Some Cognitive Engineering Aspects Applied to Product and Process Information within the Swedish Automotive Industry

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ABSTRACT:

This paper explains critical details for understanding proposed work structuring principles and tools applied in various Swedish automotive plants with unorthodox assembly systems. Especially so by relating the principles to theoretical frames of references of Gestalt psychology which comprise the concept of so-called "dual vision" but also by relating to semantics and vocational training knowledge. However, this paper focuses on the former field of knowledge.

Specifically the paper report on (1) the state of the art regarding the overarching design-oriented product structure and (2) six generic relationships exhibited by large motor vehicles. This in turn leads to explaining the (3) abstract principles underlying the design of a so-called assembly atlas based on (4) specific criteria's for grouping the components in the product.

Finally, (5) an industrial application is explained, namely how the assembly-oriented product structure interacted with the detailed assembly sequences at the Volvo Uddevalla plant.

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 trough. These seminars have earlier been arranged in September 1999 at Göteborg, and in October 2000 at Osaka. This paper was first written for the September 2001 seminar in Göteborg (see Engström, Jonsson and Medbo 2001) and later modified in accordance to comments.

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 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 paper 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, the choice of materials feeding techniques, selection manufacturing equipments and tools, etc., i.e. what is considered as synonymous with assembly system design.

Therefore this paper will specifically clarify the state of art concerning the overarching design-oriented product structure and explain how to reform the product and process information for long cycle time assembly work condensed into in one publication in order to elucidate some of the questions brought up by Japanese researchers. These are questions that, in most aspects, bring forward a relevant constructive criticism, originating from the fact that the research and development work has been published successively during the last two decades in various scientific journals and books, giving a somewhat scattered content. This is especially evident for the work structuring principles advocated, which are connected to, or based on, vocational training and psychology

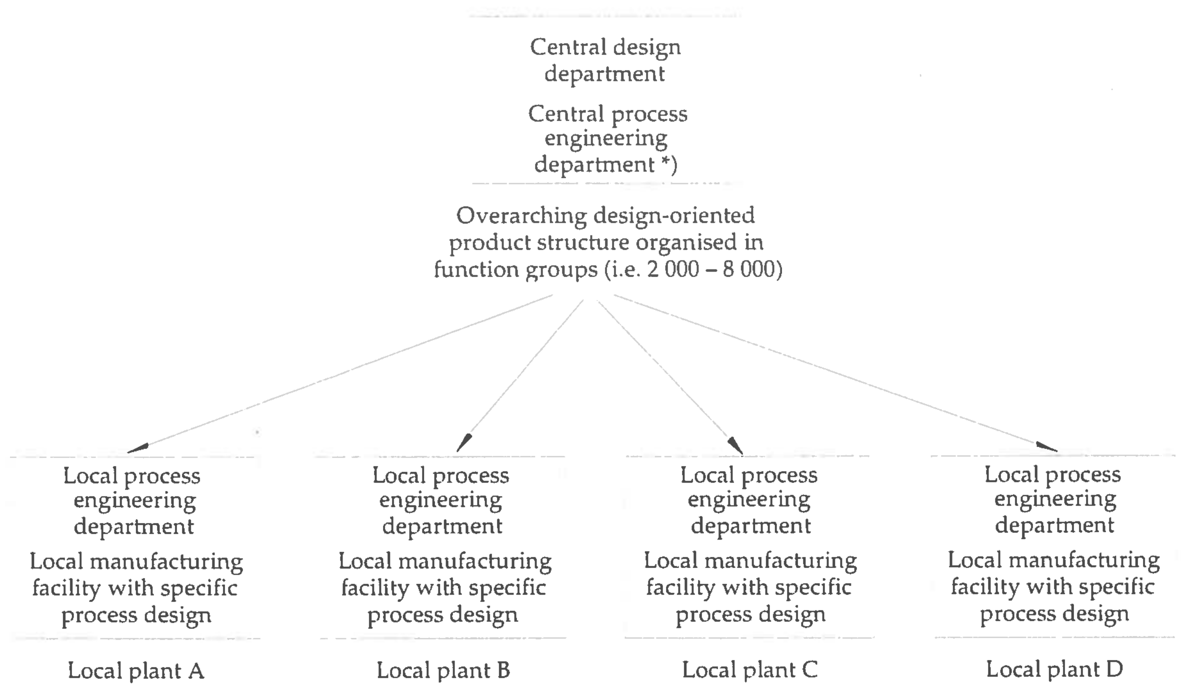
Though these results are spread on both an international level by means of traditional academic channels and also shared locally between a limited number of practitioners and researchers actually involved in the experiences referred to, it is fair to say that the detailed core knowledge has proved intriguing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

