TO BE TRANSLATED INTO JAPANESE FOR PUBLICATION IN 'IE REVIEW'

Assembly Work Structuring Based on Restructuring and Transformation of Product Information[1]

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ABSTRACT

This article explains crucial concepts underlying proposed work structuring principles and tools applied in various unorthodox Swedish assembly systems with parallel product flow assembly systems characterized by long work cycle time assembly and advanced materials feeding techniques.

The authors emphasize that the assembly work "surface structure" should be based on a "deep structure" related to an assembly-oriented logical product structure. This product structure differs from the design-oriented logical product structure, the so-called function group register, traditionally used in the Swedish automotive industry. Steps in designing an assembly-oriented logical product structure and transforming it into a suitable work structure are described with illustrations drawn from the Volvo Uddevalla Plant. In this context, design principles for information support, generic relationships exhibited by large vehicles, criteria for grouping components in an assembly-oriented logical product structure and vocational learning principles are discussed. It also ought to be noted that the proposed work structuring principles and tools have lately proved applicable for improving the quality of information at a traditional assembly line. Thus a general potential not yet prospected or recognised.

1 INTRODUCTION

Within the context of collaboration between Osaka University of Economics and the School of Economics and Commercial Law at Göteborg University, a number of 2 – 3 days seminars, named "Seminars on Comparisons of Management Practices between Japan and Sweden", have been carried through. These seminars have earlier been arranged in September 1999 at Göteborg, and in October 2000 at Osaka.[2]

In-between the seminars there have been study tours by delegations of Japanese researchers in the Göteborg area for visiting of industrial premises, such as that in March 2001 arranged by Chalmers University of Technology, specifically for studying Swedish automotive plants. During seminars and study tours, unorthodox assembly systems with parallel product flow assembly systems with long work cycle time assembly work have caught the interest of Japanese research colleagues, and process designs have thus been discussed from several points of view. However, during these discussions, which have to a large extent concerned the underlying principles and practises of these unorthodox assembly systems, it has become evident that some unclearness exists in the authors' publications. This is especially evident for the work structuring principles advocated, which are connected to vocational learning and psychology.[3]

[1] Many thanks to professor Lennart Nilsson at the Department of Education and Educational Research, Göteborg University for invaluable help during the period of the Volvo Uddevalla plant design process. The authors also want to thanks professor Hikari Nohara at Hiroshima University and his colleagues for valuable comments and careful reading of this article.

[2] This article was first written as a working paper for the September 2001 seminar in Göteborg (see Engström, Jonsson and Medbo 2001a). Later it was slightly modified in accordance with comments received and presented for the workshop in Venice October 2001 within the network "Competencies and Knowledge in the European Automobile system" (CoCKEAS). See Engström, Jonsson and Medbo (2001b). Thereafter it was complemented mainly regarding the vocational learning principles and rewritten one more time into this article.

[3] Though these results are spread on both an international level by means of traditional academic channels and also shared locally between a limited number of practitioners and researchers actually involved in the experiences referred to, it is fair to say that the detailed core knowledge has proved intriguing to comprehend for outsiders. This since, among

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This article will focus on the design of product and process information rather than process design in the sense of e.g. choice of product flow pattern, choice of buffer positions and buffer functions, choice of materials feeding techniques, selection manufacturing equipments and tools, etc., i.e. what is considered as synonymous with assembly system design.

2 BACKGROUND: THE FUNCTION GROUP REGISTER USED IN THE SWEDISH AUTOMOTIVE INDUSTRY

The standardised logical product structure[4] used within the Swedish automotive industry for describing motor vehicles, known as the function group register, is intended for motor vehicles in general, ranging from automobiles to dumpers and trucks. This is a design-oriented logical product structure, i.e. it describes a motor vehicle from the central product design department's point of view in a traditional way. For example, it separates electrical components from mechanical components, despite the fact that many product functions are in fact combinations of electrical and mechanical components.

The main function groups in the function group register are (see e.g. Volvo 1989):

2 000 Engine and equipment.
3 000 Electric power supply and instruments.
4 000 Power transmission.
5 000 Brakes.
6 000 Wheel suspension and steering.
7 000 Frame, springs, damping and wheels.
8 000 Body, cab and upholstery.

For reasons discussed below, most of the components of an automobile are concentrated in main group 8 000.[5]

In an international manufacturing corporation like Volvo, the core information emanating from the central product design department is used for specifying the product and aspects of the assembly process and comprises e.g. original drawings/CAD-models, data on torque, tolerances, etc. as well as bill of materials data guiding the materials in the industrial network. This core information is the reference for the manufacturing of the product in various local plants, as illustrated in figure 1. It also provides the basis for interaction with suppliers and customers.

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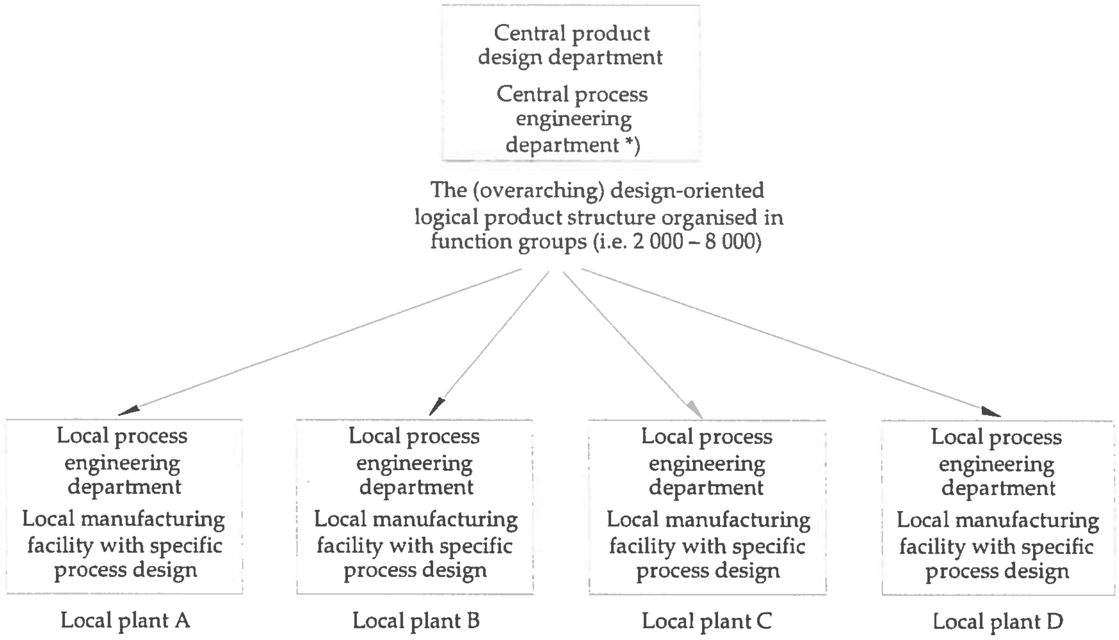
other things, specific manufacturing engineering knowledge of the automotive industry practices, and other types of frames of references are required. In addition to this, there is a need for rare in-depth insights about the idiosyncrasies of product and process information used in the automotive industry, calling for specific approaches and methods for penetrating and analysing such information as outlined below (see also e.g. Engström and Medbo 1994; Engström, Jonsson and Medbo 2000 for a detailed explanation of the actual design procedure).

[4] The logical product structure is a product description or product description scheme, in distinction to the physical product structure or product architecture, which is the aspect of the product that the logical product structure describes.

