The impact of FAMS on overall production control structures

IFIP WG 5.7: Information Flow in Automated Manufacturing Systems

The Impact of FAMS on Overall Production Control Structures

C.W.G.M. Dirne
Eindhoven University of Technology, Faculty of Industrial Engineering and Management Science, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Flexible automated manufacturing systems are seldom selfcontained, but are usually part of a larger production system. The larger system performs several planning activities in which it should take into account several characteristics of both the FAMS and its environments (such as capacity, throughputtime and lot-sizes). This paper is concerned with the impact of FAMS on these more comprehensive production control activities. The paper presents alternative control structures and problems and indicates the applicability of these structures depending on the nature of the FAMS and its environment.

Keywords: Flexible Automated Manufacturing Systems, Production Control Structures, FAMS-characteristics, FAMS-types, Deterministic/stochastic servers, Deterministic/stochastic environment.

C.W.G.M. Dirne received his Master's degree in Industrial Engineering in August 1985 from the Eindhoven University of Technology (the Netherlands). He is now working both as Assistant Professor, and on his Ph.D. thesis, at the faculty of Industrial Engineering of the Eindhoven University of Technology. His current research focuses on the impact of Flexible Production Automation on Production Control.

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1. Introduction

No doubt the advancement of Flexible Automated Manufacturing Systems (FAMS) will change our view on manufacturing. FAMS technology leads to improved utilization of machine tools, reduced manufacturing throughputtimes and reduced lot sizes. For this reason, many production companies have started investments programs in flexible automated manufacturing equipment.

However, flexible automated manufacturing systems are seldom selfcontained. These systems are usually part of a larger production system. This larger system supplies materials, tools and fixtures, and it consumes the components produced by an FAMS. The larger system performs several planning activities in which it should take into account factors such as: the capacity of the FAMS, its lead time, and its constraints with respect to lot sizes, product mix, and other characteristics. This paper is concerned with the impact of FAMS on these more comprehensive production control activities.

In many systems is not at all obvious how available capacity should be modelled for medium term planning purposes. In a network of different capacity resources, each having a different utilization rate, it is usually not easy to establish a simple overall capacity model. For example, it is not easy to determine the number of capacity constraints, and their nature. Should tooling restrictions, queue-length restrictions, change-over problems be included? Furthermore, it is not easy to determine the capacity requirements of parts to be produced, because these capacity requirements depend on lot-sizing decisions, routing decisions, loading decisions etc. The situation is similar for throughputtimes. Here too, it is not clear under what conditions a particular throughputtime model is suitable.

Current literature on FAMS is not very clear with respect to medium term modelling. In theoretical papers, capacity/throughputtime models are often discussed, but these models are aiming at simulating the (very) near future. The problem definition is often of a static nature: e.g. how to minimize make-span for a given package of work on an empty system. An appropriate theoretical framework has to deal also with the dynamic nature of work-orders arriving at and leaving the system. From such a framework, it could be concluded for a particular situation that the short-term control problem is static by nature. However, other situations may lead to different problem definitions. Also, there is a need for theoretical papers studying simpler models to be used at higher levels of control.

With respect to practical implementations it is very difficult in many reports to find out how the FMS is embedded in the larger production control structure. If throughputtimes are reported, it is not always clear whether these throughputtimes are per batch or per piece. Throughputtime predictability is hardly mentioned. Utilizations rates during unmanned periods are seldom defined precisely. Lot-sizing policies are not mentioned. We feel that considerable more empirical studies in this respect are worthwhile.

The present paper is only a small contribution to the above issues. Its aim is to point out, how flexible manufacturing systems can be incorporated in larger production control structures. To do so we first present some terms and concepts of multi-level production control theory in Section 2. This section shows capacity planning models with respect to traditional single machines, lines and queueing networks. Section 3 extends the model with some particular decisions which could be required for some FAMSs. Section 4 discusses particular characteristics of FAMS and its environment and their consequences for the control structure. Section 5 concludes the paper. An interesting conclusion is the fact that a very flexible system requires hardly any adaptation of our existing production control structure framework!

2. Concepts and Terminology

In describing production systems from a production control point of view, a top-down approach or a bottom-up approach can be used. In this paper, we shall take both approaches. The top-down approach deals with the question, whether and how the material flow should be split up into several main stages. We will call such stages "Production Units". The bottom-up approach is concerned with individual resources of capacity and networks of such resources. These resources and networks are found within production units. In order to avoid too early associations with single machines, lines, FAMSs, etc., we will call a supplier of capacity a "server". We will start our discussion with the bottom-up approach.

2.1 Bottom-Up

A *runbatch* is the set of parts positioned together on one transformation-entity (e.g. a pallet) inside the server (comparable to the definition of runquantity of Burbidge [3]). This runbatch is used as the control-entity inside the server. We will use the term *jobbatch* to refer to the set of parts belonging to the same production order that is released to the production unit. In fact this production order is used as a control-entity for production control, since progress monitoring outside the server will be done by production order. A *jobpart* finally can be defined as the set of parts belonging both to the same jobbatch and the same runbatch. In other words, a jobpart links a runbatch to a jobbatch (note, that a runbatch may consist of more than one jobpart).

A *single server* is a resource of capacity which is unable to process more than one production order simultaneously. In other words: each runbatch only contains parts belonging to the same jobbatch. The traditional man-machine system is a typical single server. It is possible that a single server requires simultaneously various kinds of capacity, e.g. humans, machinery, tools, fixtures, etc.

A *line server and a networkserver* are capacity resources that are able to process more than one production order simultaneously. In case of a line server controlling a single dimension is sufficient. The traditional belt-line is a typical line server. The capacity of a line may be expressed as an input frequency (e.g. 6 batches per hour), whereas the throughputtime is expressed in time-units (e.g. 72 hours). It is possible that a line server requires simultaneously various kinds of capacity, just as the single server. In case of a network server more dimensions should be controlled, because the server contains more bottleneck-capacities.