2 THE STATE OF THE ART REGARDING THE OVERARCHING DESIGN-ORIENTED PRODUCT STRUCTURE

The standardised so-called product structure 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 (see e.g. Volvo 1989). This is a design-oriented product description, i.e. it describes a motor vehicle from the central design department's point of view in a traditional way by e.g. separating electrical components from mechanical components, despite the fact that many product functions are in fact combinations of e.g. electrical and mechanical components.

The main function groups for an automobile like Volvo are: 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. Note that for reasons discussed below most of the components of an automobile are concentrated in main group 8 000.

In an international manufacturing corporation like Volvo, the core information emanating from the central design department is used for specifying the product 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, which constitutes the overarching design-oriented product structure organised in accordance to the function group register, is the reference for the manufacturing of the product in various local plants but also for interaction with suppliers and customers.



*) 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 data included in the design-oriented product structure which in turn is a result of the work from the central design department.

Figure 0. In an international manufacturing corporation, the core information emanates from the central design. 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 the hierarchy to disappear when applied to e.g. an automobile. Accordingly, the complete overarching design-oriented product structure describing a product will contain "implicit holes". These "holes" are denoted "implicit" due to the fact that in order to recognise them one has to be extremely acquainted with both the product architecture of the specific automobile in question and also with the "total function group register", since the recognition of the "implicit holes" is a consequence of combining these structures.It will thus not be obvious how to hierarchically divide or unite products.[1]

It must 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 the components are to be found in the last of the seven main groups (i.e. 8 000 body, cab and upholstery) in the overarching design-oriented product structure. Another reason for this distortion is that this main function group contains components not possible to obviously belonging to any other function group. The increased combinability in-between subassemblies are the result of changes in market, product architecture, choice of materials and external suppliers. This has influenced the content of the overarching design-oriented product structure more for the automobile than on the bus or truck.

[1] The general classification register used within the Swedish vehicle industry by the Volvo Group consists of seven main groups divided into sub-groups. On the third level of the hierarchy the structure consists of 271 groups and 245 "implicit holes" (i.e. as mentioned above the register "holes" contains no components included in an automobile). When this register is applied to a chosen type of automobile 122 of these groups are used, and the number of "holes" thus increases to 394. For a representative truck the corresponding figures are 90 groups and 426 "holes".

Though this paper has deliberately, to restrict the scope, omitted to explain how to consider product variation and product variant codification, it might be added that the existing method of describing variations 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 e.g. that manufacturing engineering at the local manufacturing facility requires extensive work to restore the information into a form suitable for the particular assembly system 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 product structure also obstructs feedback concerning assembly work to the central design department due to the reasons explained above.

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The overarching design-oriented product structure described here has thus proved not only to inflict the actual work of the operator on the shop floor but also obstruct the development of this work. The introduction of parallel product flow assembly systems with long work cycle time assembly work calls for not only an advanced materials feeding technique, since the materials obviously cannot be feed by traditional line stocking[2], but also specific measures to facilitate the long work cycle time. The latter has proved to require a congruence between (1) operators' perception of the assembly work; (2) the materials display on the workstation; and (3) product and process information used on the shop floor (see Medbo 1999, Engström and Medbo 1992 for a more comprehensive presentation).