[5] In the function group register, a product structure item is defined via a series of structural and textual concepts relating the individual component to the product as a whole (function, position, subassemblies, etc.). This can be exemplified by a component numbered *96 84 64* referred to as *Screw ST4,8 x 13* which is part of *Lock cylinder, side doors*, which is part of *Lock cylinder kit*, which is part of *Lock/handle*, which is a component of *Automobile type X*. The italics indicate core information. This is the formalization of the product designer's work. When exploited correctly, this core information is a great advantage in the restructured assembly work. How this can be utilised for process design is discussed in Engström, Medbo and Jonsson (2000).



*) For example in the case of e.g. Volvo Car Company the general documents defining how to assemble an automobile created by the central process engineering department are the so-called Process/Inspection Instructions (PKI) organised in accordance to the function group register. Documents which are constructed based on the product information included in the design-oriented logical product structure which in turn is a result of the work from the central design department.

Figure 1. The core information emanates from the central product design and process-engineering departments. In the case of Volvo, this data is organised according to the so-called function group register, which is general for all motor vehicles.

Since the function group register is general, it will cause parts of this logical product structure hierarchy to disappear when applied to e.g. an automobile. In addition, there may exist components that are not assigned to a function group on the next higher level of the hierarchy, and there may also exist function groups that do not currently contain any product structure items, but may do so in the future. Moreover, a function group may contain a particular product structure item for one product variant but not for another one. As a result, the function group register based logical product structure describing a particular product type or product variant will contain "implicit holes".[6] These "holes" are denoted "implicit" due to the fact that in order to recognise all of them one has to be extremely acquainted with both the product architecture of the specific automobile in question and the generic function group register, since the recognition of the "implicit holes" is a consequence of combining these structures.

It should be noted that due to both technical limitations and human error the logical product structure used at Volvo contained many obscure abbreviations and incorrect names, as well as an unfortunate mix of synonyms and homonyms. Partly because of this, it is solely the part number that identifies components on the shop floor, but this fact imposes some severe restrictions on e.g. understanding the product and the product variation.

It should also be noted that motor vehicles have changed during the last decades. This is particularly true for an automobile with a welded body, while the structural content of a bus or a truck has changed less, since they have, from a motor vehicle point of view, a more conventional product architecture comprising e.g. a separate frame. Today, for example, the complete interior of an automobile is upholstered with panels of plastic or cloth, which is why most of this product structure items are to be found in the last of the seven main groups (i.e. 8 000 Body, cab and upholstery) in this (overarching) design-oriented logical product structure. Another reason for this distortion is that components that do not obviously belong to another function group have been assigned to the last function group.

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[6] On the third level of the hierarchy, that is for entries of the form (e.g., 2340), the structure consists of 271 groups and 245 "implicit holes". When this register was applied to a particular automobile, 122 of these groups were used, and the number of "implicit holes" thus increases to 394. For a representative truck the corresponding figures are 90 groups and 426 "implicit holes".

The increased combinability between subassemblies is the result of changes in market, product architecture, choice of materials and external suppliers. This has influenced the content of this (overarching) design-oriented logical product structure more for the automobile than for the bus or truck.

Though this article has deliberately, to restrict the scope, refrained from discussing product variation and product variant codification, it might be added that the existing method of describing variation in the product is principally intended for materials control. It is therefore extremely difficult to understand the product variation from the function group register (see e.g. Engström et al. 1995 for a more detailed description of how the advocated principles and tools are linked to product variation and product variant codification).

All this means that the manufacturing engineering at the local manufacturing facility requires extensive work to restore the core information into a form suitable for the particular process design involved in order to get the quality data needed for effective manufacturing beyond materials control purposes. Besides resulting in fragmented information, the (overarching) design-oriented logical product structure used by Volvo also obstructs feedback concerning assembly work to the central product design department.

3 INFORMATION SUPPORT FOR LONG WORK CYCLE TIME ASSEMBLY WORK: THREE DESIGN PRINCIPLES

In this section we shall consider three cognitive engineering principles that concern the design of information support for long work cycle time assembly work, in the form of documents or computer-stored information.

(1) <u>In long work cycle time assembly work, the assembly work "surface structure" should be based on a suitable assembly work "deep structure"</u>.

To explain this principle, an analogy with a linguistic concept may be useful. Chomsky (1957; 1975), who created the theory of transformational-generative grammar, argues that human beings have an innate facility for understanding the formal principles underlying the grammatical structures of a language. Chomsky distinguished between two levels of structure in a language; "surface structures" which are the actual words and sounds used; and "deep structures" which carry a sentence's underlying meaning.[7] According to Chomsky, humans can create and interpret sentences by generating the words of "surface structures" from "deep structures" according to a set of abstract rules. The same rules are present in all languages and, though limited in number, they allow for an unlimited variation. Figure 2 illustrates the distinction between "surface structures" and "deep structures".

<u>Figure 2</u>. Similar "surface structure" but different "deep structures", corresponding to different meanings.

The assembly work "surface structure" includes the assembly sequence and the division of assembly work among operators. In short time assembly work, the assembly sequence is not critical from a learning of assembly work point of view, and can be based on line balancing considerations, for

[7] The analogy to Chomsky's theory has also been noted by Casti (1986), who discusses various metaphors for production systems.

example. In long time assembly work, on the other hand, learning of assembly work is critical and therefore the assembly sequence and other aspects of the "surface structure" of assembly work should be derived from a suitable "deep structure" to facilitate comprehension and learning of the assembly work – that is, to make assembly work (cognitively) meaningful, just as the underlying "deep structure" makes a sentence (semantically) meaningful. The next principle concerns what constitutes a "suitable" assembly work "deep structure".

(2) In long work cycle time assembly work, the assembly work "deep structure" used to generate an assembly work "surface structure" should be based on a suitable assembly-oriented logical product structure.

There are many different ways to arrange work elements in groups and subgroups so as to create a work structure. In line assembly, for example, work elements can be grouped according to where on the assembly line they are carried out. The resulting work structure would reflect the organisation of the assembly line involved. Such a work structure would obviously not provide adequate information support for long work cycle time assembly work, however. In this case the assembly work "deep structure" should actually be based on the product to be assembled, taking advantage of the product – process duality in an assembly context. Specifically, since each product element corresponds to a specific work element – namely the fitting of that product element to the main assembly object – each group of product elements represents a group of work elements, and each logical product structure represent an assembly work "deep structure".

Obviously, while the function group register discussed in the previous section corresponds to a theoretically possible assembly work "deep structure", it does not represent a suitable one. This is not only due to the "holes" in the function group register and similar problems, but also, and more fundamentally, the fact that the function group register, as noted above, is a design-oriented logical product structure, whereas an assembly-oriented logical product structure is needed for supporting long work cycle time assembly work

This is because an assembly-oriented logical product structure and a product-oriented assembly work "deep structure" are so to speak two sides of the same coin. An analogy can be made with the "Peter-Paul goblet" phenomenon discussed in Gestalt psychology (Koffka 1935; Katz 1947), where the roles of "figure" and "ground" may be reversed (cf. figure 3). From an process design and assembly work point of view, the assembly work will be the "figure", while the product will be "ground". From product architecture and materials supply point of view, on the other hand, the product will be the "figure", while the assembly work will be the "ground".

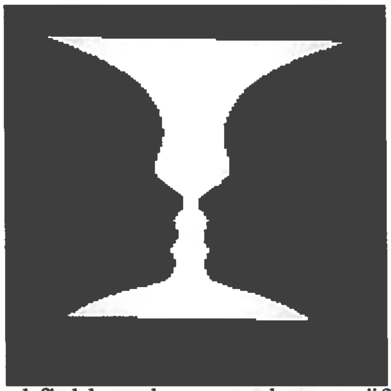


Figure 3. One region of the perceptual field tends to stand out as "figure", while the complementary region is perceived as "ground". The roles of "figure" and "ground" can however be reversed, as illustrated by the Peter-Paul goblet (Berelson and Steiner 1964).

