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EQUIPMENT NEEDS IN MATERIAL FLOW SYSTEMS AS A FUNCTION OF INTEGRATION LEVEL - A STUDY OF LOAD MODULES IN INTEGRATED TRANSPORT SYSTEMS

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1. INTRODUCTION

There is, because of high attention to logistics, a trend towards decreasing sizes of shipments in the industry of today. Extended demands regarding reliability, regularity, goods security etc are placed on these shipments. This trend also appears in distribution of consumer goods and enforces a development towards stronger connections between the internal and the external transport systems, resulting in an interest in building up large transport units early in the Material Flow System (MFS)[1] and keep these units unbroken while passing several terminals in the MFS. Motives for such units are for example the possibility of an increasing utilization of the fleet of vehicles, by shortening times at terminals. Many companies also face an irregular distribution of arrival times, which causes temporary capacity shortage in labour and storage facilities. An unbroken load module can here be used as a temporary storage, levelling the need of capacity in the receiving system. The potential for using such load modules is discussed in the next chapter, where three case studies are presented.

When developing a new MFS, calculation methods give assistance in chosing the "best system" among several proposed, but give little guidance in the basic work of proposing the systems to be evaluated. Besides methods like operations analysis, this essential work is to a high extent based on experience, including rules of thumb and common sense. In this paper an attempt is made to formalize and generalize this experience, by

[1] An MFS is here defined as equipment and activities for transport and handling in a network of links and terminals. Transport processes are taking place on links, while terminals represent positions for handling (e.g. sorting) and buffering.

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introducing the concept of integration-level as a measure of the ability of an MFS to create orderly conditions. Integration-level is introduced via the use of "entropy" as a metaphor for the degree of disorder in a position in the MFS. The concept of entropy has earlier been applied to transport related problems (1), (3), (5), (6) and (7). The use of entropy in this paper is not conformable to these references. The focus of this paper is on systems supplying assembly production processes, but the theory may be applied to other types of MFS as well. The aim of the paper is to offer a framework for contextual understanding of handling and transportation as value adding activities and show that the introduced terms are pertinent when industrial material flows are discussed.

The package is a vital part of the MFS and serves many functions in the system, e.g. carrying, protecting and separating parts from each other. These different functions often create several levels within the package. The function of separating parts is relevant in the context of entropy and integration-level and one chapter in this paper deals with this subject. Forces creating separation levels are listed and discussed.

2. LOAD MODULES AS A PART OF THE STORAGE

This chapter deals with the potential of applying external cargo carrying units for internal storage, allowing these units to pass several positions in the MFS unbroken. In addition to technical solutions, this often requires administrative changes by the receiver. For example, inspection must be made when loading the unit, which results in a different allocation of responsibility.

In a brief survey (4), it was found that hardware techniques exist for this purpose. However, no applications were found, so in searching for case study objects which could provide empirical data, we had to pick potential applications or existing ones making use of smaller size cargo units. Three case studies are briefly described below. The first study emanates from a manufacturing company (final assembly of cars) where a load module is taken into the production area. The second case deals with the possibility of letting a load module to full extent replace a wholesaler´s warehouse, for some special categories of goods. Finally, the third study treats handling of unbroken load modules in a wholesaler´s warehouse.

The main savings in the automotive case came from lower capital costs and less work-in-process (WIP), resulting in reduced need for space, storage capacity etc. In addition there were less problems concerning material shortages and poor quality. In the wholesaler cases, the savings mainly derived from less transport and materials handling operations, in addition to some administrative simplifications.

2.1 Case study: Car seats

The aim of the system is to feed car seats from a supplier located 20 kilometers from the assembly plant, into the final assembly department. This is done by using four special-purpose trailers carried by one designated truck. In general two trailers are located at the assembly plant, one at the supplier and one on its way between these positions. Each trailer carry 40 sets of seats, which cover two hours of production. The seats are loaded in assembly sequence sorted by type of seat (front left etc), into special-purpose containers. Each set is ordered eight hours before use in the assembly, at the moment when the car body is placed on the assembly line. At this time, an order is sent to and written out at the supplier by on-line data communication and the production of the set of seats can begin.

The trailers are positioned indoors at the assembly plant and used as buffer storage. The containers are thereafter unloaded by a conventional forklift truck and placed at the assembly stations. When introducing the system, receiving inspection was moved to the supplier. It can be noticed that the fraction of rejected seats decreased from two percent down to 0.25 percent. In the old system, the seats were delivered once a day from the supplier, on the basis of a production shedule fixed for one day and preliminary (95 % security) for the next two following days. Some weeks in advance preliminary shedules of lower precision were created and sent to the supplier, for the purpose of ordering materials to the supplier and start production (sewing of upholstery).

