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IMPLICATIONS OF PRODUCT ARCHITECTURE AND PRODUCT DESCRIPTIONS ON EXTERNAL AND INTERNAL MATERIALS FLOW SUBSYSTEMS

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The biological or ecological foundations of social life are increasingly being recognised. It is by now well understood that changes in ecological systems may have far-reaching social and economic implications. For example, economic growth may in the long run lead to detrimental ecological changes that prevent further economic growth; hence the concept of "sustainable growth". Thus, so-called environmental issues are redefined as issues concerning life conditions.

It is similarly a basic tenet of this paper that some issues that seem to concern only the technical means to achieve production goals and which are generally seen as technical issues are of interest, not only to manufacturing engineers. The fact is that the design of materials flow subsystems within the industrial network (production and logistics systems including supply chains) are in reality issues with far-reaching social and economic implications.

This is of course not a new type of insight; the implications of the "mode of production" for socio-economic conditions are a central theme in, for instance, the Marxist dogma. Yet, along with the demise of Marxism, this old insight seems to have vanished. Since there is a lack of insight that "technicalities" in the design of industrial network may impact socio-economic conditions, questions regarding this impact have not been sufficiently explored. This paper attempts to shred some light on this problem.

Below, we shall first consider three "technicalities" pertaining to materials flow subsystems, that is exchangeability of products, accessibility of products in buffers and materials flow patterns. In each case, two alternatives are described, namely administrative exchangeability versus non-exchangeability, restricted versus non-restricted buffer access and serial flow versus parallel flow patterns.

We then turn to the implications of choices between alternative designs of internal (i.e. inside a plant) as well as external (i.e. outside an plant) materials flow subsystems, that is materials flows within a single plant and materials flows in supply chains, respectively. Finally, we sketch social and economic implications of the two lines of development discussed. As noted above, this is an area where further research is needed, but we can offer some speculations.

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The context described in this paper is unorthodox but in coherence with the present evolution in the automotive industry comprising customisation of products, rapid technological development, supply chain development and increased flexibility demands in manufacturing. Particularly the flexibility aspect has been recognised as vital for the "factory of the future" (Bullinger et al.. 1985; Goldman et al., 1995; Hill, 1993). Flexibility is also for example underlined by the concept of agile manufacturing which summarises various trends used for designing and implementing advanced manufacturing systems, thus underlining the integration of technology, organisations and people (Kidd and Krawowski, 1994).

ADMINISTRATIVE AND PHYSICAL EXCHANGEABILITY OF PRODUCTS IN MATERIALS FLOW SUBSYSTEMS

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

The international trend towards product designs involving external subassemblies and predefined interfaces, as a so-called modular product architecture, in some cases represented by component manufacturers or special companies, has in many cases increased the number of component types assembled. For combinatorial reasons, the number of product variants tends to increase with the size of the subassembly. In order to remedy this situation the subassemblies are often treated as administratively non-exchangeable though they are in fact physically possible to substitute for one another.

Product architecture is closely related to product complexity which has been treated by Hubka and Eder (1988), who discuss complex technical systems as consisting of numerous components which could be divided into subsystems embracing product functions. MacDuffie et al. (1996) connect product and component variation to complexity in production. Ulrich and Eppinger (1995) focus on complexity in the product architecture, i.e. the relationship between physical components and product functions.

Modular architecture of automotive products and so-called platform concepts have in this context also been brought forward as a method for future product designs and assembly systems, especially in order to manage production with high variation (Muffato, 1999; Ulrich and Eppinger, 1995). However, it is not always possible to divide a product into a number of discrete physical modules that can be finalised and tested before being fitted together. In practice, the product functions impose vital restrictions on the possibility to introduce a modular architecture.