Servers may be either *deterministic* or *stochastic* by nature. If a server is (considered to be) deterministic, measuring actual progress of the production is not (considered) necessary for dispatching new production orders to the server. In other words, the behaviour of a deterministic server can be predicted with sufficient precision for each relevant planning purpose. If a server is (considered to be) stochastic, it is necessary to measure actual progress of the production volume before new production orders can be dispatched to the server. In other words, stochastic servers are not entirely predictable. It should be noted that stochasticity requires feedback to the dispatching decision. Traditional machines are often considered to be stochastic in many firms: a new production order can only be dispatched as soon as the operation of the previous production order is ready. Assembly lines are sometimes considered to be deterministic, especially if they have a constant velocity and if the daily production volume is always realized.

Servers may face *lot-sizing* problems or *set-up problems*. A set-up means that a server can have different states. In each state, the server is suited to manufacture products of a particular type or of a particular family of types. In the latter case some minor adjustments might be necessary in order to be able to manufacture a particular product type. However, these adjustments require far less time and effort than the changes between set-up states. Since set-up changes induce costs, the number of set-ups will have to be as limited as possible. In other words, the number of production orders to be produced in the set-up should be as large as possible.

Line servers or network servers (but not single servers) may face *mix problems*. A mix problem means that a particular server can only process work-orders at full speed if the mix of work-orders dispatched satisfies certain constraints. For example, a particular line server could be subject to the constraint that two subsequently dispatched work-orders should not be of the same type.

It is not uncommon to find a set of capacities being treated as a stochastic network server at a detailed level of control, whereas at the same time it is considered to be a deterministic line server at a higher level of control. In fact, this is a desirable situation. The lower level of control should be able to counteract many disturbances and therefore reduce the complexity for the higher level of control.

Within the context of this paper, the above concepts describe the bottom-up approach to capacities sufficiently.

2.2 Top-Down

For a top-down description of production control functions, it is convenient to distinguish three levels of control (cf. Bertrand and Wijngaard [1], or Burbidge [3]).

1. *Master Planning* [1] (or Programming [3]).
   At this level of control, available capacities for different stages of production are balanced with projected sales levels. Aggregate inventory levels are planned concurrently.
2. *Production order release* [1] (or Ordering [3]).
   At this level of control, the actual material flow is initiated. In a make-to-stock company, production orders start with component materials, issued from inventories, and they are finished when the ordered product arrives in stock. In other words, a production order flows from stock point to stock point, and it covers a number of operations. In the bill-of-material structure, the two stock points should correspond to two items, connected by goes-into relationships. We will call a production stage between two stockpoints a Production Unit (PU). In make-to-order companies, the main stages of the material flow are controlled, similarly, by releasing production orders. Here too, the concept of a Production Unit may be used to denote the progress of work allowed by single release decisions.
3. *Production Unit Control* [1] (cf. dispatching [3]).
   At this level of control, decisions are taken with respect to individual operations of released production orders. Other decisions involved are e.g. allocation of human operators, allocation of tools and fixtures, machine maintenance, alternative operations, etc.

It is worthwhile at this point to spend a few lines

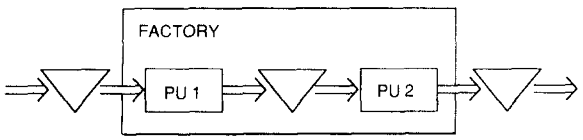

Fig. 1. Breakdown of the material flow into main stages (production units).

on the choice of different *Production Units* in a factory. Generally speaking, a PU should represent a clear-cut part of the material flow (see *Fig. 1*). Therefore, points in the bill-of-material with a strong convergency or a strong divergency are likely to correspond to PU-boundaries. Also, points in the bill-of-material where there is an unavoidable change in lot-size usually correspond to a PU-boundary. From the capacity point of view it is harmful to the control structure if the same capacity constraint is active for several PUs. Therefore, a PU should at least be so large that each capacity constraint can be associated with a single PU. For more detailed discussion of questions on choosing PU-boundaries, see [1]. Note, however, that a PU may consist of one server (a single server, a line server, or a network server), a line of servers, or a network of servers.

The *production control structure* is shown in further detail in *Fig. 2*, derived from [1]. This figure shows, that there are two important aspects to be considered in releasing production orders: the material aspect and the capacity aspect. The material aspect is covered by a materials co-ordination function. This function creates plans for future production orders while taking into account bill-of-material relationships, inventories and scheduled receipts, promised customer orders and constraints from master planning decisions. The capacity aspect is covered by a workload control function. This function determines current and future release opportunities for production orders.

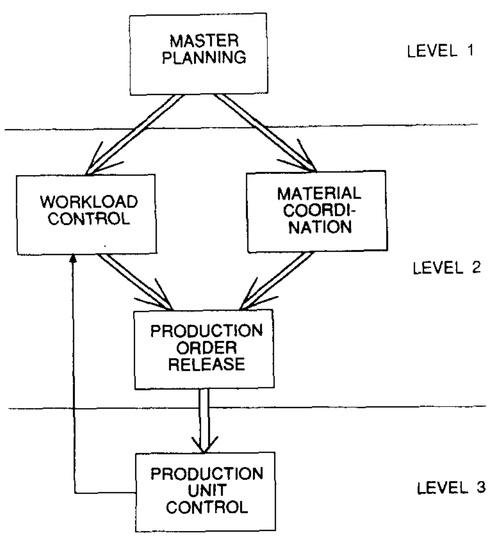

Fig. 2. Production control structure (derived from [1]).

If all capacity constraints within a PU are deterministic in nature, then these release opportunities can be computed in advance. However, this situation is infrequently encountered (mostly in assembly lines and chemical industries with very well-controlled manufacturing processes). The more common situation is, that one or more servers within a PU are stochastic in nature. This causes that release opportunities are based on feedback (represented by the single line in Fig. 2).