The total savings with the new system were 11 percent of the purchased price from the supplier. 27 percent of the savings were due to lower capital costs for WIP.

2.2 Case study: Iron goods wholesaler

The studied large iron goods wholesaler has a central warehouse, from where goods are distributed directly to hardware stores. All external transports are purchased from transport firms. There were no applications of using external cargo carrying units as storage modules,but a survey of the company´s activities showed that there was such a potential. Full units of some type of goods, 20-feet ISO containers from Far East and swap-bodies within Sweden, are purchased. A demand for application, however, is that the unit contains parts all with the same part number. Another restriction is that outdoor storage of units without climate control put special demands on the goods. Indoor storage requires new investments.

One possible application, easy to introduce, relates to full ISO containers with homogeneous contents, imported from Far East. With a fast turn over (e.g. campaign articles) of the goods, it is conceivable to keep the container in the harbour instead of transporting it 50 kilometers and unload it for warehousing. Parts can then stepwise be unloaded from the container and distributed to the hardware stores. Calculations show a 3.5 percent cost reduction per container, expressed in mean goods value. The savings came from eliminated warehousing activities (-3.8%), together with less transports (-0.4 %). Additionals costs were rentals of space and labour in the harbour (+0.7 %)

2.3 Case study: Central warehouse

This case study dealt with a nation-centralized warehouse for furniture, sport and leisure articles, carpets and textiles. Besides traditional central warehousing functions, it was also used for seasonal articles (e.g. 80 railway cars a year with barbeque coal) and as a terminal for jointly loaded goods. In a first step, an estimated share of 10 percent of the total turn over could be stored and handled in an unbroken special-size load module (2.2 x 0.9 x 2.5 meters). The potential for further applications was judged very high. A mean cost reduction of approximately two percent of the goods value was calculated in the first step, when this special purpose load module was compared to unloading and warehousing the traditional way.

3. THE USE OF SEPARATION LEVELS

When goods, in a processing chain, is to be transferred between two geographically separated production processes, there is normally a step by step procedure of creating different levels of packages or encasements. The highest and largest of these levels is used during external transportation in the shape of for example an ISO container or a trailer. The greater the distance of transfer is, the larger encasement is generally chosen. This naturally leads to a lower transport frequency for the same amount of goods to be transported. After the external transport, there is a step by step decomposition of these encasements to smaller units, the closer they get to the production process. To explain the purpose of dividing encasements into several levels and the degree of use in different MFS, we introduce the concept of separation level. This term implies the properties of level divisioning as making separation of items possible for different purposes.

The way in which different separation levels are created is a result of processes in earlier stages of production, as well as demands emanating from qualities of the transferred articles, the subsequent production processes and the product to be manufactured. Commonly used separation levels in distribution of products as well as in provisioning of components, are from the highest level to the lowest: the load module, the internal load unit, the package and the article. It is not uncommon however, that both greater and fewer numbers of levels are used. The load module level is recognized by constituting the outer encasement during external transports, which does not necessarily mean that it is actually enclosing the lower separation levels. Open truck platforms as well as ISO containers are referred to as load modules. The load module is carrying and holding the goods together during external transports and cannot be moved by its own means. Handling of load modules requires expensive equipment. The internal load unit level is normally used as outer encasement during internal transports and indoor storing. Handling of internal load units needs to be carried out with some kind of handling equipment as they generally are too heavy for manual handling. The package level is found near production processes or close to consumption and is often a closed package, that can be handled manually or with simple equipment.

It may at first seem unnecessary and costly to pack goods in several separation levels. However, the occurrence of different separation levels has several motives. In order to restrain consumtion of resources, material flows are generally not continuous flows. Instead, material is transferred in discrete units at certain repeated times. The sizes of the units are, among other factors, determined by the distance the material is to be transferred. During external transports, large units are called for. These units grow in size together with the transport distance, since the optimal transport frequency from a resourse point of view is decreasing with increasing distance. In perspective of this discussion, it is of no relevance to view external and internal transports as phenomena of different nature.

In a large number of applications it is impossible to bring large load modules close to the production process, due to lack of space. Indoor handling and storing of large units requires, apart from special handling equipment, much space for transport, handling and storage. In an assembly process where a large number of part numbers are supplied, the problems of limited space for material exposure are well known.

When several receiving positions located close to each other occur, as it does when supplying several parallel production processes, or when distributing goods to a number of small consumers, there is a need of splitting the contents of a large unit into a number of smaller units, which can be distributed to the separate positions.

