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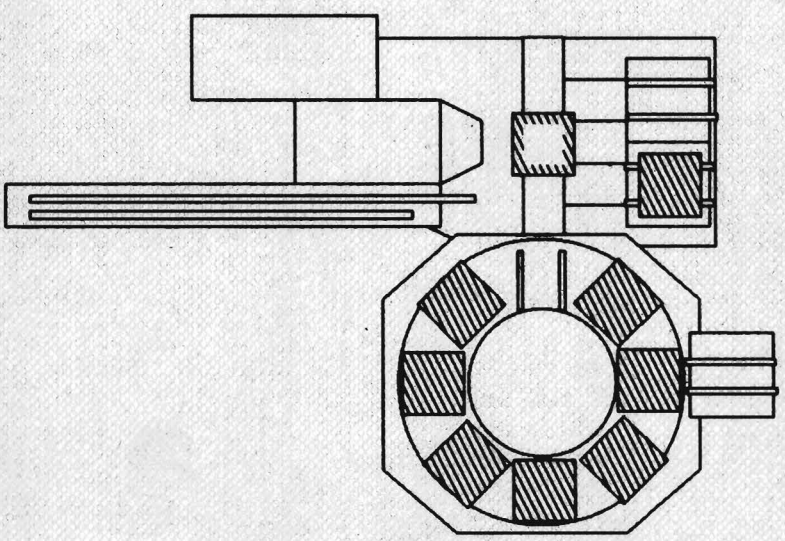
PRODUCTION CONTROL FOR FLEXIBLE AUTOMATED MANUFACTURING STATIONS IN LOW VOLUME COMPONENT MANUFACTURING



CORNÉ W.G.M. DIRNE

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PRODUCTION CONTROL FOR FLEXIBLE AUTOMATED MANUFACTURING STATIONS IN LOW VOLUME COMPONENT MANUFACTURING

PROEFSCHRIFT

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Prof.dr.ir. J.W.M. Bertrand

en

Prof.ir. P.W. Sanders

SUMMARY

The subject of this study is the production control for Flexible Automated Manufacturing Stations (FAM-Stations) in low volume component manufacturing.

FAM-Stations
A FAM-Station is a single-stage manufacturing system consisting of:
- one or more computer controlled machines capable of performing several distinct operation types,
- automated material handling equipment,
- an automated part storage system.

The FAM-Station is a single-stage manufacturing system, since parts loaded on the system visit only one machine before they are unloaded from the system. Most FAM-Stations are applied in machining shops. In these component manufacturing shops parts are loaded on the machine tools using positioning tools and pallets. A particular combination of positioning tools mounted on a pallet is called a product set-up.

Production modes
An important characteristic of a FAM-Station is the ability to produce parts unmanned for several hours. In case of manned production, product set-ups can be (dis)mounted and parts can be (un)loaded at any time. In the unmanned production mode, special change-over periods are required during which an operator is present at the station to (dis)mount product set-ups and (un)load parts. Not all operations can be performed in both production modes. In the cases we studied, the majority of the operations could only be performed during the manned production mode, since the continuous attendance of an operator was required during the operation process. Only few operations were suitable for unattended production during the unmanned production mode.
In this study it is shown that in order to check the major capacity constraints of FAM-Stations in low volume manufacturing, it should be possible for production control to distinguish on the one hand attended operations from unattended operations, and on the other hand manned production capacity from unmanned production capacity.

Flow times
Usually the machine tools in machining shops contain one fixed pallet on which a product set-up can be mounted. These machines are capable of producing parts of only one particular part type at a time. Consequently, a work order for parts of a particular part type is completed before a new product set-up is mounted and the machine is re-set for a work order for parts of an other part type. In other words, on the machines work orders are produced sequentially. As opposed to the machine tools described above, FAM-Stations contain several non-fixed pallets that circulate on the station. However, both from an economical point of view (the positioning tools can be rather expensive, and often are part-specific), and from a technological point of view, the maximum number of identical product set-ups mounted on pallets is limited. Therefore, in order to use all pallets, the product set-ups mounted on pallets are of several distinct product