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

Exchangeability of product individuals in the materials flow subsystems takes several different forms. e.g:

- Exchangeability of components or modules vis-à-vis other components. e.g. exchangeability of individual nuts vis-à-vis individual bolts or exchangeability of individual bolts vis-à-vis individual nuts. as when each nut in a box containing exchangeable nuts fits a particular bolt or vice versa.
- Exchangeability of components or modules vis-à-vis products. e.g. exchangeability of individual engines vis-à-vis individual automobiles. as when each one of several exchangeable engines can be fitted to a particular automobile body.
- Exchangeability of components or products vis-à-vis production resources or production location. as when different product individuals can be assigned to a specific workstation.
- Exchangeability of products with regard to customers. as when there is a choice concerning which one of several exchangeable product individuals to deliver to a specific customer.

Underlying these different forms of exchangeability. however. is a common "logic of exchangeability" illustrated in figure 1.

As noted above. the recent trend within industries such as the automotive industry has been to deliberately reduce administrative exchangeability of product individuals in the materials flow subsystems. making administrative exchangeability more restricted than physical exchangeability. (From a production scheduling practices point of view. the trend within the automotive industry is to connect product individuals to specific customer orders as early as possible in the physical supply chain).

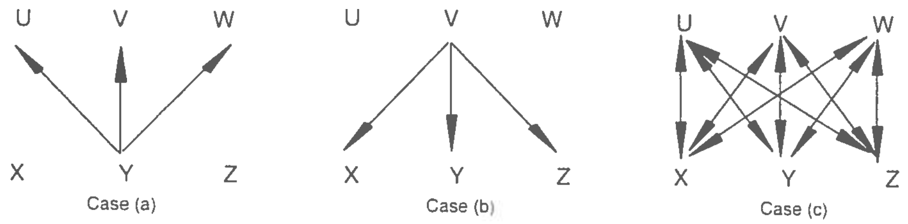

Figure 1. *Schematisation of the logic of exchangeability; in case (a).*

Y is exchangeable vis-à-vis U. V and W; in case (b).

V is exchangeable vis-à-vis X. Y and Z: in case (c).

X. Y and Z are exchangeable vis-à-vis U. V and W and conversely. This logic could also be modified to include for example complementary components. i.e. X + Y = Z meaning that a "new" component is created by merging complementary components.

Nevertheless, the benefits of exchangeability remain, particularly with regard to physical modules. Abstractly, the principle of maximal (administrative) exchangeability of product individuals in materials flows implies a principle of delayed commitment of materials - or "just-in-time" commitment of materials, to use a popular term. This could mean, for example, delaying the decision about which product a specific component should be assigned to until the component is needed; delaying the decision about which workstation a specific product-to-be-assembled should be assigned to until the workstation that becomes available next has been defined; or delaying the decision about which customer a specific product should be assigned to until the most highly prioritised customer order with an order for this type of product has been identified.

RESTRICTED VERSUS NON-RESTRICTED BUFFER ACCESS IN MATERIALS FLOWS

Briefly described there are two diverging opinions on the use of buffers. According to one opinion, buffers are wasteful and represent efficiency potentials if removed or reduced, due to reduction work in progress, the revealing of manufacturing discrepancies, etc. According to the second view, buffers are consciously positioned and dimensioned to smooth out process and product variations in order to increase efficiency and to form autonomous work groups with merits such as reduced number of planning points, creation of required operator cohesion, etc (see e.g. Benders, de Haan and Bennett, 1995; Huse, 1975; Turner and Lawrence, 1965; Wild, 1975).

Buffers can be classified according to various criteria, such as e.g. if they are due to technical or social reasons respectively or whether they are visible or not. This means that a specific buffer's varying functions are directly visible to operators on the shop floor.

Generally speaking a buffer is used to absorb technical distributions or used to accumulate the working up respectively, represented by for example a number of products defined by a deviation from the planned production. Finally, buffer volumes could be available through either individual or work group co-operation. (see Engström, 1983). However, if we connect to the discussion in section 1 and the examples presented below, it is evident that to capitalise on the distinction between administrative and physical exchangeability requires a refined perception of buffer functions. If a product is prioritised due to shifting between physically exchangeable products it must also be physically prioritised in the buffer. Thus a buffer could be said to comprise two mechanisms to absorb variations, (1) to accumulate materials or products and (2) to sort the materials or products (see figure 2). This mechanism might be denoted restricted and non-restricted buffer functions, i.e. a mechanism which is influenced by various administrative means such as how the product variants are codified.