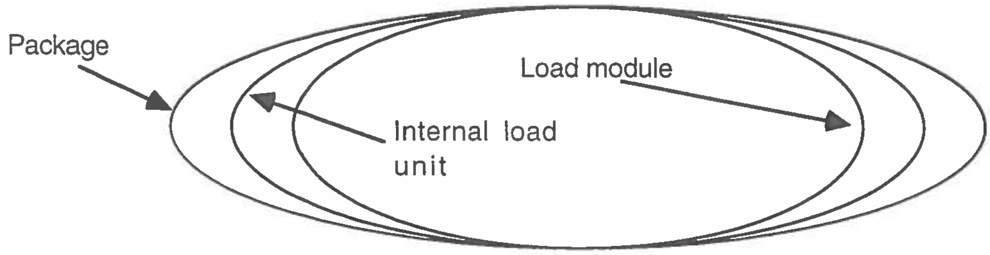

Figure 1 Expanding flows of different separation levels.

These needs result in "expanding" flows. The purpose of introducing this concept is to illustrate that lower separation level items are transferred further and pass a greater number of positions than high level items. This process can be compared to the function of a multi-stage rocket, where one stage at a time is disconnected along the way and only the capsule at the top (the goods) reaches the final destination. The transfer of other materia does not create any utility value, but is still necessary for the task. If the encasements are reused in a closed system, expanding flows can be described as if lower separation levels have wider orbits than the higher levels, in a circulating process.

When here discussing closed MFS, we refer to systems where the transferred goods is not mixed with other goods and where the used encasements at different separation levels, that are not of the expendable type, are recirculated within the system. Relative the goods handled by the MFS, the system is seen as open, since the goods passes in and out through the system limits.

Another important reason to create different separation levels is to increase accessibility. Accessibility is here considered in two different perspectives. On one hand the meaning is rational handling ability and on the other hand the meaning is free sequence accessibility. Big differences in size between two separation levels create difficulties in implementing rational handling when loading and unloading. If for instance the internal load unit level is omitted and thousands of small boxes are loaded directly into an ISO container, handling activities during loading and unloading will be excessive. This is due to relatively long distances of transfer inside the large unit and the high frequency of these transfers. If a pallet is used, a large number of boxes can be handled simultaneously with the aid of handling equipment and the highly frequent individual handling of boxes can be carried out with short transfers. The separation levels enable provisioning of materials at the right time and in the right sequence. This is of imperative importance when the items are not identical and exchangeable with each other. If designed with the relations between the different levels in mind, the division into separation levels allow flexibility in sequence of loading and unloading. An intelligent modularization makes it possible to reach single items independently. This facilitates priority changes in time and place while provisioning materials.

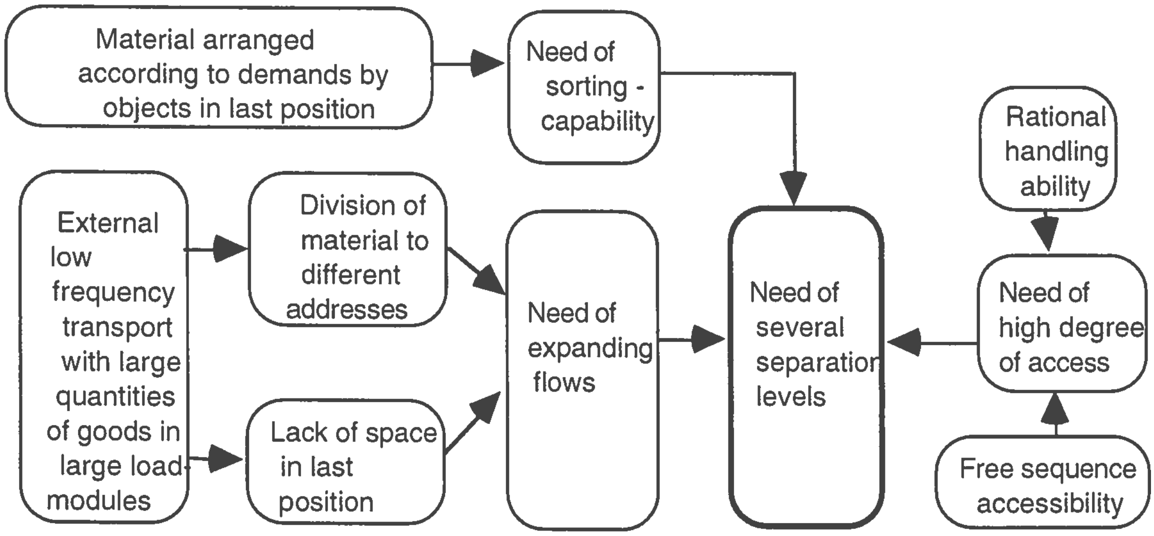

Figure 2 Motives for introducing several separation levels.