set–up types. Consequently, the parts loaded on the pallets belong to several work orders. As a result, work orders are no longer produced sequentially, but simultaneously.
After a detailed study of the flow time behaviour of work orders at FAM–Stations, we show that in most cases producing several work orders simultaneously instead of sequentially increases the average order flow time. In the manned production mode, increasing the number of work orders simultaneously in operation in most cases further increases the average order flow time. At the same time, in case the number of pallets on the FAM–Station (and thus the number of work orders simultaneously in operation) is too small, the order flow times increase due to the fact that the machine(s) get idle. Usually three pallets per machine are enough to prevent the machine(s) from getting idle. Therefore, the number of work orders simultaneously in operation should be limited, but in most cases not to one. If more than one product set–up is available for a particular order (e.g. because more product set–ups are available per product set–up type, or because a part requires more than one product set–up type in order to be completed), distributing these product set–ups over several pallets is an advantageous strategy from a flow time point of view. In such a case, it is not required to produce several work orders simultaneously in order to prevent the machine from getting idle.
In the unmanned production mode, increasing the amount of work loaded on the FAM–Station at the beginning of an unmanned shift usually decreases all order flow times, and thus also the overall average flow times. Therefore, in this case, mounting as much product set–ups on one pallet will be an advantegeous strategy. Also, if possible, especially work orders with cycles requiring long operation times should be completed during the unmanned shifts. The number of pallets used in an unmanned shift should be large enough to complete all work orders. The average flow times decrease rapidly with a small increase in the number of pallets used. The minimum average flow time is already almost obtained as soon as the pallet utilization rate is negligible (in most cases 60% or less).

Flow time estimators
In case of FAM–Stations, work orders with a small lot–size usually have a short waiting time, whereas work orders with large lot–sizes have long waiting times. Furthermore, the order waiting times are dependent on the production mode during which the work order is produced. In this study we introduce order flow time estimators to be used by production control that take into account both the production mode during which the work order is completed, and the lot–size dependency of the order waiting time. Simulation experiments have shown that these estimators are more accurate in estimating work order flow times than the flow time estimators used in most component manufacturing shops.

Sequencing
In case of FAM–Stations in low volume component manufacturing, especially the Sequencing function is affected. In this study it is shown that the sequencing decision at a FAM–Station in fact consists of three interrelated, but separate decisions. The first decision concerns the set–up of the FAM–Station. Giving a set–up, decisions should be taken on the release of pallets to the FAM–Station. The last decision concerns the sequence in which the released pallets are taken into operation.
In this work for each of these decisions several guidelines are given to be used in the decision process.

SAMENVATTING

(Summary in Dutch)

Het onderwerp van onderzoek dat centraal staat in dit werk is de produktiebeheersing voor flexibele geautomatiseerde bewerkingsstations (FAM-Stations) in onderdelenfabrikage met een lage herhalingsgraad.

FAM-Station
Een FAM-Station is een één-fase fabrikagesysteem dat bestaat uit:
- één of meer computer gestuurde machines die diverse typen bewerkingen kunnen uitvoeren;
- geautomatiseerde apparatuur voor de material handling
- een geautomatiseerd opslagsysteem voor te bewerken en bewerkte onderdelen.

Een FAM-Station is een één-fase systeem, omdat elk te bewerken onderdeel na te zijn opgespannen precies één machine bezoekt alvorens te worden afgespannen. FAM-Stations komen het meest voor in verspanende afdelingen. In een dergelijke omgeving worden de te bewerken onderdelen opgespannen op de machine met behulp van opspangereedschap en pallets.

Wijze van produktie
Eén van de karakteristieken van het gebruik van een FAM-Station is dat enige uren onbemand kan worden geproduceerd. Een belangrijk verschil tussen bemande en onbemande produktie is dat gedurende bemande produktie op elk gewenst moment opspanningen kunnen worden gebouwd en afgebroken, en onderdelen kunnen worden op- en afgespannen. In geval van onbemande produktie geschieden deze handelingen voor of na een onbemande ploeg. Uit enkele praktijkcases blijkt dat de meerderheid van de bewerkingen alleen gedurende bemande produktie kunnen worden uitgevoerd, daar de (voortdurende) bewaking van de operator nodig is. Slechts enkele bewerkingen blijken wel geschikt te zijn voor onbemande produktie (de zgn. onbewaakte bewerkingen).
In dit werk wordt aangetoond dat om de capaciteitsbeperkingen van FAM-Stations in een omgeving met een lage herhalingsgraad te kunnen beschouwen, het noodzakelijk is dat onderscheid kan worden gemaakt tussen bewaakte en onbewaakte bewerkingen enerzijds, en bemande produktiecapaciteit en onbemande produktiecapaciteit anderzijds.