The product, the assembly work, the product information and the process information all consist of a number of elements (see e.g. Dahl 1982). These elements interact to form structures in which two phenomena may consist of different kinds of elements yet have the same structure. Another way of expressing this is to distinguish between shape and substance as illustrated in figure 4.

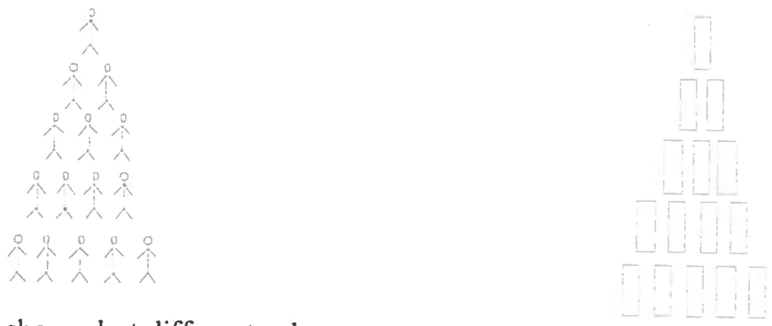


Figure 4. Similar shapes but different substances.

The third design principle concerns how elements (terms) in the logical structures refer to elements (components, operations etc) and groups of elements in the corresponding physical structures.

(3) Elements and groups of elements in products and in assembly work should be given meaningful names in the corresponding logical product structures and assembly work "deep structures".

Human articulation and perception has not only linguistic and visual dimensions but verbalisation is also of importance. Thus it is vital, regarding assembly work, to complement the part number used for identifying components with a correct name. Homonyms and synonyms may exist provided that they are recognised as such.

Terms form mental clusters which in turn form yet new clusters leading to the creation of a semantic network. Unnamed components will then be identified in relation to an established verbal network. Another effect is that certain combinations of terms are recognized to be impossible if one is acquainted with the verbal network and its physical representation (e.g. the components in a product).

Consequently there must from the beginning exist a minimum critical mass of terms in order to guide the human being and in order to transfer knowledge and experiences between humans.

4 A VOCATIONAL LEARNING PERSPECTIVE

The traditional learning curve model articulated by Wright (1936) is often used to estimate the need for manufacturing resources. This model defines how time or costs per product is assumed to decrease as the number of manufactured products increases. This learning curve model makes it possible to evaluate organisational learning through gathering relevant data, and has been widely spread (Shtub et al. 1993). Another aspect of industrial learning is the application of the learning curve model on repetitive work (De Jong 1964; Hancock and Bayha 1992).

The learning curve approach implies that learning is mainly regarded as a mathematical problem – for example, every time the number of work cycles performed is doubled, the required time per work cycle decreases by a fixed percentage. In addition, it should be noted that the learning curve model does not contain the "conditioned learning time", i.e. the time required for the operator to learn during the initial time period when he or she barely knows how to perform the work. This time period is often long, since trial-and-error learning is most often practised in the manufacturing industry (Hancock and Bayha 1992).

A non-traditional approach to learning industrial assembly work is based on what has been coined "natural work" (Nilsson 1985) during the projection of the Volvo Uddevalla Plant process design. This non-traditional approach underlines that learning, in the form of education and competence development, is not viewed only as a consequence of the process design (i.e., the manufacturing technologies chosen). This non-traditional learning approach is according to Nilsson in (in Ellegård, Engström and Nilsson 1992) applicable for "future-oriented industrial assembly". It may be perceived as a sort of antithesis to traditional learning methods.

As expressed by Nilsson, "natural work" is characterised by the facts that (I) "the worker himself has full control over the day's events" and that (II) "the work comprises an entirety". It also means that (III) "the work is meaningful to the individual and is not predetermined by the time factor" and finally that (IV) "the transfer of knowledge takes place principally from generation to generation within the profession". See also Nilsson (1985) or Ellegård, Engström and Nilsson (1992) for a more detailed explanation. In addition, this learning approach stresses the "unique content and its capabilities to enrich life by putting the product in focus" of the work.

In a parallel product flow assembly system, the product will not leave the work group until it is completed and fulfils the defined quality. Thus the operator has, from the product flow point of view, possibilities to control his work time, in accordance with characteristic (I). The demand that the work should comprise an "entirety", as stated in characteristic (II), implies a need for various means to guide the assembly work as explained in this article.

The demand for meaningful work and absence of "predetermination by the time factor", as in characteristic (III), means that the work groups and individuals have time to complete their work tasks, as discussed above, but also that they are able to accumulate the "working up". That is, time gained for various reasons should be possible to utilise freely. The freedom from the "technical system" is sometimes expressed as "technical autonomy" by scientists belonging to the socio-technical research paradigm (see Karlsson 1979).[8]

Moreover, characteristics (II) and (III) are related to the abstract principle of "deriving the details from the whole". For long work cycle assembly work, this is realised in practice by means of an assembly-oriented logical product structure, which in turn has implications for the design of the work instructions and other forms of information support, materials display on the work station, etc. In this connection, the third design principle for information support stated in section 3 (i.e. the requirement for meaningful names) must also be adhered to. To identify components to be fitted to a product by part numbers alone is obviously not sufficient according to this learning approach.

Similarly, Marton (1970) also stresses the importance for the human being of creating an internal, mental representation – a structure – to facilitate learning. It is especially important to construct a mental structure ("building up an internal representation as a structure") in the initial phase of the learning, leading to higher performance in later phases. It is emphasized that understanding depends on the relation between previous and new knowledge.

Marton argues that learning proceeds from an undifferentiated, poorly integrated understanding of the whole to increased differentiation and integration of the whole and its parts. Complex knowledge cannot be composed out of small pieces. The learning thus has a direction from the whole to the detailed and not the opposite. – "To learn something you have to have an idea of what you are learning about" (Marton and Booth 1997). The learning can therefore be regarded as either holistic, hierarchical integration of knowledge, or atomistic, focusing on the 'parts' (see also e.g. Svensson 1984).

5 EIGHT GENERIC RELATIONSHIPS EXHIBITED BY LARGE MOTOR VEHICLES

During the disassembly of automobiles undertaken by two of the present authors in connection with e.g. the Volvo Uddevalla Plant process design, several generic relationships (the product's inner logic) exhibited by all large motor vehicles with multiple product variants were identified (originally Engström 1991). Considering a single product, the following generic relationships appear:

(1) Part-whole relationships. This means that motor vehicles contain several components, subcomponents and so on.

(2) Intra-system synergies. Specific components interact and form systems of components that serve particular product functions (see e.g. Hubka and Edler 1988, who discuss complex technical systems as consisting of numerous components which could be divided into subsystems embracing product functions). For example the function of braking calls for a brake system, which is composed of a brake pedal which manoeuvres the servo/booster for pressurising the brake fluid with help from the vacuum from the engine. Thus the brake fluid is conducted by the brake lines to the callipers. These callipers grab the discs on each wheel in order to stop the motor vehicle.

[8] Technical autonomy is a vital precondition for administrative autonomy. That is, in order for individual operators or work groups to organise and schedule their own work and master enhanced administrative tasks some slack is required.

(3) Similarity of components. This means that many components are identical or similar in form and fulfil similar or almost similar functions. This applies to small components such as fitting elements, screws or bolts, studs, etc., but also to components, subassemblies or aggregates of components. However, these larger components are in some cases mirror-inverted, usually appearing in pairs, or multiples of pairs. Safety belts and windshield wipers are example of such identical pairs of components, while front and rear lamps as well as door panels fulfils the same functions but are pairs of components that are mirror-inverted.

(4) Proximity of components. In a single product some components are fitted close to each other. This means that if one component is fitted obviously another one is called for. For example, fitting a wheel without wheel nuts will obviously be in vain.