Finally, the division into separation levels facilitates an earlier physical organization of the transferred goods, according to demands set by an object or a customer in or after the last position in the system. This property of the separation levels takes us to the entropy[1] concept, by which we want to describe the degree of order, or organization, which the MFS is capable of inducing on the goods or articles transferred through the system. The introduction of several separation levels has proven to be a powerful tool to reach desired entropy.

1 For the purposes of this paper we define entropy as a measure of functional organization or order of units transferred within the system , in relation to the order that is to be accomplished after the goods has passed the system limit. A high degree of order corresponds to a low entropy.

4. THE CONCEPT OF ENTROPY IN MATERIAL FLOW SYSTEMS

The ability of the MFS to create a utility value is often related to transport utility, i.e. the ability of the system to transfer goods to its final destination. The other important utility function of an MFS is tied to its ability to reorganize the transferred units to meet the demands for specific order in the final positions of the system. This latter demand for utility on the system, does not lead to as apparent solutions when developing efficient systems as when focusing only on the choice of transportation means.

When designing an MFS, there are a number of given conditions to start from. These determine the environment in which the entropy changing properties of the system will have to be created.

If the MFS is to support a manufacturing system, the product itself strongly influences how the components of which it is built are to be organized in relation to each other. The production process that accomplishes the process of joining components to the desired constellation, determines how the final organization is shaped after the parts have passed the system limit between the MFS and the production process proper. If, for example, an assembly system that involves long cycle times succeeds the MFS, it might be wise to allocate a greater proportion of the reorganization work of parts to the MFS than otherwise. By kitting parts that are to be assembled on the same object, before entering the production process, the task is made easier for the assemblers. These then can concentrate on joining the parts together rather than finding and bringing together the right parts to be joined. By kitting parts in the MFS, the entropy is decreased to a minimum before entering the production process. It is not, however, certain that an MFS creating minimal entropy in relation to the product is the most suitable for the following process. This can be illustrated with an example from the apparel industry.

All pieces of fabric to a piece of clothing are cut out of the same sheet at the same time in a single production process. An MFS supplies these pieces of fabric to the next production process, where they are to be sewn together. Each step in this process is carried out at a separate work station. Since all the pieces of fabric belonging to one piece of clothing come from the same sheet of fabric , it seems logical to keep this order through the MFS to the next process and in this manner retain a low entropy throughout the whole chain. However, this is not suitable for the process of sewing the pieces together since these are bound for different work stations. It is rather preferable to pick the material from bundles of the same types of pieces in each station. The final entropy is then achieved inside the production process, where the right pieces are brought together step by step when passing the different work stations.

We draw the conclusion that conditions dictated from both the product and the process of manufacturing determine the final entropy to be acomplished by the MFS before the goods pass through the system limit. The measure of entropy is made in relation to the final entropy constituted by the completed product.

Given the ingoing entropy and the demand on outgoing entropy for the goods transferred through the system, there are yet other factors affecting the way entropy declines while the goods is moving through the system. One of these factors is the predictability of what the specific demands are going to be, or put in other words, how far ahead and with what precision demands can be foreseen. The structure of the environment in which the system is to work is also important for the way the entropy changing properties of the system are shaped. Variables related to structure are; number of sending positions, number of receiving positions, available means of transportation and handling, distances between positions etc. Furthermore, the volume or intensity of material flows and factors related to the physical qualities of the material affect the way in which entropy will change in the system. The ability of an MFS to decrease entropy early in the transfering process is greatly related to what extent the system can be made closed and thereby to what degree the components can be interadapted.

In principle, what has been stated earlier is applicable also to systems dealing with distribution of consumer goods. The main obstacle here is, however, that the final entropy is not known in advance. There is no index to which the ability of the system to change entropy may be related. Final order can only be expressed in terms of probability. This paper will not be concerned with these problems.

Basically we consider the difference in entropy that an MFS can achieve, as a measure of value adding properties of the system. Entropy in this application is connected to transport utility which in turn is a function of distance. It is natural that the entropy is declining when the distance between the components, that in the final state are to be brought together, is decreasing. Consequently the entropy is changed during transfers between positions in an MFS. We are not concerned here with the mathematical relations between distance and entropy, but merely pointing out distance as a suitable indicator of entropy in this dimension. Within the positions, the entropy is manipulated by sorting processes where goods is being separated, brought together or reoriented. The change of entropy of goods travelling through an MFS can be illustrated as in figure 3, with two curves and their superposition in a diagram with an ordinal scale of the consecutive positions passed by the goods on the x-axis and the entropy on the y-axis.