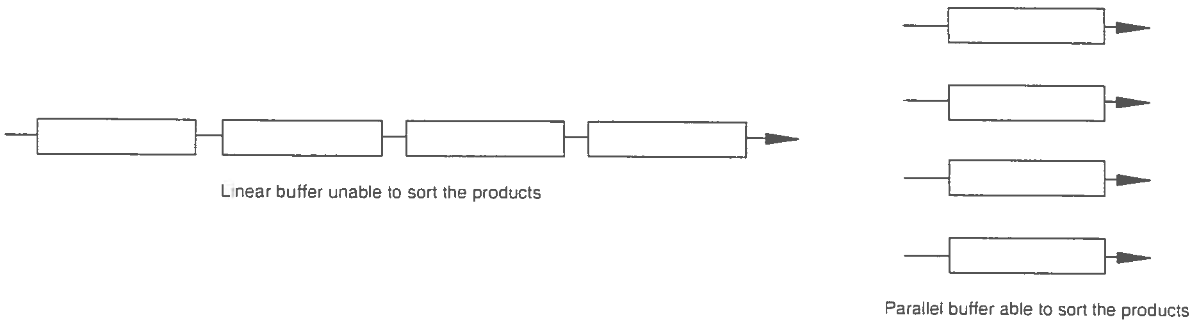

Figure 2. Buffers with restricted versus non-restricted access to buffered products (sorting versus non-sorting buffers); in some cases it is more appropriate to visualise the buffers in form of triangles, as has been the case in figure 3.

SERIAL VERSUS PARALLEL PRODUCT FLOW PATTERNS

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

- Refining repetitive, short cycle time work, in serial product flow assembly systems (assembly lines), drawing inspiration from Japanese success cases.

- Developing unorthodox long cycle time work in parallel product flow assembly systems, which might be recognised as a new manufacturing paradigm, drawing inspiration from Swedish experiences.

In a serial product flow system, the product being assembled passes all the workstations along the flow. The cycle time is short. In a parallel product flow system, on the other hand, the product passes only one workstation or workstation system, and the work is less repetitive due to the increased cycle time. If operators co-operate on one or more products collectively, a special type of working denoted collective working is present in a defined subsystem of workstations and workers, i.e. workstation systems.

The parallel product flow alternative has been assumed to be contradictory to traditional production engineering practice, striving for reduced manufacturing costs and using mechanisation and standardised work as important means towards this goal by advocating parallel product flow. Instead, this new alternative has been supported by the argument that, due to humanisation, sick leave and turnover would decrease, and this would compensate for increased manufacturing cost in unorthodox assembly systems. The fact is, however, that parallel product flow assembly does, correctly designed, simultaneously achieve increased efficiency and a more humane work compared to the assembly line (e.g. Engström et al., 1995 and 1999; Karlsson, 1979).

ALTERNATIVE LINES OF DEVELOPMENT IN THE DESIGN OF MATERIALS FLOW SUBSYSTEMS

The three design dimensions defined by the "technicalities" pertaining to materials flow subsystems (i.e. administrative versus physical exchangeability, buffers with restricted versus non-restricted access and serial versus parallel product flow patterns) discussed above are clearly interrelated. For example, if access to buffers is restricted, products in such buffers are not exchangeable vis-à-vis downstream destinations. Also, as will be discussed in section 6, parallel product flow assembly systems require components and products to be exchangeable vis-à-vis parallel workstations if potential efficiency gains are to be realised.

It is in fact possible to discern two alternative lines for the development of industrial networks with respect to the design of internal as well as external materials flow subsystems:

- A trajectory involving (1) early coupling of customers to the product individuals, product individuals to production resources and component individuals to product individuals (2) restricted access buffers (non-sorting buffers) and (3) serial product flow patterns as in line assembly. In this approach, the administrative exchangeability between product and components in the internal and external materials flow subsystems is deliberately reduced.