(5) Bilateral intra-product symmetries. Some components are positioned bi-symmetrically, i.e. appearing in pairs positioned around the product's assumed mid-axis, while others appear only on one side of the axis. This is an "organic" symmetry, analogous to that of the human body, which has e.g. two arms and legs but only one heart and liver (see figure 2).

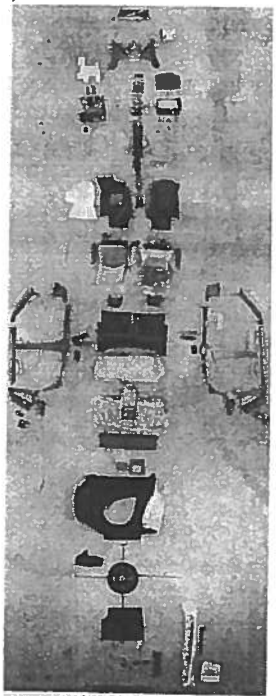


Figure 2. Photography of 1/4 of an automobile[9] laid out on the floor of the authors' experimental workshop in Göteborg 1986 (the components in the main group 4 Interior included in the assembly-oriented logical product structure as described in section 6). In this case, some of the generic characteristics of this motor vehicle are evident.

Comparing multiple products the following generic relationships appear:

(6) Contingent inclusion relationships. When comparing selected products by considering them as each other's mirror images, it becomes obvious that a component may be present in one product and absent in another, and that components may be substituted for one another. For example, an automatic gearbox may replace a manual one – or an air-conditioner may or may not be included.

(7) Genealogical links. A specific component included in a particular product goes along with another specific component, thus forming long chains of interrelated components. Such relationships may be based on intra-system synergies and product functions, but not necessarily so. Thus, e.g. a specific product function with a corresponding

[9] That is the components in the photography correspond to approximate one fourth of the assembly time required to assemble a Volvo 700-model. Though subassembly work is excluded.

component system may generate a long chain of components to be fitted, but similarly one chromed trim detail usually requires the rest of the trimming to be chromed, in opposition to being surface dressed in black. Also, similar colour and materials of the product's interior components may generate such links.[10]

(8) Bilateral inter-product symmetries. When comparing selected products, some components may appear to the left of an assumed mid-axis in one product and to the right of this axis in another one. For example, if a left hand drive automobile is compared with a right hand drive, the driver's controls in form of pedals, steering column and steering wheel, combination instrument and instrument nacelle are found at opposite sides of the mid-axis, while the location of some components or component system functions are independent of if the motor vehicle is e.g. left or right hand driven.

These eight types of relationships are themselves conceptually related as shown in table 1.

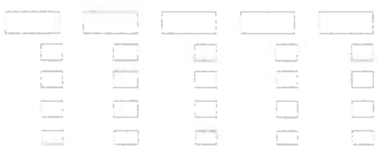
	Relationships involving a single product:	Relationships involving multiple products:
Composition:	- Part-whole relationships	- Contingent inclusion relationships
Association:	- Intra-system synergies – Similarity – Proximity	- Genealogical links
Symmetry:	- Bilateral intra-product symmetries	- Bilateral inter-product symmetries

Table 1. Overview of eight generic relationships exhibited by large motor vehicles.

These generic relationships provide the foundation for describing single and multiple products in an assembly-oriented logical product structure. In this article, relationships involving multiple products will not be considered further, since the issue of product variants will not be dealt with.

6 CRITERIA FOR GROUPING COMPONENTS IN AN ASSEMBLY-ORIENTED LOGICAL PRODUCT STRUCTURE

As described in some detail below, one way to develop an assembly-oriented logical product structure for an automobile type, e.g. the Volvo 700-model, is to disassemble one or more automobiles and lay out their components on a suitable large surface, e.g. a floor, and then iteratively rearrange the components to represent the allocation of components into a hierarchy of main groups and subgroups. At the same time, a hierarchy of terms corresponding to the components and groups of components is developed – a hierarchy that constitutes the core of an assembly-oriented logical product structure. These two hierarchies should exhibit structural similarity (congruence) as illustrated in figure 6. The hierarchy of terms can be used as an assembly atlas to navigate among physical components and groups of components as well photographs or illustrations of components and groups of components.

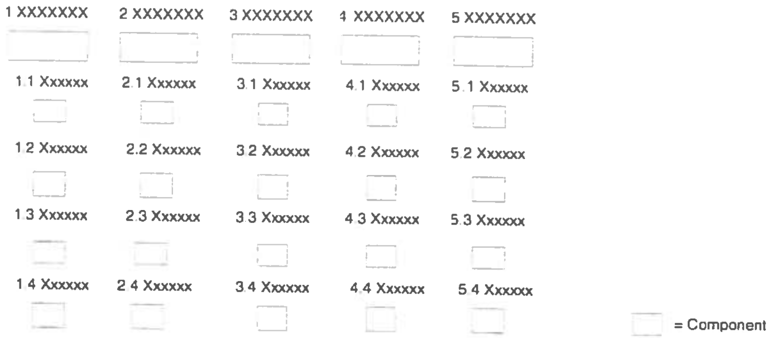


Hierarchy of physical components (substance = physical components).

1 XXXXXXX	2 XXXXXXX	3 XXXXXXX	4 XXXXXXX	5 XXXXXXX
1.1 Xxxxxx	2.1 Xxxxxx	3.1 Xxxxxx	4.1 Xxxxxx	5.1 Xxxxxx
1.2 Xxxxxx	2.2 Xxxxxx	3.2 Xxxxxx	4.2 Xxxxxx	5.2 Xxxxxx
1.3 Xxxxxx	2.3 Xxxxxx	3.3 Xxxxxx	4.3 Xxxxxx	5.3 Xxxxxx
1.4 Xxxxxx	2.4 Xxxxxx	3.4 Xxxxxx	4.4 Xxxxxx	5.4 Xxxxxx

Verbal hierarchy of terms (substance = terms).

[10] Or if, for example, a Volvo 700 series is to be fitted with air-conditioning, a rectangular rubber plug is fitted in the upper firewall, with two holes for the AC-leads. If the automobile is not to be equipped with air conditioning, this rubber plug has no holes.



Congruence exhibited by similar forms.

Congruence exhibited by hierarchies with similar forms but different substances.

Figure 6. Illustration of structural similarity (congruence) between hierarchy of physical components and verbal hierarchy of terms (i.e. a verbal network).

Even though all Volvo documentation in form of e.g. service manuals, spare part catalogues, assembly instructions from various Volvo plants, so-called Process/Inspection Instructions (PKI) from the central process-engineering department, etc. was available to us, and valuable help was also received from various Volvo manufacturing engineers and other specialists from the Volvo Torslanda assembly plant, it proved almost impossible to understand the automobile as a whole by means of the Volvo documentation alone. For example it was not possible to use the documentation for disassembly of a complete new automobile, neither was it possible to order all the specific materials included in a complete automobile.[11]

It proved more practical to apply a "reverse engineering" approach, i.e. to disassemble an automobile to improve the understanding of both the product and its documentation.[12] It was first necessary to understand a single product, which was a product variant stripped of most options, identical to the first fifty automobiles assembled in the training workshop at the Volvo Uddevalla Plant. Then followed the dismantling of a number of extensively equipped product variants.

This work was carried out in stages over a number of years. During this period, empirical manual explorative studies were made with pens, scissors, glue, paper, copying machines, and a word processor in order to gain insights into product and process information as well as a detailed understanding of the product architecture and product variation.

For three years, all the components remained on the floor of the experimental workshop for regrouping, marked with information to enable the authors to check when we felt uncertain and to

[11] Given the insights reported in section 2 it might have been a successful course of action to engage specialists from the central product design department. However, the state of the art concerning the Volvo information was of course puzzling for the authors. How was it possible, for example, that no one was able to specify the assembly sequences, materials volumes, etc, and why was it so complex to understand the available information when comparing with physical products?