Doorlooptijden
Bij de meeste machines binnen verspanende afdelingen is er sprake van een vaste pallet (ook wel 'tafel' genoemd) waarop het opspangereedschap wordt gemonteerd. Na de opbouw van een opspanning wordt meestal eerst de hele werkorder afgewerkt alvorens men de opspanning afbreekt en een nieuwe opspanning voor een volgende werkorder opbouwt. We noemen deze manier van werken het sequentieel afwerken van werkorders. In het geval van FAM-Stations is er evenwel sprake van een aantal losse pallets die 'vrij' op het station kunnen circuleren. Zowel om economische redenen (het opspangereedschap kan nogal duur zijn en de opspanning is vaak produkt-specifiek) als om technologische redenen is het aantal beschikbare identieke opspanningen beperkt. Om alle pallets te kunnen benutten zijn daarom verschillende typen opspanningen nodig, behorende bij verschillende werkorders. Het gevolg is dat werkorders niet meer sequentieel, maar min

of meer simultaan worden afgewerkt.
Uit nadere bestudering van het doorlooptijdgedrag van werkorders bij FAM-Stations blijkt dat in de meeste gevallen de gemiddelde werkorder doorlooptijd toeneemt indien werkorders simultaan worden afgewerkt in plaats van sequentieel. De manier waarop de werkorder doorlooptijd wordt beïnvloed, hangt sterk af van de manier waarop de werkorder wordt afgewerkt (d.w.z. bemande of onbemande produktie). Bij bemande produktie zal een toename van het aantal werkorders simultaan in bewerking meestal ook leiden tot een toename in de gemiddelde doorlooptijd. Alleen bij een zeer klein aantal pallets zal een toename van het aantal werkorders simultaan in bewerking leiden tot een daling in de doorlooptijd. De reden hiervan is dat bij minder dan zo'n drie pallets per machine regelmatig een machine stil zal komen te staan in verband met het ontbreken van een pallet met nog te bewerken onderdelen. Daarom moet enerzijds het aantal werkorders simultaan in bewerking zoveel mogelijk beperkt worden, doch is anderzijds meestal meer dan één werkorder nodig om de machine(s) draaiende te houden. Indien zich meer dan één opspanning voor een bepaalde werkorder tegelijkertijd op pallets kunnen bevinden (bijvoorbeeld omdat er meer identieke opspanningen zijn, of omdat meer typen opspanningen nodig zijn), dan zal het verspreiden van deze opspanningen over meer pallets de gemiddelde doorlooptijd doen dalen. Immers, in dat geval kan het aantal orders simultaan in bewerking beperkt worden zonder dat de machine stil valt.
In geval van onbemande produktie zal een toename van de hoeveelheid werk geladen op pallets aan het begin van een onbemande ploeg over het algemeen leiden tot een daling van de doorlooptijd van elke werkorder, en dus ook van de gemiddelde doorlooptijd. Daarom is het voor onbemande produktie aan te raden opspanningen zoveel mogelijk te combineren op één pallet. Daarnaast zijn bewerkingen met een lange bewerkingstijd zeer geschikt voor onbemande produktie. Het aantal pallets op het FAM-Station moet groot genoeg zijn om alle werkorders te kunnen verwerken (op den duur). Uit onderzoek is gebleken dat de doorlooptijd snel daalt indien het aantal pallets boven dit minimaal vereiste aantal pallets uitkomt. De minimale doorlooptijd wordt reeds bereikt indien de pallets minder dan zo'n 60% van de tijd bezet zijn.

Doorlooptijdschatters
Door de simultane afwerking van werkorders wordt een deel van de wachttijd van een werkorder afhankelijk van de seriegrootte van die order. De wachttijden zijn bovendien nog afhankelijk van de produktiewijze (bemand of onbemand). Tijdens het onderzoek zijn enkele doorlooptijdschatters getest die met deze afhankelijkheden rekening houden. Simulatie experimenten tonen aan dat deze schatters duidelijk betere schattingen afgeven dan te bereiken is met de reeds bestaande schatters.

Sequencing
Tenslotte blijkt uit het onderzoek dat de volgorde beslissing (beter bekend als 'sequencing') bij een FAM-Station opgesplitst wordt in drie met elkaar samenhangende, maar onderling te onderscheiden beslissingen. De eerste beslissing betreft de instelling van de machine (incl. opspanningen). Gegeven deze instelling dienen vervolgens pallets (voorzien van te bewerken onderdelen) te worden vrijgegeven aan het FAM-Station. De laatste beslissing betreft de volgorde waarin de op pallets geladen onderdelen worden bewerkt.
In dit werk worden enkele richtlijnen gegeven ter ondersteuning van deze drie beslissingen.