If one or more servers with a PU face *set-up or mix problems*, there are two possibilities. On the one hand, it is possible that such set-up and mix problems are considered to be local problems of a specific server. In this case, these problems are dealt with in the dispatching decision. On the other hand, it may occur that set-up and mix problems of servers are dominant factors, which determine the production progress of the PU as a whole. In the latter case these problems are dealt with in the production order release decision. This requires, of course, that the problems are made known to the release function.

An interesting production situation which may be used to illustrate the above concepts is the Toyota Production System [9]. Because this system produces virtually without stocks, the whole system (including certain suppliers) should be considered as a single PU. The system has hardly any set-up problems, but it is designed in such a way that mix-constraints should be strictly enforced. The leadtime of orders is nearly constant. The volume of production is measured in a single dimension, viz. the number of cars produced. Therefore the PU is considered to be a line-server. Although the system is well-controlled and seldom disturbed, both the dispatching and the release function is based on feedback (the "pull system"). Therefore, the whole system is apparently treated as a stochastic line server by higher levels of control.

In the general control structure of Fig. 2, the most general situation is the situation where:
- the volume of production is stochastic
- the progress of production should be measured in several dimensions
- the PU faces lot-sizing and mix problems to be dealt with at release level.

In this case the release decision will be based on:
- material considerations (need dates, lot sizes)
- actual production progress (in several dimensions)
- actual state of servers with respect to lot-sizing
- actual mix of open production orders.

Many FAMSs described in literature seem to be treated as a complete PU. In order to illustrate this point, we include in *Appendix 1* a description of the well-known Caterpillar FAMS in terms of the theoretical framework presented here. However, our experience indicates, that a FAMS can be also just a part of a PU. Two examples of real production systems where it would be inappropriate to consider a FAMS as a separate PU are included in *Appendix 2* and *3*.

3. FAMS Control Structure

In this paper we are especially interested in the medium and short term control structure of a FAMS. As a framework we will use the control structure of Bertrand and Wijngaard as presented in the previous section. Before adapting this structure to our problem situation, we will first have a closer look at some specific characteristics of FAMSs as technical manufacturing systems.

3.1 FAMS as Technical Manufacturing System

A FAMS typically combines characteristics of automated manufacturing systems with characteristics of manufacturing systems that can be called flexible. The machine(s) in the system are all under computer control. They are individually or as a group capable of performing several operations and may have a toolmagazine positioned next to the machine and/or a central toolmagazine. The system contains an automated material handling system (MHS) and some workpiece-bufferplaces. Loading and unloading of workpieces (e.g. on pallets using fixtures) takes place in load/unloadplaces and not in the machines themselves. All transformations inside the system are automated (e.g. transport to and from buffer- and loadplaces, changing of pallets containing workpieces from MHS to machine and buffer- and loadplaces or vice versa, changing of tools and NC programs). A FAMS has the technical potential of working several hours without operator-interference. The smallest type of FAMS is the Flexible Automated Manufacturing Cell containing e.g. one machine center and a pallet buffer (see e.g. [5] or Appendix 2). An example of a large system is the Fanuc-plant near Mount Fuji (see [6]) or the Caterpillar FAMS described in [14] (see Appendix 1).

It may be concluded that a FAMS typically contains more than one runbatch. Only if all these runbatches contain jobparts belonging to only one jobbatch, one could speak of a single server. This will seldom be the case: in most cases a FAMS can be characterized as a line server or a network server.

3.2 The Production Control Structure

As has been said before, we are especially interested in the impact of FAMS on larger multi-level production control structures. *Fig. 3* presents a

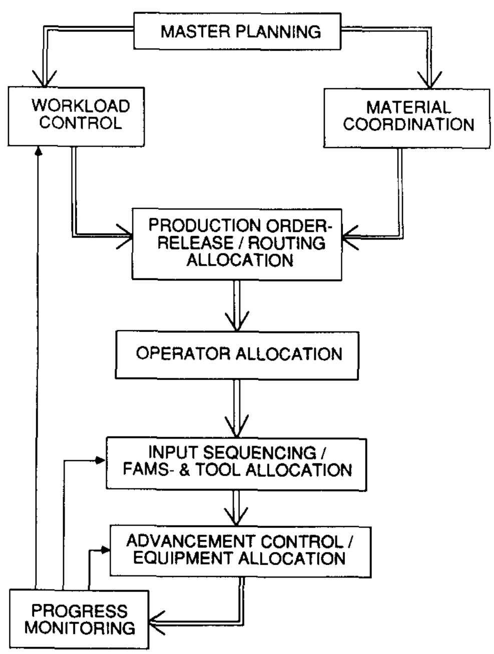

Fig. 3. FAMS production control structure.

typical FAMS-control structure. This structure combines both control functions of such a multi-level control structure as mentioned by Bertrand and Wijngaard (see previous section) and "new" typical FAMS control functions as mentioned in literature.

3.2.1 Order Release, Operator Allocation and Production Unit Coordination

Before jobbatches arrive at the FAMS they will have to be released to the PU often based on the PU-state (in terms of release opportunity or pattern as determined by Workload Control) and the jobbatch priorities (as determined by Material Coordination). In order to be able to do so routings will have to be "allocated" so that the operation sequence can be determined (note that the possibility of selecting an alternative server (e.g. another FAMS) for carrying out a specific operation is still open!). Operators should be allocated as late as possible, but probably at a lower frequency than the FAMS-allocation. The PUs are coordinated by Master Planning, both in terms of material flow and in terms of capacity.

3.2.2 Input Sequencing and Advancement Control

A clear distinction is made in literature between what can be called Input Sequencing and Advancement Control (e.g. [4,12,14]). At the Input Sequencing-level the sequence of new jobparts entering the FAMS is determined and new runbatches are formed. In case there are alternative servers available, this requires a final allocation of the FAMS that will produce the required parts. At this point tools are allocated among the individual machines or machine groups that might carry out the specific operations (see e.g. [8,11]). At the Advancement Control-level the advancement and sequence of the runbatches is controlled resp. determined. At this point specific equipment (such as the next machine tool or transport cart) will be allocated. Depending on the specific computer-configuration used for the FAMS-control, this Advancement Control might be split up into for example Cell Control and Equipment Control (see e.g. [8]).