[12] This was not a new experience for some of the authors who had earlier been involved in e.g. design of the so-called mini-line at Saab Scania in Trollhättan, a Toyota Tahara plant look alike built approximately fourteen years earlier (Engström 1983). There it proved necessary to make a special inventory of all materials contained in an automobile to grasp materials volumes, number of components, etc.

illustrate the principles for numerous visitors. Another reason for keeping the components for so long was that during this period we also produced specially designed visual illustrations, which described the assembly-oriented logical product structure (see figure 7) used at the Volvo Uddevalla Plant. To help us with the illustrations we employed an architectural research student specializing in visualization techniques.

We used several types of criteria for grouping components when designing assembly-oriented logical product structures (see section 5) in order to achieve distinguish groups of components, i.e. the phenomena to strive for was that the components in themselves more or obviously was in structural similarity with hierarchy of terms as discussed in section 6.

Firstly, components were grouped according to characteristics such as form, size, weight, materials (e.g. metal or plastics), location in the product, product architecture (e.g. physical modules) and product functions. Note however, that not all characteristics where of the same significance for forming each group of components. This means that components were grouped in order to form hierarchies according to part-whole relationships, intra-system synergy (i.e. contribution to a common product function), similarity, proximity and bi-lateral symmetry – that is, the five generic relationships involving a single product listed in Table 1.

Secondly, since we were dealing with an assembly-oriented logical product structure, a rough assembly sequence, dictated by the product architecture, has to be taken into account, meaning that groups of components should be ordered in a way that reflects a logical rough assembly sequence determined by the product architecture. For example, most of the plugs in the automotive body must be fitted early and could accordingly be placed in the first subgroup of the first main group, while hubcaps, the triangular warning sign, etc. would be put into the rear trunk towards the end of the assembly sequence and could be placed in the last subgroup of the last main group.

Thirdly, again because of the fact that we were dealing with an assembly-oriented logical product structure, the assembly time represented by e.g. included components in each main group should be taken into account. This means that an even division of labour between the main groups in the assembly-oriented logical product structure is facilitated if the components in each main group represent approximately the same assembly time, i.e. approximately the same amount of components or so-called fittings points (e.g. type of fasteners, screws, nuts, etc. which require various time consumptions see e.g. Engström 1983).

Rules of thumb can be used to estimate the assembly time represented by components in a particular group. For example, wiring harnesses can, for an extremely rough estimation of the assembly time, be assumed to correspond to the same number of small components as the number of times these where fixated (by clips, clamps, etc.) plus the number of lead-throughs in the automobile body panels. For example a wiring harness with twelve fixations and three lead-throughs was assumed to require the same assembly time as fifteen small components.

The assembly-oriented logical product structure arrived at through the disassembly process comprised five main groups:

(0) Doors.
(1) Leads for electrics, air and water.
(2) Drive line.
(3) Sealing and decor.
(4) Interior (see figure 2).

The first group thus corresponded to subassembly work on the doors, while the other four main groups corresponded to work on the automobile body.[13]

[13] The fact that group (0), for example, refers to part of the product, from one point of view, and part of the assembly work, from another point of view, is an example of the product-process duality discussed in Section 3.

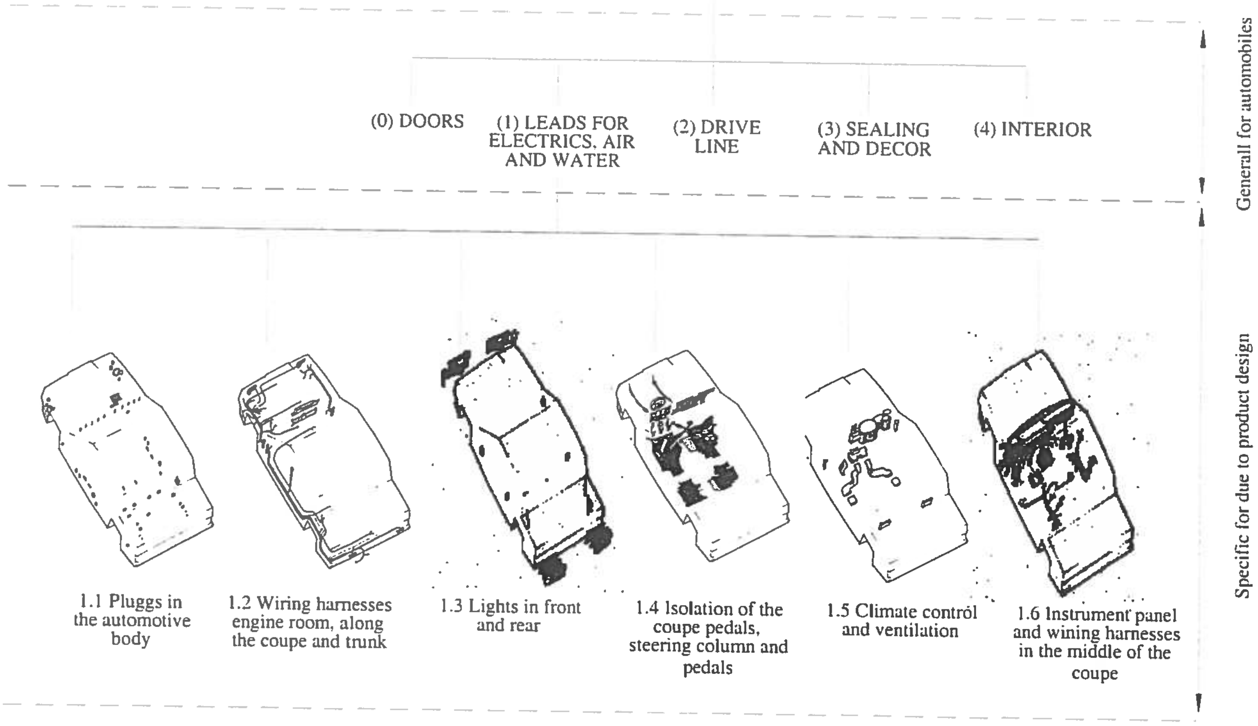


Figure 7. The assembly-oriented logical product structure as applied for automobiles (i.e. Volvo 200, 700, 800, 900 and C70 series), showing the five main groups and the six subgroups of main group (1). The lower part of the hierarchy is dependent on the product architecture, while the upper part has proved to be more general. Note the specially designed illustrations normalised against a transparent outline as discussed by Engström, Hedin and Medbo (1992).

The main groups became to some extent obvious. However, the subgroups where trickier to define and to designate correctly in order to establish a meaningful correspondence between the physical components and their positions in the automobile (a spatial network) and in the hierarchy of terms (a verbal network). It is fair to state that so far the main groups in the assembly-oriented logical product structure have latter proved to be general for Volvo automobiles (the rear driven 200 and 700 series as well as the front wheel driven 800 and C70-models), while the subgroups have varied dependent on product architecture.

Note that the three types of criteria listed above where based exclusively on the product to be assembled, that is they are dependent on the product's inner logic but independent of the specific facility (or, more generally, the process design) where the product is assembled. This generic assembly-oriented logical product structure is utilised in the design of a specific process design.

How to adapt the generic assembly-oriented logical product structure for a specific process design (such as a specific process design with a specific process design in the form of product flow pattern, specific buffer positions and buffer functions, etc.) is explained below by recapitulating some of the experiences and work from the Volvo Uddevalla Plant process design.