The entropy in an MFS is frequently not a monotonously decreasing function of the distance negotiated inside the system. The reason for this is interaction with other MFS due to savings of cost of transport and handling on a wider scale. Examples of entropy increasing phenomena are joint loading of goods to different destinations on the same transport for improved transport economy, or storage of units with the same destination in different parts of a store with fluent location of goods, due to optimal use of storage volume.

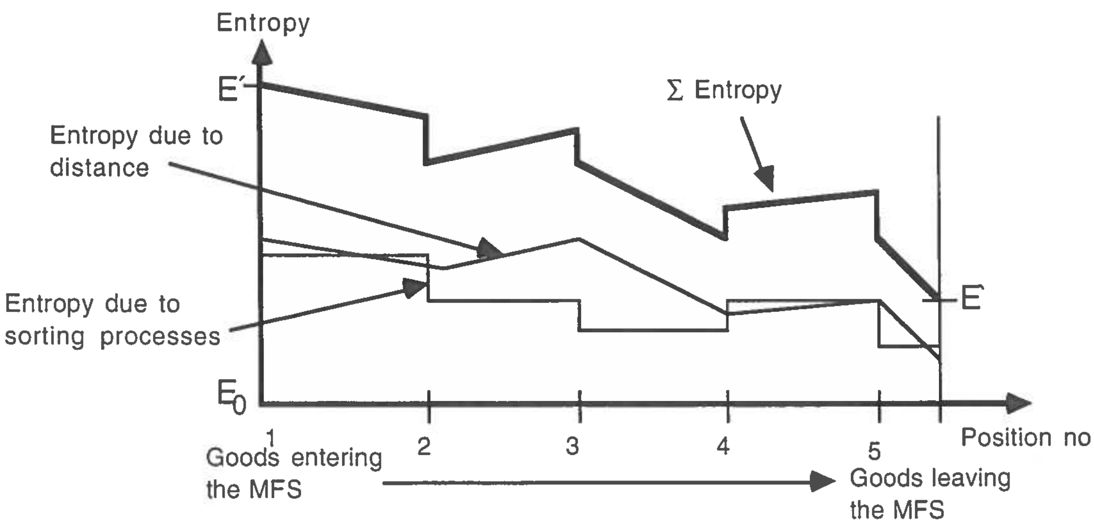

Figure 3 Illustration of the changes in the two dimensions and the total entropy of goods transferred through an MFS. E´ indicates the entropy when goods is passing in through the system limit and E` the entropy when passing out. $E_O$ is the final,minimal entropy constituted by the produced object in the subsequent production process. E´- E` corresponds to the ability of the system to add value in terms of entropy.

5. THE RELATION BETWEEN ENTROPY AND INTEGRATION-LEVEL

We have earlier stated that the reduction of entropy within an MFS is influenced by variables related to predictability of demands in the following process, system structure, material flow intensity and physical qualities of the transported material. We have also stated that the entropy E` when leaving the system is set by the following process and the product to be produced therein. By introducing the concept of integration-level we aim at creating a measure of the ability of the MFS to adapt to demands for changes of entropy, made by an object outside the system, towards which the material flow is directed.

Figure 4 illustrates the connection between entropy and integration-level. The integration-level is defined as inversely proportinal to the area under the curve described by the entropy of the goods transferred through the system. Consequently a small area is related to an MFS with a high integration-level. Since the area is affected by how rapid the system is able to decrease entropy, equifinal systems can have different integration-levels. Irrespective of the characteristics of entropy decline in the system, there is a reversed variation between the outgoing entropy, E` and the integration-level. Consequently, the integration-level expresses both the value-adding ability of a whole MFS in terms of change of entropy,(E´-E`) and also how fast the system reduces entropy. Generally, but not necessarily, a quick adaptability of the MFS is connected with the openness of the system. The more closed the MFS is, the greater is the possibility to specialise its components to their specific tasks and thereby obtaining a highly integrated system.