3.2.3 Feedback Loops

In this control structure there are several feedback loops necessary (single lines in Fig. 3). Advancement Control needs information both on the equipment-state (e.g. machine availability) and on the runbatch progress (for runbatch dispatching). Apart from information on the possibility of a new jobpart-entrance (availability of pallet, fixture and sufficient toolpockets), more detailed information on the progress of (other) runbatches and the influence of this new entrance on their progress might be necessary for Input Sequencing. Often jobbatch progress monitoring is necessary for Workload Control to be able to determine the release pattern (see previous section).

4. The Influence of FAMS-Characteristics and the Environment on the Nature of the Control Functions

Many FAMS-characteristics and constraints are mentioned in literature. The most important characteristics which may influence production control are the following:

- *Limited space in tool magazines* (see [11]).
  Mostly, current FAMSs have for each piece of machine equipment a magazine with a limited number of pockets for different tools. Fully automatic exchange of tools between the magazine and the machine spindle is quite common nowadays. Fully automatic exchange of tools between magazines of different machine centers is less common. The same goes for the use of a centralized tool magazine. Therefore, limited space in tool magazines is often an important constraint. We assume that workpieces are only loaded on a FAMS if all tools required for the operations on the runbatch are loaded in the automated tool magazines. This assumption will be called: the *tooling assumption*.
- *Limited number of fixtures (or jigs) per product-type* (see [13]).
  The investment in fixtures and jigs for a specific product-type to be processed in a FAMS is often considerable (also, this investment may be much larger than for conventional machines). For this reason, there is often only one fixture per product-type. Therefore, a jobbatch (i.e. a series of identical products) is split up into jobparts. A new jobpart of a jobbatch may be loaded on the FAMS only if the previous jobpart is completely finished, in case of a single fixture. As mentioned, some fixtures are suited for more than one product-type. This may lead to the

possibility of creating runbatches with several pieces of different product-types.

- *Set-up time.*
  It may take considerable preparation effort before a new jobbatch of a product-type can be started on a FAMS.
  This is due to fetching, installing and measuring fixtures and jigs on a pallet, loading programs, changing tools, etc. Therefore, the well-known lot-sizing optimization is not entirely eliminated in many FAMSs. There are two strategies with respect to lot-sizing mentioned in literature.
  One strategy is *set-up batching* (see [15]). In this strategy, a number of jobparts are taken together into one major set-up activity. The purpose of this strategy is to take advantage of tool and fixture commonality. Also, mix problems can be avoided if a proper mix is matched during set-up batching. All jobparts are fully processed before a new set-up batch is formed. During the change-over period between two set-up batches the system is empty. The strategy is suitable in our opinion, if the system will become empty periodically anyway. This may occur in some systems after unmanned periods. If an "artificial" set-up period has to be chosen, the set-up batching strategy may be less suitable, because it leads to suboptimization. A further disadvantage of this strategy is that during one system set-up arrivals of new jobbatches at the system will be ignored. In case of a small set-up batch (and thus a small set-up period) this will only be a minor disadvantage.
  The other strategy is to perform set-ups gradually while the system is operating. Obviously, this strategy has less advantage of tool and fixture commonality. Mix constraints require continuous attention of Input Sequencing. However, the FAMS may continue to produce smoothly while set-ups are being made, and arrivals of new jobbatches are not ignored.
- *Unmanned production* (see [6]).
  An important property of many FAMSs is the ability to produce for a considerable number of hours when no human operator is available. Of course, this property requires that new runbatches are loaded at a higher rate before the start of an unmanned period and that finished runbatches are unloaded at a higher rate just after the end of a unmanned period.
- *Limited total number of runbatches in the FAMS* (see [6]).
  The total number of runbatches in the system is often constrained by the physical size of the system. For example, the number of pallets on which fixtures are mounted, is finite. Furthermore, the number of runbatches may be constrained by the number of fixtures and tools actually set-up.
- *Buffer place distribution* (see [4]).
  Runbatches may be waiting at local bufferplaces in front of specific machine centers or at central bufferplaces. If bufferplaces are dedicated for specific machine centers, Advancement Control will have to perform a "bufferplanning" function. If no dedicated bufferplaces exist, Advancement Control should continuously monitor the machine status, in order to prevent idle capacity.
- *Material handling system* (see [7]).
  The material handling system (MHS) may induce three types of constraints. First of all, the material handling system determines the routings which can be followed by runbatches. For example, the MHS can or cannot change priorities in a queue, it may or may not allow for by-pass in a flow-line, etc. Second, the MHS may itself require a substantial throughputtime. If so, Advancement Control should take this throughputtime into account in all planning activities. Finally, the MHS may become a bottleneck itself, with associated queueing times.

The influence of these characteristics on FAMS production control depends on the type of FAMS. Broadly speaking, we can distinguish three types of FAMS used in industry nowadays (see e.g. [2,10]):

- Flexible Automated Manufacturing Cell (FAMC, see Subsection 4.1): each runbatch visits only one machine center (note that this does not limit the number of (different) machine centers!)
- Flexible Automated Transfer Line (FATL, see Subsection 4.2): the routings of the runbatches are similar (with the possibility of bypassing some machinery equipment).
- Pure FAMS (see Subsection 4.3): the routings of the runbatches differ substantially (this type of FAMS is sometimes also called a random FAMS).

It is important to notice that Production Control decisions will be affected not only by these

FAMS-characteristics, but also by the characteristics of the larger production system of which the FAMS is a part. In particular, the Input Sequencing function and the Advancement Control function of the FAMS itself are often influenced by characteristics of the environment of the FAMS. We can categorize these characteristics into three groups, being the characteristics of the arrival pattern, of the demand pattern, and the possibility of sharing capacity resources. Subsection 4.4 discusses the influences of these groups of characteristics.