7 AN INDUSTRIAL APPLICATION REGARDING LONG WORK CYCLE TIME ASSEMBLY WORK

In accordance with the second principle in section 3, the assembly-oriented logical product structure is used to generate a recommended assembly sequence. Or to formulate it in another way, "the assembly-oriented logical product structure is a taxonomic product information from which the detailed assembly sequences are derived". These sequences are based on the process design, but may be changed in detail within these restrictions for specific automobiles to be assembled and by local work group constraints due to absent operators, competence overlap, etc. A process design for a number of parallel work groups should also stipulate how the components are organised in e.g. materials kits. As was the case at the Volvo Uddevalla Plant.[14]

In this connection it should be noted that the interaction of product architecture and process design imposes process restrictions. For the 700 series assembled in the Volvo Uddevalla Plant, for example, the assembly sequence was influenced by the fact that the subframe, comprising engine and gearbox assembly, was inserted from below the automobile body, as was also the case for the rear axle arrangement.

The point of departure thus was (a) the generic assembly-oriented logical product structure, but there were also three process-dependent restrictions, the first of which was (b) the choice of one tilting device and one lifting table for each complete automobile built.[15] The tilting device was designed to allow the automobile to be continuously adjusted up to a 90° sideways tilted position whenever required. It also allowed continuous height adjustment during the assembly. The tilting device was comprised of two pillars mounted on the floor of the workshop with adapters for the automobile body. Thus the body could be raised and lowered as well as rotated around a horizontal axis longitudinally along the centre of the automobile body. The adapters fitted the automobile body at the bumper attachments

Furthermore, (c) the subassembly workstations were integrated into the work group in order to increase the number of work positions for the operators in a work group and to reduce the number of unique complete subassemblies under transportation to the work group. Thus were only the most time consuming subassemblies integrated into the work groups, i.e. doors (requiring four subassembly stations), sun-roof, engine dressing, instrument panel and torpedo panel (requiring one workstation each). The subassemblies that required expensive investments (like cutting and bending the brake lines) and the subassemblies which were rational to assemble many at the same time (like fitting door locking knobs on the lock-mechanics linkage by means of a fixture) were designated to the materials workshop. These subassemblies were contained in the materials kits.

Finally, the original experiences from the Volvo Uddevalla Plant training workshop, predating the actual starting-up and full scale running, where the automobile was assembled by four separate work groups according to the assembly-oriented logical product structure showed that (d) the feasible operator concentration varied between the main groups in the assembly-oriented logical product structure. The following variation of recommended operator concentration without operators disturbing each other was noted: (1) Leads for electrics air and water and the (2) Drive line had a recommended operator concentration of two operators per product. On the other hand, on the (3) Sealing and decor and (4) Interior it was possible to work three operators at the same time without creating unnecessary waiting times due to blocked work positions along the automobile body, waiting for tools and materials, etc.

Since, for the work performed directly on the automobile body, the number of operators per automobile was not maximized, non-occupied work positions along the automobile bodies were

[14] At the Volvo Uddevalla Plant; (1) an AGV-system was utilised for the supply of materials kits (comprised out of kitting fixture and various types of packages) and automobile bodies and the materials store was separated from the assembly workshops, (2) the materials kits contained all types of materials categories, i.e. small components in plastic bags, semi-small on shelves including plastic boxes and large components or hooks or shelves – all of these materials categories were organised into six pairs of materials kits, each specifically designed for the materials carried. On the other hand, the resurrection of the Volvo Uddevalla Plant (the Autonova Plant now Volvo Car Plant) the materials feeding technique are as follows; (1) the AGV-system was been giving better space utilisation well as ending the intriguing business of matching the production scheduling to the interaction between the AGV-system and the work in the materials and assembly workshops, the different types of materials categories were fed separately. This means that, instead of containing all components in the materials kits (a) small plastic bags with small components are supplied by an outside supplier, (b) semi-large components are put into plastic boxes by operators in a separate workshop far from the assembly workshops forming a stack of plastic boxes, (c) large components put in materials kits in a separate workshop near the assembly workshops, (d) direct deliveries of the most synchronised large components (engines, front and rear bumpers, seats, etc.) are delivered directly to the assembly workshops.

[15] The ambition to reduce the total number of tilting devices meant that as much assembly work as proved possible without impairing the ergonomics was transferred to a workstation equipped with a lifting table workstations in order to avoid under-up work. One criteria for the ergonomics was that no operator should be working with his or her hands above shoulder height.

created. These free work positions, which were in total equivalent to one free automobile out of four available for each work group, functioned as buffers of non-assembly active automobile bodies and enabled operators performing assembly on an automobile body to e.g. switch tasks and help their co-operators when they had finished their own tasks.

In addition, assembly work not performed on the automobile body was also used to introduce a buffer capacity. This became possible because the subassembly workstations were not fully utilised and there was also a possibility for buffering subassemblies within the workgroup. Thus operators who during certain periods performed subassembly tasks could also help their co-operators nearby.

More specifically, the three operators on the second half of the work on the automobile body, i.e. (3) Sealing and decor and (4) Interior, could help each other using the free work positions on the two automobiles available, while the four operators working on the first half on the automobile body, i.e. (1) Leads for electrics air and water and (2) Drive line, mainly utilised the subassembly work stations for similar reasons.

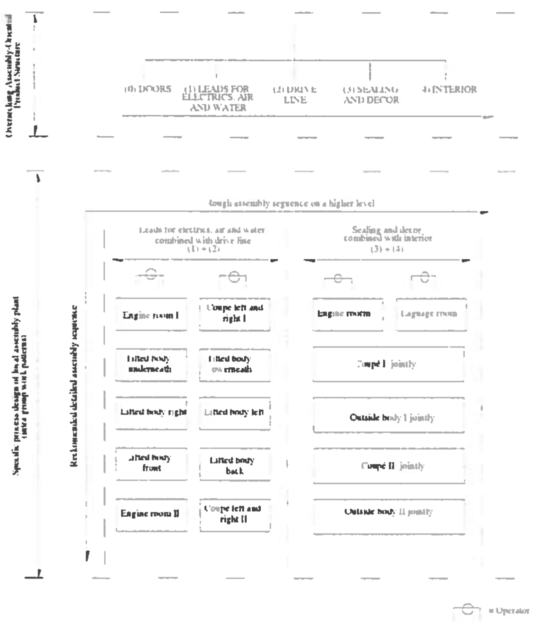
It might be added that, in the case of the Volvo Uddevalla Plant, quality demands on the product did also influence how the assembly work was derived from the assembly-oriented logical product structure. This was the reason for combining (1) ”Leads for electrics, air and water” with (2) ”Drive line” to be assembled on one workstation, since these main groups were focused on correct torque on the nuts and bolts used for fitting of components, which also called for a tilting device. On the other hand, (3) ”Sealing and decor” and (4) ”Interior” were combined and allocated to a workstation featuring a lifting table, because these components called for quality in form of correct tolerances between components. The work at this workstation involved adjusting mostly “cosmetic components” like panels and other interior components against each other and in relation to an automobile body recognized as having a dimensional inaccuracy, combined with the fact that some components are hard and prone to break (especially the plastic panels), while others are not very accurate in regard of measures, all this resulting in extensive fiddling.

In addition, when fitting components from groups (1) and (2) the operators hands were usually somewhat soiled, while fitting of components from group (3) and (4) called for cleaner hands due to e.g, interior related components.