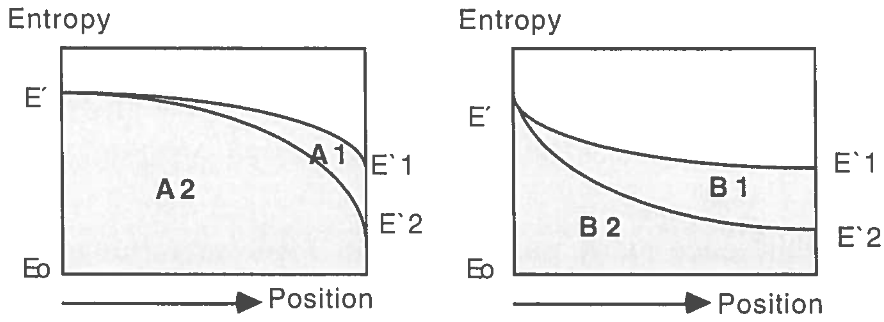

Figure 4 The integration-level is defined as being reversely proportional to the area limited by the curve described by the entropy. As a consequence the integration-level is depending on the ingoing entropy E´, the outgoing entropy E` and the shape of the entropy curve inside the MFS. The area A1, A2, B1 and B2 represent the integration-level of four different MFS with the same value on ingoing entropy E´ and final entropy on products $E_0$. Area A1/B1 is greater than A2/B2, due to different E`-values. Area A1/A2 is greater than B1/B2 due to different characteristics in the decline of entropy.

6. INTEGRATION-LEVEL APPLIED IN THE INDUSTRIAL PROCESS

In the previous chapters, the concept of entropy and integration-level were discussed in general terms and a theory was outlined with the aim of making the role of the MFS in industry more visible and provide a contextual understanding of handling and transportation as value adding activities. The ultimate object of such a theory is to connect it with economic measures. This is not done here. Nor is a more formal treatment of entropy in mathematical terms given. Attempts in this direction will be described in a separate paper. However, an attempt is made here to operationally define the entropy in a position in the MFS.

A great many variables seem to be relevant in the context of entropy in an MFS, but when starting to develop a new MFS one could not consider all variables as independent. Most of the variables are strongly interrelated and thus must be treated as dependent or effect variables. The variables chosen here are such that they give opportunities for quantitative measurements. Only measurable variables can effectively be used for controlling the development of the system. Furthermore, we have not found one single variable with the ability to fully describe the entropy in a position. The chosen variables below should therefore be considered as alternative descriptors and treated separately.

Note that since many positions in an MFS have the role of changing the entropy, there is one value when entering the position and another when leaving the position. The variables chosen for measuring the entropy are:

a) Number of identities[1] per separation level
b) Number of units per identity and separation level

Low entropy is obtained through a large number of identities or a small number of units per identity and separation level.

It should be stated that achievement of low entropy early in the MFS does not automatically lead to low cost. A number of restrictions can exist in the production process, which obstruct the use of a high integration-level system. Furthermore, such a function does not have to be linear. In a given system, there can be intervals in the scale of entropy where the curve breaks. On each side of this interval the marginal effect of a change in entropy is very low, but within the interval the marginal effect is very high. This can be expressed as "nothing or everything is functioning".

When saying that a large number of identities means low entropy, one should remember that the value in a position in the MFS relates to the demands set by the product and the production process. It is for example apparent that packing of two part numbers in one separation level does not decrease the entropy, if the two parts are not to be used at the same assembly object.

Figure 5 shows the number of identities per separation level in a case study where two types of material supply systems, feeding manual assembly stations, were compared; continuous supply and kitting[2]. A mean

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1 An identity can be defined by saying that two units have the same identity if they are totally interchangeable with each other in a specific application.

2 Continuous supply refers to a material supply system where all part numbers allowed according to existing product specifications are exposed at the work station and parts are sorted by their part numbers.

of eight part numbers are used for one assembly operation. The positions in the system are presented at the y-axis. Note that only the first position in the system, positions where the number of identities are changed on any separation level, or positions where repacking is taking place, are presented. The x-axis describes the separation levels. The z-axis shows the value of the variable. Separation level 1 always refers to the highest level which occurs at a position. From this figure it can be seen that the number of identities for kitting is higher than for the continuous supply case. This is achieved through a repacking operation in the store, where parts are matched with each other with regard to the assembly objects. According to what has been said earlier, entropy is decreased earlier in the kitting case. In the continuous supply case, the assembler himself has to decrease entropy by performing the kitting as a part of his assembly job.