The main task to be performed when designing parallel product flow assembly systems with long work cycle time assembly work is to ensure this congruence. Such congruence cannot be achieved by means of the traditional design-oriented product structure, but requires certain common structuring principles and tools, notably (a) six generic relationships exhibited by all large motor vehicles with multiple product variants, (b) criteria for grouping components together, (c) a structured semantic network reflecting (a) and (b), thereby forming what in an abstract sense is denoted an assembly atlas (originally Engström and Medbo 1992). These common structuring principles and tools will be described in the following sections.

3 SIX 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 design of the Volvo Uddevalla Plant, 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) <u>Part-whole relationships</u>. This means that motor vehicles contain several components, sub-components and so on.

(2) <u>Intra-system synergies</u>. 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 sub-systems 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.

(3) <u>Bilateral intra-product symmetries</u>. 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 axle. 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.

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[2] See Engström (1983) for explaining how to organise the materials feeding in parallel product flow assembly systems.

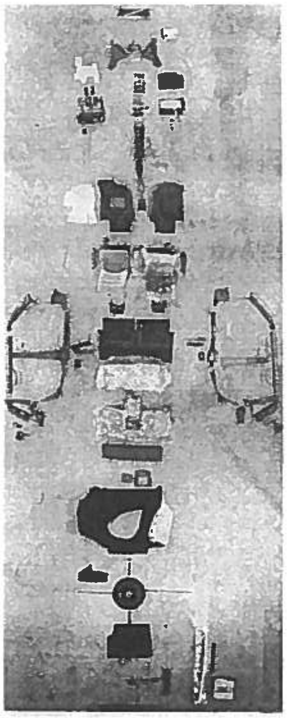

Figure 1. Photo of 1/4 of an automobile laid out on the floor of the authors' experimental workshop in 1985. In this case, some of the generic characteristics of this motor vehicle are evident. Note e.g. that the automobile has an "organic" symmetry, i.e. the components are organised around an assumed symmetrical axle running in the middle of the product from back to front in analogue to a living organism.

Comparing different products the following generic relationships appear:

(4) 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.

(5) 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 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 interior components may generate such links.

(6) 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 drivers 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 systems functions are independent of if the motor vehicle if e.g. left or right hand driven.

These six 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	- Genealogical links
Symmetry:	- Bilateral intra-product symmetries	- Bilateral inter-product symmetries

Table 1. These six types of relationships are themselves conceptually related as shown.

4 ABSTRACT PRINCIPLES UNDERLYING THE DESIGN OF AN ASSEMBLY ATLAS

In order to achieve coherence between (1) operators' perception of the assembly work, (2) the materials display on the workstation and (3) product and process information used on the shop floor the components to be fitted must be overviewed and grouped together according to criteria described in the next section. That is, the components to be fitted to an automobile body or the frame of a bus or truck must form a coherent hierarchical structure, from top to bottom, based on the characteristics of the components (such as form, functions, size, materials) as well as other criteria. This means that the component groups consist of components, which together and separately constitute subgroups of components forming a hierarchy described by means of meaningful names. In analogy to an atlas ("the assembly atlas") comprising continents, countries, districts, etc. described with different grades of resolution, by exact names as well as schematised maps. Various routes in this atlas will then be analogous with chosen assembly sequences, i.e. the process is usually unique for each specific process design, but also for products that are assembled.

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Three interrelated abstract principles may be cited as providing the theoretical foundation for the design of assembly atlases.

Firstly, an assembly atlas may be regarded as product information that reflects the assembly point of view, in contrast to the design-oriented product structure explained above, that is it may be regarded as a so-called assembly-oriented product description. On the other hand, an assembly atlas may also, conversely, be regarded as assembly process information that takes the structure of the product into account.