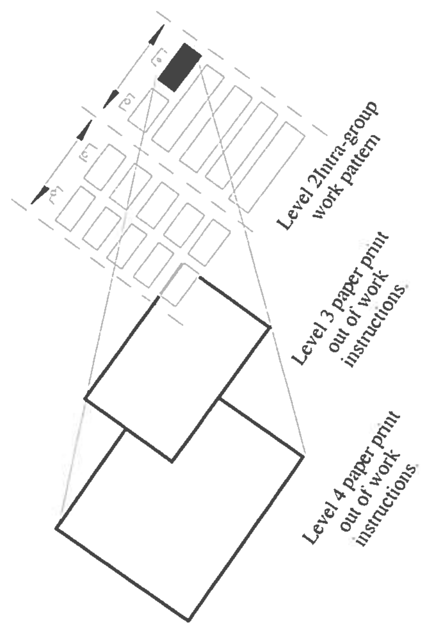
As a result of the considerations described above, the work was organised into work modules derived from the assembly-oriented logical product structure and the fact that a tilting device and a lifting table were used, thereby forming a matrix defining an intra-group work pattern as shown in figure 8. These work modules were related to the work positions on the automobile and were consequently given names related to the operator and these work positions.

For example, the work module denoted “tilted body left” meant assembly work performed by an individual operator on the left side of a tilted automobile body. Also, the work module “outside body I jointly” referred to the first time (coded by the roman number I) assembly work was performed on an automobile body at the “ordinary” height (i.e. in a lowered tilt device corresponding to the automobile body standing on the floor) by two operators jointly, where the one who completed the previous work module first started directly on the next work module. As a final example, “coupe left and right II” described that this was the second time assembly work on a automobile body positioned as on the shop floor was performed by operators individually but from both the left and right side of the automobile body.

The design of these work modules was both facilitated by, and expressed for the manufacturing engineers and operators, by a schematised automobile body, where the body is sketched as three boxes as shown in figure 9 to the right.



So-called intra-work group pattern, a matrix that is a consequence of intersection the assembly-oriented logical product structure with specific characteristics/restrictions of a process design. The intra-work group pattern is schematised e.g. the work are not normalised in accordance to assembly time i.e. their height ought to differ in regarding time consumptions. Moreover is the subassembly work represented by one quadrate (in fact a number of different subassemblies were integrated in the work group as discussed in this section).



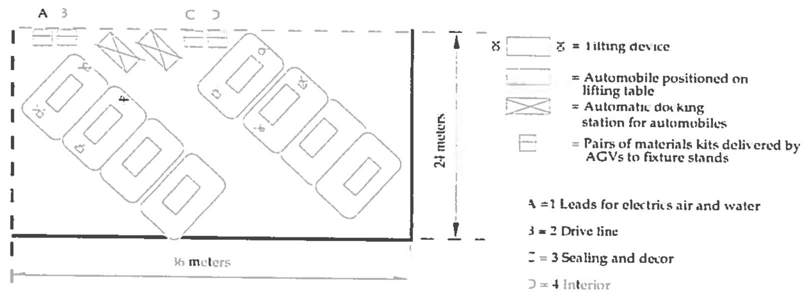
Blow-up of work modules on level 2 into levels 3 and 4.

Figure 8. To the left a so-called intra-group work pattern, defined by a matrix using both product and process dimensions. Note that some of the work modules were assigned to pairs of operators, since the product architecture either called for or allowed co-operation where the first operator reaching the common module (denoted "jointly" in the intra-group work pattern) starts with this work. To the right is illustrated the fact that each work module in an intra-group work pattern is described with various degrees of resolution from schematisations down to details.

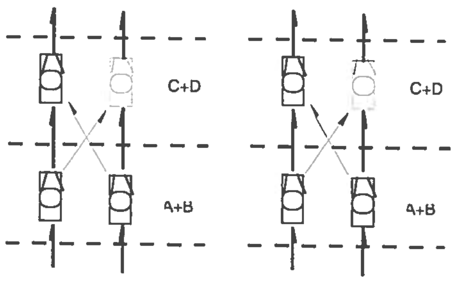
*

The assembly work in the Volvo Uddevalla Plant was performed within some 30 work groups and there was a detailed, predetermined time-and-motion study based division of labour (assignment of work tasks to operators) within each workstation system. The complete assembly work was organised into 50 work modules representing about 15 minutes work each. These modules were combined to form the task of each operator. The work modules consisted of work elements, totally 1 100, which in turn consisted of subelements, totally 2 100. These subelements were defined and time-studied through the so-called SAM method (Viklund 1990), similar to the so-called MOST system (Zandin 1980). The average time of each subelement was 27 seconds.[16]

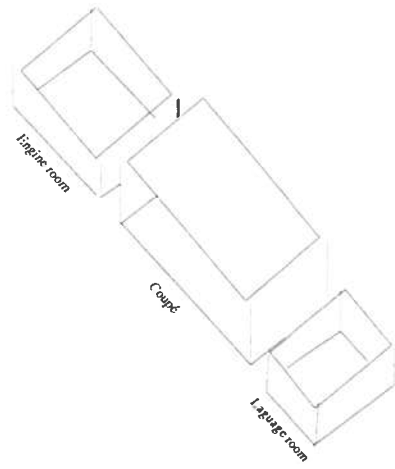
[16] Note there is some general misunderstanding concerning the practical application of these work structuring methods. In some cases (e.g. Moestam Ahlström 1997), it has been implied that individual operators completed product functions/subsystems. This is not the case. It is in fact impossible to designate specific product functions/subsystems within a large motor vehicle to be completed by single operators, in one continuous assembly sequence, due to the product architecture.



The actual layout at the Volvo Uddevalla Plant.



Schematised layout at the Volvo Uddevalla Plant.



Schematised automobile body sketched as three boxes.

Figure 9. To the left the actual and schematised layouts used for two work groups in the unorthodox Volvo Uddevalla Plant. To the right, a schematised automobile body, where the body is sketched as three boxes. One box represents the engine room, which is open from underneath as well as from the top, one box represents the coupe that opens from the left and right side, and one box represents the luggage room which is open from the top only. This schematisation was used to determine how to relate the automotive body to the operators to minimise operators' interference during assembly work as well as optimising the use of equipment like tilting devices and lifting tables. The surfaces and edges on the three boxes were marked on a number of schematisations based on the original experiences from the Volvo Uddevalla Plant, training workshop, predating the actual starting-up and full scale running (see Engström and Medbo 1994 for a more detailed explanation). Thereby is was possible to identify so-called work modules by names such as "tilted body left", meaning assembly work on the left side of a tilted automobile body performed by an individual operator. For an ergonomic evaluation of assembly work see in this plant see Kadefors et al. (1996) and Engström, Johansson Hanse and Kadefors (1999).[17]

A print out of all work instructions totalled approximately 100 pages. This should be compared with the documents from the central Volvo process-engineering department, which consisted of 25 binders totally including illustrations, albeit not used for the same purpose. (These documents are denoted Process/Inspection Instructions (PKI) and they specific how to assemble automobiles according to worldwide Volvo standard.)

This illustrates a dramatic reduction of information required to specify products and assembly work, which contributed to a better overview than that available within Volvo at the time, leading in turn to a superior flexibility manifested in the Volvo Uddevalla Plant by lower costs in connection with annual model changes as shown by comparisons of the unorthodox Volvo Uddevalla Plant with the serial product flow assembly system of the main Volvo Torslanda plant.

[17] The work modules were arranged into an intra-group work pattern according also to the impact of e.g. the product variation on the assembly work. Totally 170 so-called variant designators[17] were used to specify the product variation with regard to the tasks (see Engström et al 1995). A number of standardised intra-group work patterns were available (two standardised patters were most common in the Volvo Uddevalla Plant, for seven and nine operators respectively).