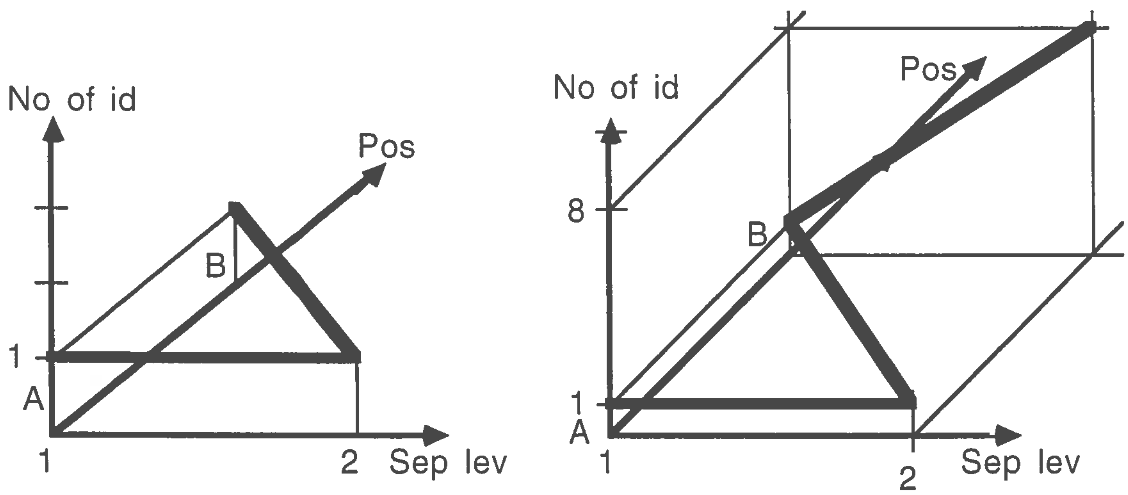


Figure 5 Number of identities for the two cases continuous supply (left) and kitting in a case study.

The preceding figure can be drawn in another way, where only the lowest separation level is shown and the X-axis represent the positions in the system. If the y-axis is to represent the entropy, we have to transform the variable "number of identities" in such a way that an increased number of identities corresponds to decreasing entropy. This can be done by dividing the number of identities used together in the assembly operation with the number of identities at the separation level and subtract one from this quotient. Such a figure corresponds to the way of writing in

Kitting is defined as a system where a selection of part numbers are exposed at a time and where parts are sorted by assembly object (2).

the previous chapter and allows the integration-level of the system to be calculated. The integration-level becomes even higher if the supplier performs the kitting operation, which can be related to the current trend of having fewer suppliers deliver complete sub-assemblies. Figure 6 below shows this transformation.

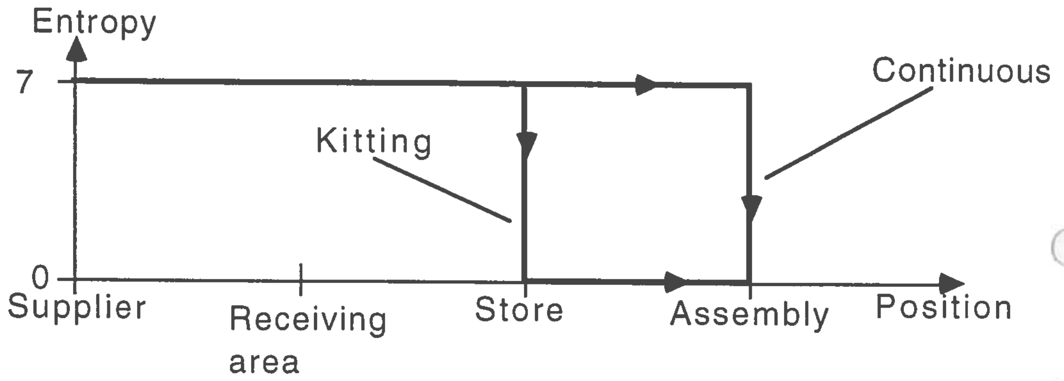


Figure 6 Entropy in different positions for the cases continuous supply and kitting.

Assembly systems in some countries go toward parallel flows and extended cycle times. These systems often call for new types of materials supply systems like material markets and kitting supply systems. A common argument for these supply systems is that the increased number of points to be supplied result in poor control of the material, if the traditional supply system (continous supply) is used. In our terms, the systems would get too high entropy. The assembly system in the presented case study have 50 final positions (assembly stations). Using continuous supply this results in 400 relations (a link on which a specified article is to be transported), while kitting (the low entropy case) results in only 50 relations.

Just as with the former variable, the variable "number of units per identity and separation level" is related to demands set by the product and the production process. The production process requires a specific number of parts for one production cycle (or job). In an object oriented process (e.g. assembly), the number of each identity often equals one, i.e. one unit of each part number. A requirement of the ideal assembly system with regard to integration-level is that part numbers which will be asembled on one object are packed together. Two types of materials supply systems can meet this requirement; batch supply and kitting. In the former type of system parts are held together and sorted by part number, while kitting means that parts are sorted by assembly object[1]. Figure 7 is an example from the case-study earlier treated in this chapter and shows the variable "number of units" for one part number. In the batch supply case, one pallet with four cartons each containing 2000 units are received from the supplier. A repacking is taking place in the storage because of problems related to space and number of receiving positions in the assembly department. The box delivered to the assembly stations contains 150 units. The assembler then, for each assembly object, picks the required number of units and places them in another box together with other parts. In the kitting case, this final repacking is done in the storage. Figure 8 is analogous to figure 6.