4.1 FAMC Production Control

Fig. 4 displays the main relations between the FAMC-characteristics and the typical FAMS production control functions. An uninterrupted arrow symbolises a rather strong relation, whereas an interrupted arrow stands for a minor relation. If no arrow is drawn there is hardly any relation at all (apart from exceptional cases).

If there is a limitation in *space in the toolmagazine* this will affect not only the sequence in which first jobparts of new jobbatches are loaded on the FAMC, but because of the tooling assumption it also affects the number of jobbatches that simultaneously have jobparts on the system (see below). The (limited) *number of runbatches* will directly influence the (average) time a jobpart spends on the system and therefore total jobpart throughputtime. If more jobbatches have jobparts on the FAMS this will affect total jobbatch throughputtime on the system. In order to reach a high due date reliability, it is important for Input Sequencing to take this into consideration. As long as the total number of runbatches is not too small or too large, Advancement Control will hardly be influenced. A *limitation in fixtures* (per producttype) limits the number of concurrent jobparts on the FAMC belonging to the same jobbatch and it affects therefore Input Sequencing (see above). Only in exceptional cases, Advancement Control will be affected, viz. when the jobbatch throughputtime has to be shortened (e.g. a rush order, or an order containing many jobparts).

The same goes for *considerable set-up times*: again the input sequence will be affected for the reason mentioned above. In case of an *unmanned period*, Input Sequencing might want to (consciously) build up a large workload (in order to gain as much capacity-load as possible). In this case,

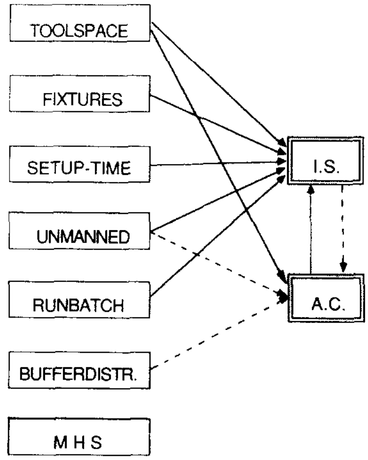

Fig. 4. Relations FAMC characteristics, Input Sequencing (I.S.) and Advancement Control (A.C.).

Advancement Control will have to give low priority to runbatches with large runtimes during manned periods.

However, total throughputtime of jobbatches with jobparts that require large runtimes has to be guarded by Input Sequencing as well: running just one jobpart e.g. per day (viz. in the unmanned period) might lead to unacceptable throughputtimes!

The influence of *bufferplace distribution* limits itself largely to the case of absence of local bufferplaces in front of the machine centers. If this is the case, Advancement Control will have to give some slight attention to the state of the machines (e.g. still empty or still running). As Buzacott has shown [4], a large local buffer should be avoided. Finally, as far as the MHS is concerned, it is very unlikely that the handling system in a FAMC will take considerable throughputtime or will become a bottleneck itself (if that is the case one might question the appropriateness of system design!).

Advancement Control may have substantial influence on *Input Sequencing*, since this function determines which and when a runbatch will be available for unloading. This is especially important in case there are indeed limitations on the number of runbatches, on the number of fixtures, on the toolspace and in case of considerable set-up time. On the other hand, Advancement Control is directly dependent on Input Sequencing for the available number of runbatches per machine (which affects the possibility of choice at runbatch dispatching). However, in most cases a rough load-levelling will be sufficient.

4.2 FATL Production Control

The relations between the FATL-characteristics and the typical FAMS production control functions are schematically drawn in *Fig. 5*. The influence of *limited toolspace* will – because of the tooling assumption – be limited to the sequence in which jobparts of new jobbatches will be loaded on the system, the number of jobbatches that simultaneously have jobparts on the system and the question if and – in case of automatic toolexchange – in what sequence (although it is very likely that there will be little freedom of choice in a FATL) runbatches will visit machine centers (thus affecting Advancement Control).

The timing of input is more or less determined by the line-speed. The mix of jobparts however may influence this line-speed. Apart from the already mentioned toolspace, this mix will be affected by a *limitation in fixtures*. In case of mix problems and fixture limitations, Input Sequencing has to plan its short term schedule in order to prevent a low utilization of the line. In the worst case a set-up for only one jobbatch remains with just one fixture available (and thus only one runbatch will be on the system!).

In case of *considerable set-up time*, all jobparts of a jobbatch should have been loaded before a new set-up is made. On top of that, the line might

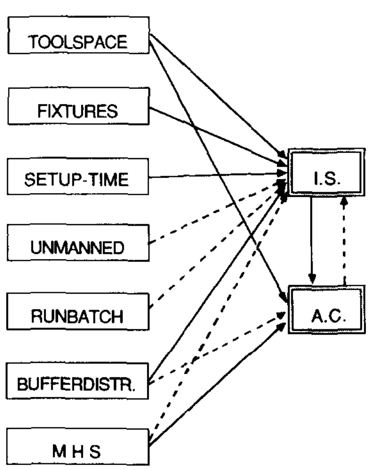

Fig. 5. Relations FATL characteristics, Input Sequencing (I.S.) and Advancement Control (A.C.).

be delayed if Input Sequencing does not pay enough attention to this factor.

For *unmanned periods*, Input Sequencing might want to build up a workload. The priorities used in building up this workload are the same as before since a certain mix has to be maintained. Therefore, this building up "simply" means speeding up the input. In this case, extra bufferplaces are required. During unmanned periods Advancement Control will face the same problems as in manned periods: the extra bufferplaces will have hardly any effect on the nature of Advancement Control.

The number of pallets on the FATL determines largely the linespeed and is to be determined by Master Planning. However, Input Sequencing might have the freedom of adapting the *number of runbatches* in order to speed up or slow down the line to some extend. This might be necessary for instance to build up a workload for unmanned production. In order to keep up the line-speed in a FATL with a certain *distribution of bufferplaces*, the jobpart-mix should be constrained. However, Advancement Control might still have to compensate for very limited local bufferplaces.