- Another trajectory calling for (1) administrative exchangeability of products and components at the level of physical exchangeability mainly aimed at improving flexibility, (2) unrestricted access buffers (sorting buffers) to improve administrative exchangeability, and (3) parallel flow patterns as in some innovative production systems (e.g. the Volvo Uddevalla plant discussed below).

While the dominating trend in the automotive industry has been the first alternative, there are some examples of applications of the second one in other industries and also in "experimental" production (so-called pilot plants) facilities in the automotive industry. In addition, the second line of development is sufficiently promising to merit attention as an alternative to traditional materials flow subsystems design.

INTERNAL FLOW IMPLICATIONS ILLUSTRATED: "ASSEMBLY VARIANTS" AND PRODUCTION SCHEDULING

To capitalise on physical exchangeability in internal materials flow subsystem in parallel-flow assembly systems we have developed the concept of so-called "assembly variants". This concept groups product variants into clusters according to how a specific product variant impacts the assembly work, i.e. discriminate product variants with respect to the assembly system (Engström and Medbo, 1992; Medbo, 1999).

The concept of "assembly variants" means that product individuals belonging to the same "assembly variant" will thereby be both administratively and physically exchangeable from an assembly point of view. The identification has its origin in the categorisation of the characteristics of the products. The basic idea of the categorisation is that different product individuals of the same "assembly variant" will be exchangeable between a number of parallel workstation systems. That is, a particular product could be assembled at any one of several workstations by the team located at that workstation system, and a particular team at a particular workstation could assemble any one of several products scheduled for assembly.

There are three principal categorisation criteria

- Competence requirements.
- Assembly time.
- Tool and equipment needs.

There may be further demands, related to specific assembly systems (for example, low frequency variants), or if the concept is applied outside the chosen assembly system. In the latter case this can imply that the principal criteria to form categories of products might be specific regularities in the industrial network like process localisation and choice of transports.

Because product variants differ considerably, all products cannot be assembled at all workstations, limiting the exchangeability of products between workstations. We distinguished several levels of exchangeability based on different degrees of similarity of products and assembly tasks:

- Level 1: The same assembly work, but with different components, for example panels of different colours.

- Level 2: The assembly work is marginally different. Different components but relatively "obvious" regarding assembly; a gear stick boot, for example.

- Level 3: Assembly tasks that, according to decision, all workers must be able to manage both in respect of knowledge and equipment. For example, all the product variant characteristics of the doors can be placed here. The door pre-assembly can then be used for levelling an intra-group work pattern, thus decreasing the waiting time between operators due to an increased number of free work positions within a workstation system.

- Level 4: Assembly differences dependent on competence, assembly time or equipment. It is characteristics on this level that usually inflict the assembly work substantially and thereby define the various "assembly variants".

Having thus established the physical exchangeability of products, the logical next step is to devise a concept (product codification) where exchangeable products are coded/named identically, allowing administrative exchangeability to increase to the level of physical exchangeability. This is a coding complementary to traditional product numbers to specify complete individual product variants through the manufacturing process, not only to distinguish the materials content of the products but also in respect of administrative phantoms. (For example Volvo uses product numbers comprising 25 alphanumerical characters accompanying each individual vehicle or vehicle-to-be during product ordering, product planning, product assembly, product storage and product delivery phases.)

The number of different "assembly variants" is considerably smaller (approximately 1:200) than indicated by the traditional way of codifying product variants by means of product numbers. When the frequency of the different "assembly variants" is known, it is possible to optimise the materials flow within a specific assembly system.

Figure 3 shows a simplified example with different "assembly variants". The difference in function between the buffers is shown schematically in both cases. The large triangle to the left indicates that the grouping of the "assembly variants" gives the automobiles different degrees of exchangeability depending on the frequency of each "assembly variant" (represented by the smaller, inserted triangles). The ones with the highest frequency will automatically be exchangeable and thus form a common buffer for all the queues to parallel workstations systems concerned. The significance of this is that there will be degrees of exploitation by commonality ranging from the highest to the extremely low frequency "assembly variants". Such low frequency variants must always be treated separately, being defined to specific workstation systems.