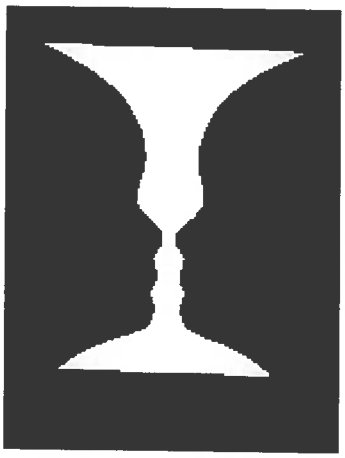


Figure 2. Dual perception illustrated by using the Peter-Paul goblet used to illustrate the "figure-ground effect" (Berelson and Steiner 1964).

This phenomenon is analogous to the so-called "figure-ground" effect explored in Gestalt psychology. Briefly, one region of the perceptual field tends to stand out as "figure", while the complementary region is perceived as "ground" (Berelson and Steiner 1964). The roles of "figure" and "ground" can however be reversed (cf. figure 2).

Thus, the first principle concerns product – process duality. The assembly atlas is in reality a product information which is coupled to the process information. From an assembly process design and assembly work point of view, the assembly process will be the "figure" while the product will be "ground", while from a product architecture and materials supply point of view the product will be the "figure" while the assembly process will be the "ground".

Secondly, both the physical product, the assembly process and information about them consists of a number of elements (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 3.

As discussed above, one conclusion concerning the Swedish automotive industry is that the overarching design-oriented product structure and process designs practised has figuratively "destroyed" the product's inner logic, with the consequence that the elements of the 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 physical product, the assembly process and information about them, an assembly-oriented product structure, where components are given meaningful names and arranged in a hierarchy as described below, is required.

Figure 3. Similar shapes structures but different substance.

To explain the third 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. 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 4 illustrates the distinction between surface structures and deep structures.

The assembly sequence is analogous to the surface structure of a sentence, and according to the deep structure transformation principle, the assembly sequence should be derived from a "deep structure" to make assembly work (cognitively) meaningful, just as the underlying "deep structure" makes a sentence (semantically) meaningful. Also, according to the principles of product process duality and structural similarity this deep structure will be closely related to the inner logic of the product to be assembled.

