product identities used for the planning, in respect of market, design and for the customer, showed. To the right, we illustrate the cumulated distribution of automobile product identities used (a) neglecting assembly characteristics respectively (b) codified according to "assembly variants" relevant for final assembly. Note that the number of "assembly variants" is considerably less than the product identities required for marketing and design (Engström and Medbo 1992).

Product individuals belonging to the same "assembly variant" will thereby be both administratively and physically exchangeable from an assembly point of view. Individual recognisability is maintained in order to match correct automobile body to correct materials kit. This is in fact possible, which is evident from Figure 14.

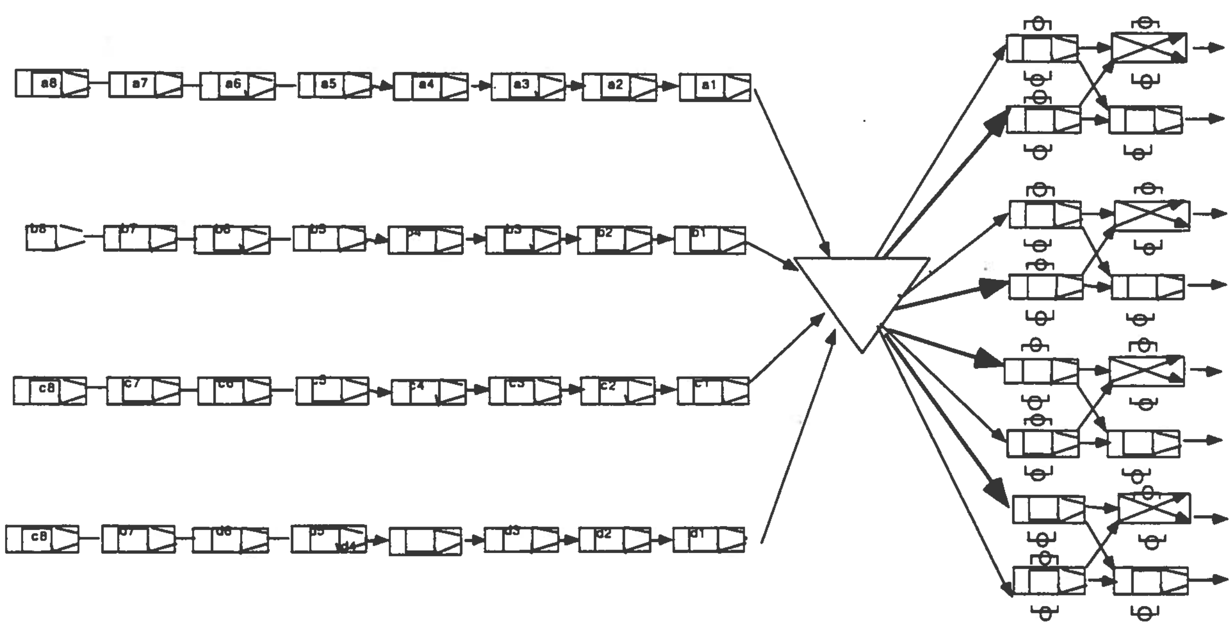


Figure 15. Schematisation of product flow structure which ought to be practised at the Volvo Uddevalla using planning by so-called "assembly variants". The codification of automobiles above illustrates the requirements due to the three subshops within the materials workshop, i.e. automobile a1, b1, c1 and d1 require three deliveries of three pairs of kitting fixtures from each subshop, etc. Such a reformation of the production scheduling system was planned but never realised due to the closing down. The figure is simplified by illustrating one common buffer only; in reality the

automobiles ought to be classified according to assembly characteristics as discussed above and illustrated in figure 14, thus dividing the common buffer into levels containing the same "assembly variants". This is in fact the opposite extreme compared to the situation shown in Figure 13.

9 Interfacing internal and external materials product flow structures

It should be noted, that while the original production scheduling system in the Uddevalla plant was not well suited for parallel flow assembly, it was consistent with the "logic" of external material flow systems used in traditional assembly lines. According to this "logic", the production process in the final assembly plant should be synchronised with component production and transportation processes, and this requires the chronology of the final assembly process to be predetermined.