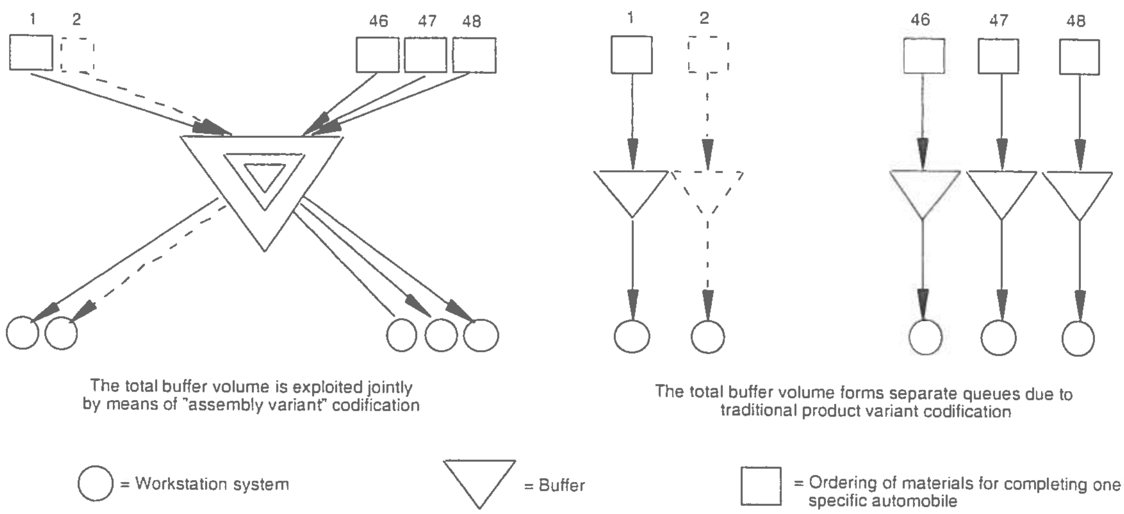

Figure 3. Schematisation demonstrating the difference between using and not using "assembly variants" at the Volvo Uddevalla plant, comprising 48 separate queues of materials feeding for each workstation system (only eight shown in the figure). The consequence is that the total buffer volume is either exploited jointly (i.e. sorting buffers) or the total buffer volume is turned into separate queues (i.e. non-sorting buffers).

EXTERNAL FLOW IMPLICATIONS ILLUSTRATED: THE AUTOMOTIVE INDUSTRY VERSUS THE PERSONAL COMPUTER INDUSTRY

As indicated above, the two lines of development introduced in section 5 apply to external as well as internal materials flow subsystems. There is furthermore a connection and parallel between internal and external subsystems. For example, internal materials flow subsystems in the automotive industry tend to be characterised by restrictions on exchangeability of components and products, restricted access to buffer and serial flow patterns, and the situation with regard to external materials flow subsystems is similar.

In the automotive industry, the companies and plants responsible for the assembly operation tend to be large, while most of the suppliers positioned in the lower part of the supplier pyramid are small. For instance, at the top of the pyramid we find OEM companies like GM, Ford and Toyota, while at the bottom of the supplier pyramid a number of garage enterprises are located. The industrial network, constituted by the manufacturers of automobiles, and personal computers display a resemblance that mirrors or is congruent with the product's hierarchical structures.

In the automobile industry, an increasing part of the topmost tier of the supplier pyramid is tied to the assembler by means of sequence-bound deliveries of components, in effect creating an invisible assembly line that extends into the suppliers' plants (see e.g. Smitka, 1991). This industrial structure is not universal, however. For example, in the consumer electronics industry, the situation is quite different where the personal computer industry is a pertinent case.