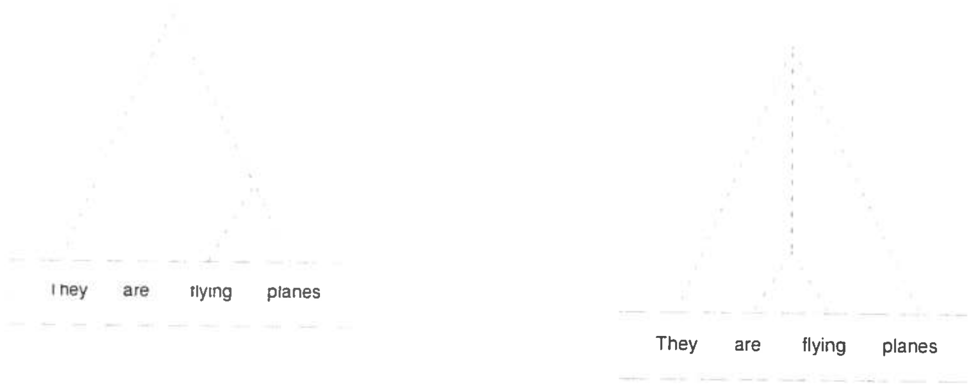
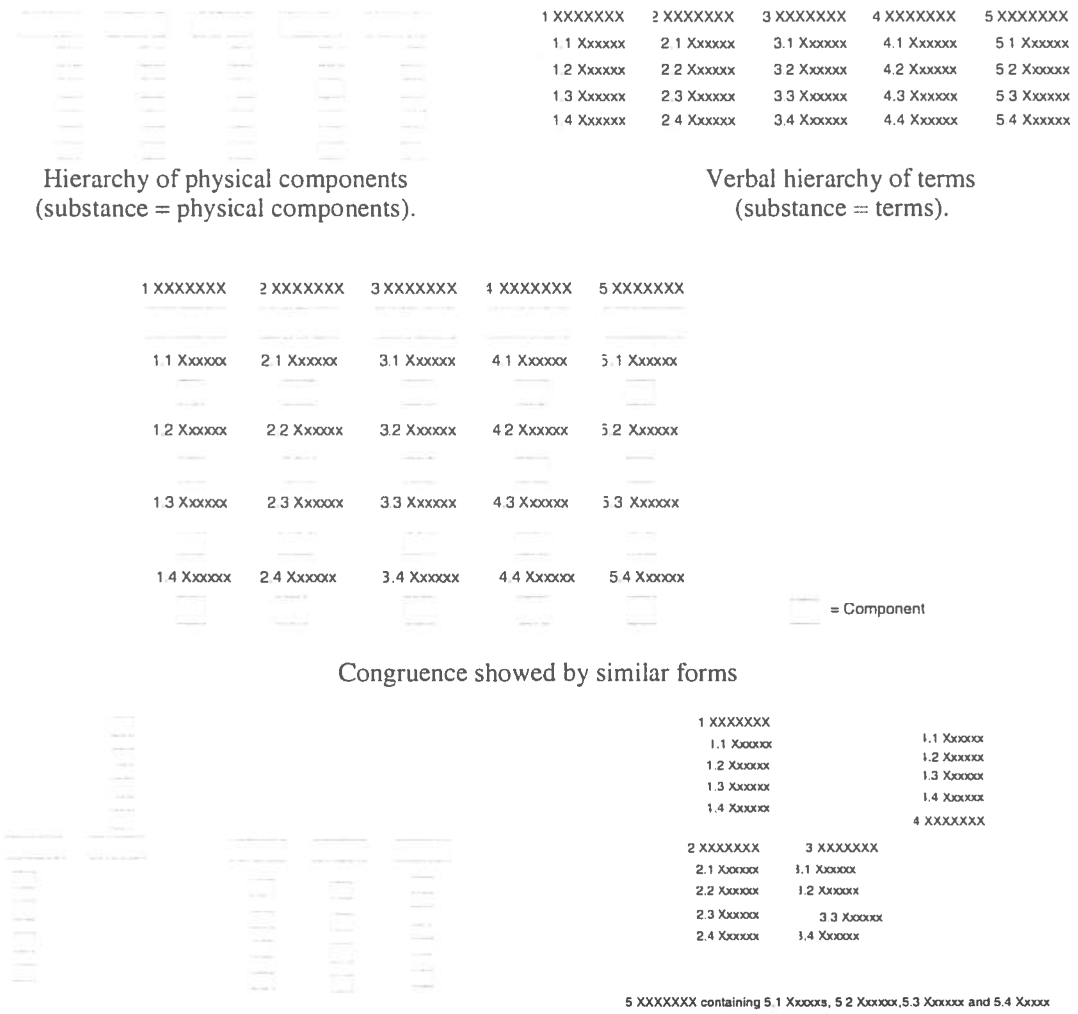


Figure 4. Same surface structure – different deep structures.

Other important influences on the results presented in this paper are Marton (1970) and his disciples who stress the importance for the human being of creating an internal, mental representation – a structure – to facilitate learning. Complex knowledge cannot be composed out of small pieces. It is especially important to construct a mental structure ("building up an internal representation") in the initial phase of the learning, leading to higher performance in later phases. In this connection (see Nilsson 1994) speaks about from two qualitatively different perspectives, the mechanistic contra the organic perspective. However, these influences are not explained here – they certainly merit a separate paper.

5 CRITERIA FOR GROUPING COMPONENTS IN AN ASSEMBLY ATLAS/ASSEMBLY-ORIENTED PRODUCT STRUCTURE

To develop an assembly-oriented product structure for an automobile type, e.g. the Volvo 700 series, one or more automobiles are disassembled, their components are laid out on a suitable large surface, e.g. a floor, and the components are then iteratively rearranged to represent the allocation of components into a hierarchy of 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 product structure. These two hierarchies should exhibit structural similarity as illustrated in figure 5. 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.