3.1 Lifted body - Leadings for electrics, air and water and Drive line

Work seguence	Turque	Socket size	Tools
Hjulhus fram:			
1 1 Fjäderben, höger- och vänster utförande	48±8	17	Vinlelmaskin+hylsa 17 mm
2 1 Tätningslister hjulhus, höger sida			
3 1 Propar och plugg			
2 Sprutskydd höger- och vänsterutförande	3,5±0,5	10	Batterimaskin+magnethyllsa 10 mm
3 Fästen bromsrör främre hjulhus			
4 Bromsslangar till rör	14±2	11	Spärmyckel, öppen momentnyckel och U-ringsnyckel 14 mm (mothåll)
- Momentdrag fäste bromsrör ("konsol")	14±0,5	12	Spärrhandtag+magnethylsa 12 mm
- Tryck bromsrör i clips			
- Fixtur till fjäderben			
Hjulhus bak:			
4 1 Slanghållare /bromsrör)	48±8	11	Spärmyckel, öppen momentnyckel och U-ringsnyckel 14 mm (mothåll)
2 Propp och plugg			
Kontroll och justring			
- Bromsrör frigång, minst 2 mm mellan rör och kaross			

Level 3 of paper print out of work instructions used in the Volvo Uddevalla Plant.

3.1 Lifted body - Leadings for electrics, air and water

Work seguence:	Materials position:	PKI-nummer:
Hjulhus fram:		
1 1 2 st FJÄDERBEN.		
4 st brickor 10,5 x 28 x 2.		6110-1001
4 st flänslåsmutter M10.		6110-1006
2 1 1 st TÄTNINGSLIST HJULHUS INRE	Låda "Tätningslister höger"	8450-1008
2 st TÄTNINGSLIST HJULHUS YTTRE	Låda "Tätningslister höger"	
3 1 1 st plugg (fjäderbenstorn).		8995-1008
2 st plugg (små).		8995-1031
1 st plugg (stor).		8995-1020
1 st plugg (avlång sidobalk).		8995-1024
2 1 st SPRUTSKYDD.		8631-1001
3 st sems skruv 14 x 22.		
3 1 st fästen bromsrör främre hjulhus.		5220-1003
1 st låsskruv 8 x 12 för fästen bromsrör.		
4 2 st SLANGHÅLLARE.		5220-1003
- Momentdrag fäste bromsrör ("konsol")		
- Tryck bromsrör i clips.		
- Fixtur till fjäderben.		6110-1007
Hjulhus bak:		
4 1 1 st slanghållare (bromsrör).		5220-1002
2 3 st gummipropp /stora).		8995-1024
3 st tätningsplugg (stel bakaxel).		8110-1023
1 st plastplugg (avlång).		
2 st gummipluggar (hjulhusbalja).		8995-1020
1 st gummipluggar (hjulhusbalja).		8610-1013
Kontroll och justring		
- Bromsrör frigång, minst 2 mm mellan rör och kaross		

Level 4 of paper print out of work instructions used in the Volvo Uddevalla Plant.

Figure 10. Print-out and blow-up of the work instruction system used in the Volvo Uddevalla Plant (i.e. the right part of figure 8) on levels 3 and 4, in this case of the work module "luggage room".

Figure 10 shows a print out of the Volvo Uddevalla Plant assembly instructions. Note the use of typography: large components are written with upper-case letters, small components use lower-case letters, nicknames are given within parenthesis with citation mark, assembly work requiring no materials (e.g. connecting wires from an harness already fitted, checking, adjusting) are set in italics. This codification facilitated e.g. finding the materials in the materials kits since different materials were supplied by different methods comprised into materials kits.

The detailed assembly sequence was available for two levels of detail, denoted level 3 and 4 in this figure. The typography was congruent on both levels. Lines demarcated work task belonging together of various reasons, e.g. the same tool, position along the product, etc.).

The correct component names were derived from the Volvo design-oriented logical product structure. This work instruction system was not fully developed during the plant's life. For example, the number of ways to search for information was extensively restricted (in fact only one way of scrolling was possible) and illustrations were never integrated into the system. Thus unfortunately, in many respects this information system successively turned into the manufacturing engineers "notebook" for product and work specification not fully utilised by the assembly operators.

8 FINAL COMMENTS

Let us summarise the proposed work structuring principles and tools.[18] (1) The "internal logic" of large motor vehicles in the form of generic relationships makes it possible to design an assembly-oriented logical product structure which is general for e.g. automobiles on a high level but product specific on the lower levels. Pre-structuring of external information and materials before the assembly work within a plant is initiated is guided by this product structure. (2) Specifically, this product structure can be used to create work modules, which are combined according to specific preconditions of a particular process design. (3) The detailed assembly sequence can be hierarchically divided into work modules, which have a varying assembly time depending on product architecture and product variation. (4) The work modules may be combined into a number of alternative intra-group work patters in order to gain an internal flexibility within a work group or as was the case in the Volvo Uddevalla Plant, to suit two principally different layouts in the assembly workshops. (5) The work modules will relate to the materials kits configuration, e.g. one materials container might correspond to one work module.

The state of affairs in the Uddevalla Plant was due to experiences from the extended running-in process, which were successively taken into account. Some of the work shops (see layout to the left in figure 9) had tilting devices and lifting tables between which the automobile body was transferred, while others used only tilting devices in which the body was fixed during the total assembly process.[19] Generally speaking, this internal flexibility of the work groups had the benefit to allow different intra-group work patterns thereby reducing foremost the production losses, i.e. reduce waiting times (Wild 1975).

The work structuring method proposed may lead to an efficient, flexible process design (see Engström, Jonsson and Medbo 1996 for an evaluation of performance aspects). This method also reduces the need for "standardised human beings" as is the case on the traditional assembly line. As discussed above, one conclusion concerning the Swedish automotive industry is that the Volvo (overarching) design-oriented logical product structure and process designs practised has figuratively "destroyed" the product's inner logic, with the consequence that the elements of the design-oriented (overarching) logical product structure on the shop floor, and also in the manufacturing engineering department of the local assembly plant are perceived as fragmented. To remedy this situation, and create structural similarity between the product, the assembly work and information about them, an assembly-oriented

[18] Some of these work structuring principles and tools where verified by a crucial experiment performed in the authors´ experimental workshop in Göteborg 1985 – 1993, which predated the Volvo Uddevalla Plant training workshop. Especially enlightening was, in this case, the performance by a 16-year old trainee who alone assembled one-fourth of an automobile at almost full production pace the second time he assembled the same automobile after two weeks' training (Engström, Johnson and Medbo 1994).

[19] It should be noted that the variation in, e.g. assembly sequences, was quite similar even though a large variation in intra-work group patterns and work group sizes existed in the Volvo Uddevalla Plant (Medbo 2001). In one extreme case, two female operators regularly assembled complete automobiles by themselves.

logical product structure, where components are given meaningful names and arranged in a hierarchy as described above, is required.

The proposed work structuring principles and tools have lately proved applicable for improving the quality of information at a traditional assembly line at the Scania diesel engine plant in Södertälje. Thus, the Volvo Uddevalla Plant experiences are of general interest even though this specific plant is closed down, since the reasons and preconditions for reforming the assembly work within the automotive industry might not be specific for Sweden.[20] It would be especially interesting to investigate whether or not e.g. logical product structures and product information are also restricting the development of the assembly work in other countries.

To summarise, this article explains critical details for understanding proposed work structuring principles and tools applied in various Swedish automotive plants with unorthodox assembly systems. These more than twenty-five years of experience for some of the authors underlines that the technology can be reformed to suit the human being. However, this calls for some extensive work both within technology and social science. In this case the contributions of senior research competence within vocational learning has proved to be invaluable.

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[20] In short, the required restructuring of the existing information system at Scania (see e.g Portolomeos and Schoonderwal 1998 whom, under the authors guidance initiated this work) was required due to the fact that it was almost impossible to "secure the product specification" (i.e. being sure that the product was fulfilling specification regarding correct component fitted and meeting various other specified quality demand). As a result of this work, the work orders (i.e. specification following each individual diesel engine) were possible to reduce from 43 pages down to one, containing correct information for specifying product variation.

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