In the personal computer industry, in contrast to the automobile industry, many suppliers operate on an extremely large scale, while the enterprises assembling the personal computers may be small. The giants in the personal computer industry are suppliers such as Intel and Motorola, which develop and manufacture microprocessors, and Microsoft, which among other things supplies the Windows operating system. Intel, for instance, might sell microprocessors to a manufacturer of so-called motherboards, who in turn forwards those boards to the "box makers" who afterwards supply these to a company which composes "systems" of personal computers, peripheral equipment and cables. There is thus a pattern of parallel assembly of personal computers or integration of computer-based "systems", being performed in many parallel facilities or shops. The automotive industry suppliers pyramid is thus, in most respects, turned on its head within the personal computer industry.

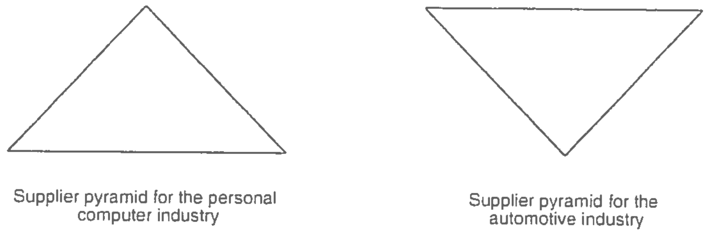

Figure 4. Schematisation of the supplier pyramids within the automotive and the personal computer industries respectively, as discussed by Smitka (1991). Today, ten years later, the number of OEM companies has decreased further, a trend which also concerns the first-tier suppliers.

Yet another difference between the two industries is that the components and the interface between various components are more standardised in the personal computer industry than in the automobile industry, meaning that components are more exchangeable in the personal computer industry. In other words, some of the component manufacturers in the personal computer industry have, due to the potential of automating the work completely, a strong incentive for standardised interface between individual electronic components and the circuit card in order to automate the assembly work. This means that small electronic components are delivered pre-oriented in magazines. This has in some Swedish firms led to "insourcing", i.e. temporarily hired operators from external firms for a planned period of time until specific electronic components have been rectified and have been provided with a standardised interface. The "insourced" personnel are thus usually working with short-cycle time, machine-paced work which is to be substituted by robots. The automobile industry also strives for standardised interfaces through the introduction of modular product architecture and platform concepts, however foremost with respective OEM manufacturers.

It may be that the differences between the structure of supply chains in the two industries can partly be attributed to differences between their respective products. There are in fact significant differences with regard to size and weight between the products, which may influence the degree of geographically centralised component manufacturing in the supply chain. For example, the fact that it is much less costly to transport microprocessors than engine blocks can help explaining the differences between the two types of supply chains.

On the other hand, some of the differences in the industrial network can be seen as consequences of design decisions concerning internal and external materials flow subsystems involving choices between the "technical" alternatives discussed in sections 2 – 4.

It should be noted that a buffer allowing non-restricted access may be used as a "time machine" that moves the future into the present, in a sense allowing a component to be consumed by an in-house process before it is delivered from an upstream process. In reality, what happens is that a particular component in an in-house free access buffer is used instead of an exchangeable component to be delivered later. For example, any red-coloured four-door automobile body with sunroof, not just one specific automobile body with a specific chaisse number, can be ordered from the body storage.

If the "time machine" is taken away by either removing the in-house buffer or imposing buffer access restrictions as in sequence-bound delivery, time becomes scarce. As a response to this, assemblers typically strive to cut supplier-to-assembler lead times. Such lead-time cutting usually involves measures to reduce transportation times, which in turn usually involves moving first-tier suppliers close to an assembly plant, as in "Toyota City" style supplier villages.

We have come to the conclusion that structures of entire supply chains – and social and economical implications of these structures – are influenced by "technicalities" such as those discussed in this paper.

CONCLUSIONS

With regard to internal materials flow subsystems, as we have seen, some of the highlights of the two lines of development sketched above are:

- The parallel product flow results in efficiency and flexibility implying low-scale manufacturing premises by means of extremely competent operators (i.e. in the most extreme case, comprising only one workstation system). This contrast with high volume manufacturing by means of high-division of labour by operators, who today in the western world are either low or multipurpose qualified.

- The new product variant codification implied by the "assembly variants" results in flexibility, making it possible to prioritise the internal work of materials handlers and operators involved in the direct manufacturing – in contrast to the demand for total synchronisation of materials handling and direct manufacturing.