Finally, the MHS puts constraints on the possible actions Advancement Control might take (e.g. to bypass). It might even have impact on Input Sequencing (e.g. in case of the MHS being a bottleneck).

In comparison to the FAMC, *Input Sequencing* and *Advancement Control* are related in a opposite way. Advancement Control is largely dependent on the input of jobparts coming from Input Sequencing. This control function has only minor possibilities of correction by e.g. bypassing. However, because of these (minor) possibilities of correction, Advancement Control affects the set of runbatches available for unloading and therefore affects to some extend Input Sequencing.

4.3 Pure-FAMS Production Control

Fig. 6 gives the relations between pure-FAMS-characteristics and the typical FAMS production control functions. A *limitation on toolspace* will have the same kind of influence on the Input Sequencing of a pure-FAMS as it has in case of a FAMC. A *fixture limitation* will of course influence Input Sequencing to some extend. However, this constraint might not be too tight since Input Sequencing already has got to deal with mix constraints in order to keep up the utilization rates of the FAMS machinery equipment. Advancement Control will be affected by this constraint only in exceptional cases (e.g. rush-orders).

Considerable set-up times will affect Input Sequencing more or less in a similar way as it affects a FAMC. However, the sequencing decision in this case will probably be more complicated since the workload of more machine centers will be affected. *Unmanned periods* require special attention of Input Sequencing in order to gain as much capacity-load as possible. Similar to the case of the FATL the mix of this workload should be taken into account. However, the problem of building up extra workload is more complicated in this case. Both the limitation on the *number of runbatches* and the *distribution of bufferplaces* may demand special attention of Advancement Control in order to keep the machinery equipment running (e.g. by means of a WINQ-priority rule). Input Sequencing will have to keep an eye on the number of runbatches per machine center. The last FAMS-constraint (the MHS requiring substantial time or being a bottleneck) demands some kind of scheduling action of Advancement Control.

Advancement Control is closely related to *Input Sequencing* in case of a pure-FAMS. Input Sequencing determines the workload and mix per machine center and sets therefore the boundaries between which Advancement Control is able to manoeuvre. On the other hand, Input Sequencing requires feedback information on the progress of jobparts and bases its decisions on this progress. In fact, the relation between these control functions is quite similar to the relation between Order Release and Production Unit Control in job-shops (see Fig. 2). Because of the extra FAMS-constraints (e.g. on queues) the relation may even be stronger.

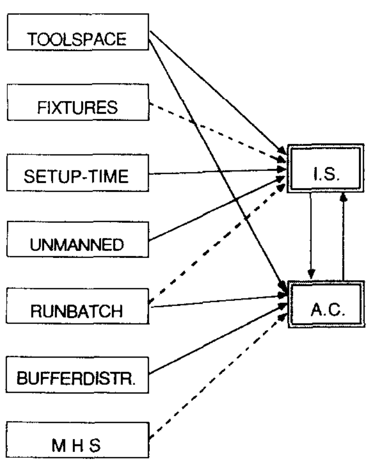

Fig. 6. Relations pure FAMS characteristics, Input Sequencing (I.S.) and Advancement Control (A.S.).

4.4 Environmental Characteristics

As has been said before, the environmental characteristics that may influence the nature of the control functions, can be categorized into the following groups:
- demand pattern
- arrival pattern
- sharing of capacity resources.

The four factors that are important in the *demand pattern* are the required jobbatch size, the productmix, the demand frequency and demand predictability. If the Production Unit not only contains a FAMS, but also conventional machinery equipment, jobbatch sizes are often determined by those conventional machines. The larger the jobbatch size, the longer the jobbatch throughputtime will be. If our policy in case of considerable set-up time would be to deal with these set-up times by creating "artificial" set-up batches (see above), then the period covered by such a set-up batch would have to be even longer. This will lead to a high degree of suboptimalization, since new arrivals of jobbatches and changes in predicted demand, e.g. rushorders and duedate changes, during this period will be ignored. Such a suboptimalization can only be accepted if, by following such a policy, the remaining control problem would be simplified considerably (and thus become more manageable). In case of a high demand frequency it might be possible to limit the mix of products that will be produced on the FAMS and allocate the tools necessary for these products permanently to the toolmagazines. Even fixtures could be allocated to pallets permanently. This would simplify the control problems, especially for Input Sequencing. Such a FAMS could be controlled by a Kanban-like control mechanism.

The *arrival pattern* influences the production control in three ways, viz. by its frequency and distribution in time, its jobbatch size and its predictability. In case of set-up batching, the arrival-frequency and distribution in time together with the predictability affect the possibility of taking future arrivals (during the set-up period) into account when set-up batches are formed. This possibility, again, affects the degree of suboptimalization by set-up batching. If the arrival pattern is deterministic then it is possible and even desirable to solve some Input Sequencing problems at the point of orderrelease. By doing so, queues of jobbatches in front of the FAMS can be limited. In case of a deterministic FAMS-behaviour all Input Sequencing problems might be solved by Order Release. If this behaviour is not fully predictable, some slack will be required. Examples of a deterministic arrival pattern are the cases of a FAMS being the first server after orderrelease (e.g. in case the FAMS is a Production Unit by itself, see Appendix 1) and a FAMS being the first server after one or more fully predictable lines (cf. Appendix 3). In case of a non-predictable arrival pattern the relation between Order Release and Input Sequencing will limit itself to workload and mix-constraints (as we have seen, especially in case of a FATL or pure-FAMS these mix-constraints may be important). If the jobbatch sizes in the production system in front of the FAMS are considerable larger than jobbatch sizes required by the rest of the production system, it might be wise to create an orderrelease-point just in front of the FAMS.