Congruence showed by different formed hierarchies using/utilising various substances.

Figure 5. Illustration of structural similarity between hierarchy of physical components and verbal hierarchy of terms (i.e. a verbal network).

There are several types of criteria for grouping components when designing assembly oriented product structures. Firstly, components are 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. This means that components are grouped in order to form hierarchies according to similarity, proximity and complementarity or synergy (i.e. contribution to a common product function).

Secondly, since we are dealing with an assembly-oriented product structure, a rough assembly sequence, dictated by the design of the product, 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 the last sub-group of the last main group.

Thirdly, again because of the fact that we are dealing with an assembly-oriented product structure, the assembly time represented by e.g. included components in each main group must be taken into account. This means that an even division of labour between the main groups in the assembly-oriented 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 time these where fixated (by clips, clamps, etc.) plus the number of lead-troughs 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.

Based on the above considerations, the main groups defined for the Volvo 700 series during the authors' involvement in 1986 (Volvo Uddevalla plant process design) were (0) Doors; (1) Leads for electrics, air and water; (2) Drive line; (3) Sealing and decor and (4) Interior. These main groups were to some extent obvious. However, the sub-groups were trickier to define and to designate correctly in order to establish a meaningful correspondence between the physical components and their positions in the automobile (forming a spatial network) and in the hierarchy of terms (forming a verbal network). It is fair to state that so far the main groups in the assembly-oriented product structure have proved to be general for Volvo automobiles (the rear driven 200 and 700-models as well as the front wheel driven 800 and C70-models), while the sub-groups has varied dependent on product architecture.

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Note that the three types of considerations listed above are 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 assembly system) where the product is assembled. This generic assembly-oriented product structure is utilised in the design of a specific process design.

Finally, the specific assembly-oriented product structure is used, in accordance with the principle of deep structure transformation, to generate a recommended assembly sequence. Or to formulate it in another way, "the assembly-oriented product structure is an 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, product variant manufactured, etc. A process design for a number of parallel work groups should also stipulate how the components are organised in e.g. the materials kits. 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 Uddevalla plant, for example, the assembly sequence was influenced by the fact that the sub-frame, comprising engine and gearbox assembly, was inserted from below of the automobile body, as was also the case for the rear axle arrangement. The assembly-oriented product structure is thus adapted and amended to the specific process

It might be added that, in the Volvo Uddevalla case, quality demands on the product did also influence how the assembly work was derived from the specific assembly-oriented product structure mentioned above. 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 bults 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.

6 THE INDUSTRIAL APPLICATION REGARDING LONG WORK CYCLE TIME ASSEMBLY WORK

As mentioned above, the successive rearrangement of components on the shop floor in the experimental workshop during 1985 – 1993 led to an assembly-oriented product structure for the Volvo 700-model comprising five main groups of components. 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 in product and process information as well as a detailed understanding of the product architecture and product variation.

Even though all Volvo documentation in form of e.g. service manuals, spare part catalogues, assembly instructions from various Volvo plants, process controls instructions from the central process engineering department, etc. was available, 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 the specific materials included in a complete automobile.[3]

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.[4] 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.

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 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 product structure (see figure 7). To help us with the illustrations we employed an architectural research student specializing in visualization techniques.

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To recapitulate the assembly-oriented product structure comprised: (0) Doors; (1) Leads for electrics, air and water; (2) Drive line; (3) Sealing and decor and (4) Interior. The first group thus comprised subassembly work on the doors, while the other four main groups were work on the automobile body.

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[3] Given the insights reported in section 2 it might have been a successful course of action to engage specialists from 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 were 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?

[4] 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. There it proved necessary to make a special inventory of all materials contained in an automobile to grasp materials volumes, number of components, etc.