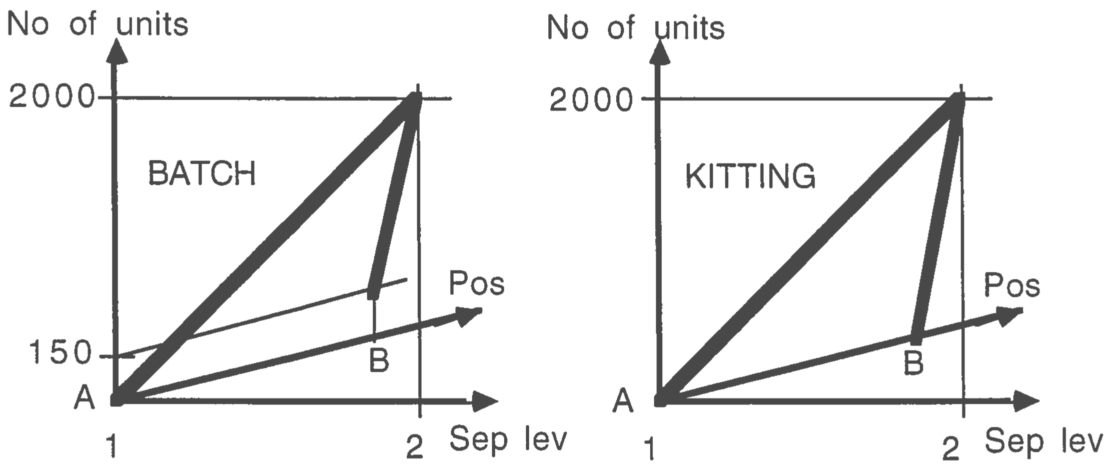
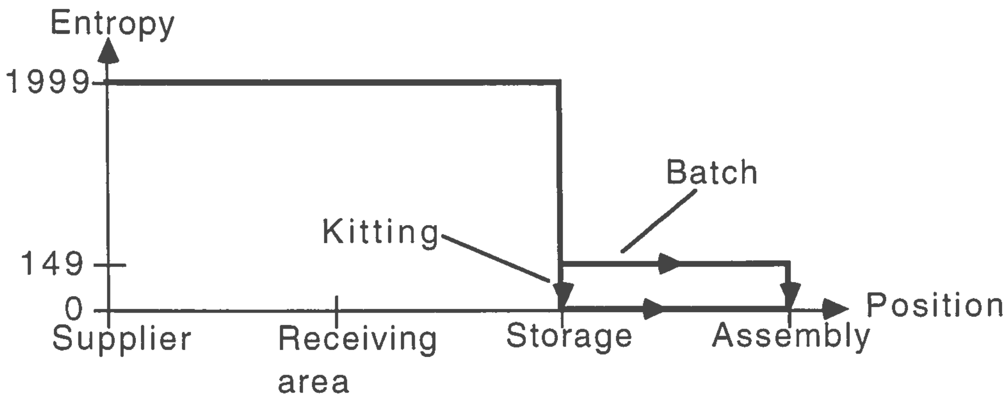


Figure 7 Number of units for the two cases batch supply and kitting.



1 Actually, batch supply sometimes can be described as kitting at a separation-level one step higher. The parts are sorted by part number, but the boxes containing the parts are sorted by assembly objects.

Figure 8 Entropy in different positions for the cases batch supply and kitting.

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REFERENCES

1. Erlander, S., (1977), Accessibility, Entropy and the Distribution and Assignment of Traffic, Transpn Res, 11, 3, pp 149-153.

2. Johansson, M.I., (1989), Kitting Systems for Small Size Parts in Manual Assembly Systems, Paper presented at the 10th Int Conf on Prod Res, Nottingham, UK.

3. Mathur, M.C. and Satsangi P.S., (1985), Entropy-Maximizing Methods of Transport Analysis vis-a´-vis a Physical System Theory Modeling Framework, IEEE Trans on Systems, Man and Cybernetics, 15, 2, pp 281-290.

4. Sjoestedt, L., (1985), Load modules in integrated transport systems (in Swedish), Meddelande 2, (Göteborg: Inst för Transportteknik, Chalmers University of Technology).

5. Tomlin, J.A. and Tomlin, S.G., (1968), Traffic Distribution and Entropy, Nature, 220, pp 974-976.

6. Wilson, A.G., (1970), The Use of Concept of Entropy in System Modelling, Operat Res Quart, 21, pp 247-265.

7. Yao, D.D., (1985), Material and Information Flows in Flexible Manufacturing Systems, Material Flow, 2, 2-3, pp 143-149.