The introduction of the assembly line at the beginning of this century is commonly viewed as a breakthrough for efficient mass production. Less publicly recognised but just as important is the concomitant introduction of standardised, exchangeable components. This meant e.g. that any XYZ-screw fitted any XYZ-nut. This possibility to exchange components is today a matter of course, but was at the turn of the century a great step forward. On closer analysis it becomes evident that the possibility to exchange components, as well as products, is somewhat limited even today. It is in fact in some respects even diminishing due to the accelerating number of product variants, which calls for more different variants on the component level.

The international trend towards external subassemblies by component manufacturers or special companies has in many cases increased the number of component types in final assembly. For combinatorial reasons, the number of product variants tends to increase with the size of the subassembly. In order to remedy this situation the subassemblies are often treated as administratively non-exchangeable though they are in fact physically possible to substitute for one another.

A representative example showing that administrative exchangeability is usually more restricted than the physical is the sequence bound components delivered to a final assembly plant. Sequence deliveries mean that component individuals are assigned to specific product individuals as early as at manufacturing by the supplier. Two different components which are physically identical and thereby physically exchangeable, but from the production scheduling point of view designated for different product individuals, will therefore be treated as non-exchangeable.

There is, however, an alternative "logic" for external material flows more suited for parallel flow assembly. The experiences from the Volvo Uddevalla plant, in which there was a mix-up between a non-traditional assembly system design with what was basically a traditional production scheduling system, imply the existence of two trajectories for the design of assembly systems´ interrelation with the external infra-structure in the form of planning routines, supplier relations, product descriptions, etc:

- A trajectory advocating early coupling of customers to the product individuals, product individuals to production resources and component individuals to product individuals. In this approach, the administrative exchangeability between product and components in the internal and external materials flow structure is deliberately reduced.

- Another trajectory calling for an administrative exchangeability of products and components at the level of physical exchangeability mainly aimed at improving flexibility.

The experiences from Uddevalla reported here imply that in most cases of automotive manufacturing it is favourable, under the Swedish premises, to take advantage of the administrative exchangeability, i.e. adopting the revised Uddevalla production principles as described above.

10 Conclusions and some comments

The Uddevalla plant's layout and mode of operation were unfortunately far from optimal in several respects. It is our opinion, based on our involvement in the design of the Uddevalla plant and our prolonged research collaboration with the personal at this plant and other Volvo facilities, that the "proper way" to operate the plant was not fully understood during the running-in and full-scale production phases. In fact even today the experiences from the Uddevalla plant are not fully analysed or understood by practitioners and researchers. Nevertheless, the experience from the Volvo Uddevalla plant showed that it was possible to create humane work which is efficient. It provided proof based on full-scale production of the efficiency of long cycle time work, the human learning abilities and the materials feeding techniques suited for parallel flow assembly systems. The two latter aspects constituted the prevailing restriction towards applying the parallel flow production principle used in Saab Scania's body shop in Trollhättan during the 1970s for final assembly work. Uddevalla also confirmed earlier assumptions about the saving in space and number of tools compared to the assembly line.

This conclusion is consistent with established theoretical frames of references and empirical evidence, as shown e.g. by our comparison with the Kalmar plant.

We also like to underline that the discussions about long cycle time contra short cycle time work often implicitly presuppose that the extended cycle time in itself is something to strive for. This is too simplistic since the qualitative nature of the work tasks is crucial in this connection. A qualitatively different job calls for a more complex conception of manual work, where the term autonomy is an important ingredient. For example welding one hundred metres instead of one metre, hardly makes any difference for the humanisation of the work. On the other hand, a repetitive assembly work of two minutes compared to the 2 – 5 hours work in a correctly designed parallel flow assembly plant is something quantitatively and qualitatively different.

Note however, that in the latter case certain technical and administrative preconditions must be fulfilled in the form of e.g. production scheduling systems. Neglect to create these preconditions leads, as has often been the case in the Swedish automotive industry, to failure to take advantage of the options of parallel production system available.

On balance, though, the achievements of the Uddevalla plant were more important than its imperfections. This pioneering plant provided empirical proof of the viability of parallel flow, long cycle time assembly of automobiles. It refuted the conventional wisdom asserting the superiority of assembly systems based on extensive division of labour. Its imperfections were imperfections of implementation, not of concept.

The existence of considerable imperfections in the Uddevalla plant may even be seen as encouraging. Despite these imperfections, the work environment was superior to that in line assembly plants, and the plant's performance was competitive compared with similar plants, producing similar products. In this situation, the significant imperfections of the Uddevalla plant translate into an equally significant improvement potential.

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