In fact, the new product variant codification implied reformed product descriptions results, complementing the traditional concept of basing product descriptions and production scheduling on component numbers and alphanumerical characters. Instead it has, in the case of the Volvo Uddevalla experiences, proved necessary by means of introducing a nomenclature to recreate the logic of the product on the shop floor. Thus, a "semantic and spatial network" is formed giving a holistic perception of product and work, closely coupled to the product – a network which in fact could be derived from the designers' nomenclature (Engström, Jonsson and Medbo, 1997). The "semantic and spatial network" in turn creates increased operators competencies that enable operators to control their work and perform administrative work, such as creating work instructions and dealing with product change orders, earlier inevitably done by white-collar personnel. This is opposed to traditional fragmented product descriptions generated from a distant design department, which inevitably causes excessive administrative work at the local plant.

In the first case the training and learning is constituted by the technical preconditions for work, i.e. the implicit technical structure promotes and demands qualified operators (for materials handling, assembly, administrative work, etc.). In fact, the training and learning can be performed from the direction of a whole to the details and not the opposite. The learning can therefore be regarded as holistic (hierarchical integration of knowledge) instead of atomistic (focusing on details) (see e.g. Marton and Both, 1997). This leads to a work that utilises the specific human capabilities as a valuable complement to the technology of the future.

These effects could be transferred to the external materials flow subsystems and thereby affect the external industrial network, creating two contrasting scenarios:

- *Homogenous high volume standardised assembly plants versus heterogeneous plant designs.* Represented by the trend of modularization and outsourcing by means of engaging so-called system suppliers resulting in reduced manpower requirements at a delimited number of high volume OEM assembly plants. If this trend continues, the plants will ultimately consist of few marriage-points, which are either fully automated or prepared for increased automation; all in coherence with the trend of standardising the local plants' assembly process, forming industrial networks of carbon copy plants. This stands in contrast to a heterogeneous structure of plant designs adapted to the local preconditions, custom barriers, local suppliers specialities, etc. forming an industrial network composed of a larger number of low-volume plants forming an industrial network, in itself a "virtual plant". Such an industrial network would be "monitored" by the product structure chosen and the shop floor work and supplier structure would be a direct result of product architecture which both are examples of important "virtual artefacts".

- *Differentiated supplier systems due to product development engagement (such as system suppliers) versus differentiation due to other reasons.* There is today a trend within the automotive industry to differentiate the suppliers according to level of responsibility in respect of product development. Thus, a national as well as an international network of high volume (i.e. specialised, independent system suppliers) will arise, while at the same time the dependent suppliers are categorised (class A. B and C) – This may be in contrast to industrial networks where the nodes have other, from the automobile industry point of view, non-traditional functions. The industrial network cannot be perceived as a number of predefined, rectilinear, materials flow subsystems, starting upstream at the suppliers and ending downstream at the customer. Instead the industrial network turns into a multi-dimensional matrix comprising a number of materials and information handling processes.

In all, this implies that the industrial network of the future is more concerned with the "virtual artefacts" than with physical products, i.e. the means are the appropriate content in the information system backed up by various software methods, supporting this information handling. This is not the case in the Swedish automotive industry where the "virtual artefacts" such as product descriptions are mirroring structures of old products. The product is expressed by means of an obsolete digital context such as basing the component addressing on component numbers and variant designations, which is cryptically expressed and stochastically generated and obviously not in accordance with the product architecture, products functions and nomenclature (see Engström and Medbo. 1992). This results in restricted work content on the shop floor, in form of short cycle time assembly work, but also in unnecessarily time consuming and complex administration on materials and information.

The product architecture's relation to "virtual artefacts" and the human perception of these artefacts are, according to the authors' experiences, a critical key factor to attend for the digital economy, which probably successively will replace the physical economy and increase flexibility and performance of the industrial network of the future. This might, however, be seen as inevitable for the young generations of human beings while the old "fogies" are adducing the investments as the sole arguments for the present state of art.

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