Examples of *sharing of capacity resources* are the usage of tools and fixtures elsewhere in the production system. For the FAMS, a jobbatch is only available for Input Sequencing if the availability of fixtures and tools (because of the tooling assumption) is guaranteed (see [7]). This means either the physical presence of these capacity resources, or the allocation of these resources (with the guarantee of a short resource delivery time). If this aspect should cause (serious) problems, investment in more resources should be considered. By doing so, extra bottlenecks which complicate production control even further will be avoided.

4.5 Discussion

It should be noticed, that the environmental characteristics have considerable impact on the nature of Input Sequencing and Advancement Control. As an example, consider lot-sizing problems. If the demand pattern for FAMS-products shows considerable lot-sizes, and if the supply pattern to the FAMS delivers products in the same lot-sizes, it seems logical that the FAMS Input Sequencing aims at processing the whole jobbatch as quickly as possible. On the other hand, if the supply and demand pattern are not batched, the FAMS Input Sequencing function should avoid batching as much as possible.

As another example, consider the above mentioned set-up batching strategy. If several products to be produced in the same set-up batch happen to be parts of the same assembly order, (artificial) set-up batching may be an advantageous strategy. If such parts are known to be always consumed by assembly orders which have a considerable difference in due dates, set-up batching becomes disadvantageous. As a generalized conclusion, we may state that the proper definition of the FAMS control problem is often determined by environmental characteristics, and not only by the (technical) nature of the FAMS itself.

A related point of discussion is the following issue: Many FAMS studies approach the FAMS control problem as a static, deterministic problem. More specifically, given a set of production orders for the foreseeable future, the problem is treated as a Gantt-chart optimization problem with the objective of maximizing machine utilization under due data and arrival date constraints. If some disturbance occurs in the FAMS (e.g. tool wear or machine-breakdown), this is considered to be a regrettable fact which should lead to a new detailed "optimal" schedule. If the predictability of the environment of the FAMS is poor, we feel that the effectivity of this optimization approach has to be doubted. This is first of all due to the fact that PU-control and Production Order Release can take many decisions which fall outside the scope of the FAMS, such as job-splitting, alternative routings, changing allocation of tools, fixtures and personnel, etc. Secondly, the above analysis shows that the Input Sequencing function and the Advancement Control function of the FAMS may often exercise proper control if they react quickly to the actual state of the system.

If the FAMS production control functions apply simple, robust rules, then the FAMS behaviour will become transparent to higher level control functions. This may, in turn, lead to improved decision making by these higher level control functions in dealing with many problems outside of the FAMS.

5. Conclusions

The conclusions from this research may be summarized as follows. First of all, we feel that in many papers it is supposed implicitly, that a FAMS covers a full Production Unit (PU) in the material flow. Current practice with FAMS shows, that a FAMS is often a part of a PU, with preceding workcenters and succeeding workcenters (especially in case of a FAMC).

Second, a distinction should be made between the release of a production order to a PU and the Input Sequencing function of the FAMS. Also, a distinction should be made between sequencing decisions in a PU outside of the FAMS and the Advancement Control within a FAMS.

Third, considerable differences occur between flexible automated manufacturing cells (FAMC), flexible automated transfer lines (FATL) and the pure-FAMS. These differences were investigated in Section 4, and depicted in Figs. 4 to 6. The analysis suggests, that Input Sequencing is often a more complicated and more important decision than Advancement Control.

Fourth, if a FAMS is not constrained by tools, fixtures, set-up times, unmanned periods, number of runbatches allowed, buffer sizes, or material handling systems, we may conclude that:

- Input Sequencing reduces to maintaining an optimal mix of runbatches with respect to available capacity (or even to a conventional sequencing problem in case of a FAMC).
- Advancement Control either resembles the classical Job-Shop sequencing control (in case of a pure FAMS) or becomes fairly trivial (FAMC or a FATL).

As more and more constraints are added, these two FAMS control problems become more and more complicated.

Moreover, these constraints may become dominant to the extend that they can no longer be handled effectively at the level of FAMS control, but should be included at higher level production control functions. More specifically, highly constrained FAMSs will lead to a more complicated Production Order Release function, because this function has to consider FAMS-related constraints. Still one step further is the situation, where Master Planning is forced to take into account certain FAMS-constraints, in order to guarantee that lower levels of control will face solvable problems.

Finally, two conclusions can be drawn more specifically with respect to the relationship between an FAMS and its environment. First, a definition of the FAMS production control problem may be influenced considerably by the nature of the environment. In particular, a problem definition based only on the technical characteristics of the FAMS itself is likely to be incomplete. Second, assuming that the FAMS is part of a non-deterministic environment, a detailed deterministic optimization approach to FAMS production control could yield unstable results, which are only optimal within a narrow scope. Simple, robust control rules based on feedback are worthwhile to be considered instead.

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Appendix 1: A Case of Pure FAMS

FAMS-Characteristics

A FAMS well known in literature (see e.g. [11]) is the Caterpillar-FAMS. It consists of four large 5-axis machine centers (Omnimills), three 4-axis machine centers (Omnidrills), two vertical turret lathes and an inspection machine. The system can be characterized as a *pure*-FAMS (according to [2]). Each machine has a *limited-capacity tool magazine*. A part will not visit a particular machine of the correct type unless all the tools required for the current operation are already available in the tool magazine (the tooling assumption!). A 16-stations load/unload area also provides a *central buffer* area for in-process inventory. The *number of runbatches and fixtures* are constrained. *Set-up times* seem to be considerable, since set-up batching is advocated. The MHS consists of two rail guided transporters. From [14] it may be concluded that handling-times are neglectable and that the MHS is not a bottleneck: scheduling is done only on machine operations.

Environment

The parts machined on this system (i.e. the *productmix*) are covers and cases of housings for automatic transmission. There are two sizes of housings. The covers and cases first seem to be processed separately and later on in an assembled form. The parts arrive at the facility in rough casting form and leave as an assembled matched pair. Note that covers, cases and assembles do not only have two sizes, but also several operation sets to be performed (each requiring its own set of tools). Demand is *predictable*, since all production requirements are given in advance. *Jobbatches* seem to consist of just one jobpart. The FAMS is considered to be a Production Unit: all *jobbatches arrive* at the FAMS immediately after releasing and have no further operations after leaving the FAMS. The system is subject to many *random disturbances* (see [11]).

Production Control

The production control of this system is based upon the principle of set-up batching. Since jobbatches are small, the time-period in which a set-up batch is produced, can be limited. Because of the fact that jobbatches arrive at the FAMS immediately after release and production requirements are given (coming from Master Planning), the arrival pattern is predictable. In this case, set-up batching is therefore an appropriate strategy in order to cope with the FAMS-constraints (such as toolspace limitation and fixture limitation). Stecke calls these problems "the planning problems" (for an exact formulation of these problems, see [12]). After a set-up batch is formed, the input sequence within the set-up batch is determined. Because of the random disturbances, system behaviour cannot be considered to be deterministic. Stecke [11] advocates therefore dispatching rules instead of a deterministic schedule. Advancement Control attempts to move parts first to the machine that is idle and has the largest workload (total assigned processing time). For that machine the part with the highest priority is chosen.

Appendix 2: A Case of FAMC in a Job Shop [1]

FAMS-Characteristics

A Dutch firm that produces complicated parts (e.g. for the aviation industry) has recently started an investment program in flexible manufacturing. They have installed a FAMC, consisting of two identical machine centers. Each machine has a local tool magazine with a *limited number of pockets*. The system contains two load/unload places and *five central bufferplaces*. *Local storage* of one runbatch in front of each machine center is possible. Both the *number of runbatches* and the *number of fixtures* (per producttype) are constrained. *Set-up times* are considerable: the change-over between jobparts of different jobbatches takes about 1.5 manhour whereas a change-over between jobparts of the same jobbatch takes about 8 minutes. The MHS consists of one railguided transporter. Handling-times are neglectable and the MHS-utilization rate is low. Up till so far, *unmanned production* has been avoided. However, in the future the aim is to produce unmanned for several hours during the night shift.

Environment

The FAMC is part of a large machine department. About *60 different operations* are performed on the FAMC on about 35 parts. Apart from these operations on the FAMC, the parts have many other operations on other machines (ranging from 10 till 70 operations!). Almost all parts produced on the FAMC have several operations left and arrive from and go to many different machines. The department has some typical job-shop characteristics. This means that *demand is not (entirely) predictable*. The same goes for the *arrivals* of the jobbatches (with an average of 1 batch/day). The *average size of the jobbatches* (both arriving and demanded) is about 30 jobparts with an average runtime of 0.75 hrs/jobpart. The system is subject to many disturbances.

Production Control

In this case, obviously the FAMC cannot be considered to be an entire Production Unit, nor is there any reason to create an orderrelease points in front of (or right after) the FAMC. In fact, the entire machine department should be considered as one Production Unit (because of the structure of the bill-of-material, lot-size changes and the capacity constraints). Because of the large jobbatch-sizes, the arrival frequency and the unpredictability of the arrivals, set-up batching is not used as a principle for production control. Instead, set-ups are made gradually while the system is operating. Most FAMC-constraints are dealt with at the point of Input Sequencing. For Order Release the FAMC behaves like a single server (with two parallel machine centers). For Input Sequencing however the FAMC is a (stochastic) line server. No deterministic schedules are used. Because of the considerable set-up time and of the fixture-limitation, fixtures are allocated to pallets until the last jobpart of a jobbatch is unloaded. Machine-states are hardly taken into account by Advancement Control (because of the local bufferplaces). The Input Sequencing depends very much on the state of the pallet that could be loaded (e.g. a pallet containing a fixture for a jobbatch with remaining jobparts that not have been loaded yet, or an empty pallet).

Appendix 3: A Case of FAMC in Line Production [2]

FAMS-Characteristics

An example of a FAMC that is part of a larger production system that consists mainly out of production lines, is the FAMS in a component manufacturing department of an other Dutch manufacturer. In this department a FAMC has been installed. The cell consists of six identical machine centers, each having a *limited local toolmagazine*. Apart from the load-/unloadplaces, which can be used as a central buffer, only *local bufferplaces* are available. The number of runbatches is limited (especially due to the limited number of bufferplaces). Again, *sest-up times* are considerable (comparable to the operation time of one runbatch). The FAMC is only operating in *two-manned shifts* (unmanned production is hardly possible because of the limited buffersize). The MHS consists of a rail guided transporter, which has a low utilization rate and neglectable handling-times.

Environment

The parts that are to be produced by the FAMC arrive from several production lines and continue their production process on several other lines. *Jobbatch sizes* on these lines vary between 100 and 800 workpieces. The *demand quantity* per parttype per year varies between 600 and 14000 workpieces. *Six parttypes* are partly produced by the FAMC, each requiring considerable toolspace (often a machine is setup for just one jobbatch). Apart form minor disturbances, the lines in front of

[1] This case description is based on the work of M. Swinkels for his Master Thesis.

[2] This case description is based on the work of M. Brantjes, M. Ridder de van der Schueren and H. van Rooij for their Master Theses.

and after the FAMC are fairly *predictable*. Production requirements during a planning period are fixed according to the Master Plan (although they may change in a new planning period).

Production Control

Because of the similarity in lotsizes required by the several conventional lines in front of and just after the FAMC, of the gain in throughputtime and of the typical line-production characteristics of the whole department, the FAMC should be considered as part of a larger Production Unit. Each line can be characterized in deterministic terms (such as the input frequency and throughputtime). The FAMC too can be characterized as a line server with each machine set up for just one jobbatch (resulting in a natural set-up batch). The number of machines set up per jobbatch depends on the required input/output frequency, which is determined by the linespeed of the other lines. For each planning period, a deterministic schedule is made at the orderrelease-level. Only minor adjustments can be made by Input Sequencing, whereas Advancement Control is reduced to system-monitoring and a simple FIFO-control.