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Chapter 1
INTRODUCTION

In this first chapter we will introduce the main subject of our interest, i.e. production control for Flexible Automated Manufacturing Stations (FAM–Stations) in low volume component manufacturing. After a discussion of the use of flexible automation in manufacturing systems (especially on systems called 'Flexible Manufacturing Systems'), the applications and diffusion of these systems will be discussed. The third paragraph introduces the problem area addressed in this study and discusses the relationships of this problem area with other important problems concerning the use of these kind of manufacturing systems. We will conclude the chapter with an outline of our study.

1.1 Flexible automation in manufacturing systems

In literature the term 'FMS' (an abbreviation for Flexible Manufacturing System) is used quite often. Stecke defines an FMS as *"...An integrated, computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium–sized volumes of a variety of part types..."* [Stecke, 1983]. Buzacott and Shantikumar give a similar definition. They state that *"...An FMS consists of machines where production operations are performed, linked by a material handling system and all under computer control. The FMS should be able to process a large total volume of small to medium batches of parts..."* [Buzacott and Shanthikumar, 1980]. Other, but similar definitions can be found in [Groover, 1980], [Schütz, 1984], [Seidman and Schweitzer, 1984], [Huang and Chen, 1986], and [ECE, 1986]. We conclude from these definitions, that many manufacturing systems may have flexible characteristics, but only a subset of these systems is called 'FMS'. This subset has the specific characteristic that all manufacturing systems that are part of the subset, are fully automated. This is exactly the reason why we prefer the term *Flexible Automated Manufacturing Systems* (FAMS): the manufacturing systems that will be called FAMSs are a subset of both the set of flexible manufacturing systems (i.e. manufacturing systems with flexible characteristics) and the set of automated manufacturing systems (see Fig.1.1). For the time being it is sufficient to describe FAMSs as automated manufacturing systems with the ability to manufacture a variety of product types without long change–over times. In Chapter 3 we will give a more precise definition.

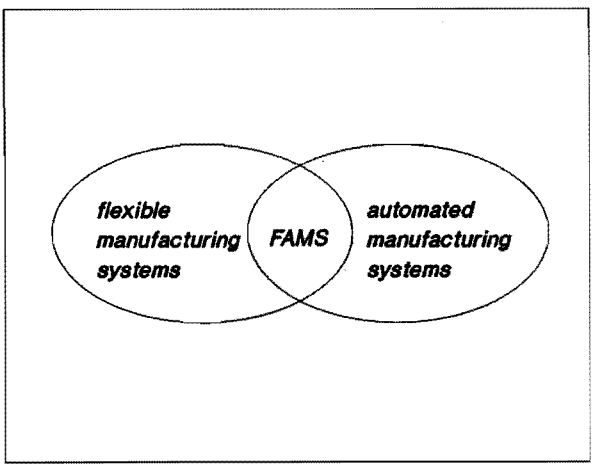

Figure 1.1:
Flexible Automated Manufacturing Systems as a subset of the set of flexible manufacturing systems and the set of automated manufacturing systems.

Hartley states that *"...with FMS it is practical to combine high productivity with small batch sizes and short lead times..."* [Hartley, 1984]. He proceeds to state that although FMS also reduces direct labour costs, a larger gain can be achieved in reduced overheads and reduced work-in-progress. According to Hartley another advantage of FMSs is the possibility of maintaining a high standard of quality by a high level of automation. Also the plant size can be reduced drastically. Furthermore these manufacturing systems incorporate a level of flexibility that is required to cope with the increasing fluctuations and changes in the market. Finally, an FMS makes it possible to increase the capacity of a plant with one or two unmanned shifts.

1.2 Diffusion of flexible automation in manufacturing systems

In order to be able to understand the importance of FAMSs as an object of study, we will discuss the application areas of these systems. At first we will discuss their application in different manufacturing process areas. After that we will have a look at the geographic areas, i.e. the world-wide use of FAMSs.

1.2.1 Application in manufacturing process areas

The concept of FAMS is applicable to many processes. In this subsection we will discuss these applications based on an overview of literature.

Machining
Most FAMSs (especially the larger systems) are concerned with machining processes (see e.g. [Hartley, 1984], [Mortimer, 1984], [Bilderbeek and Kalff, 1985], [ECE, 1986]). Bilderbeek and Kalff state that about 75% of all functioning FAMSs containing several machines (or *multiple–FAMSs*) manufacture prismatic parts (cf. [ECE, 1986]). Multiple–FAMSs for rotation–symmetric parts are less common due to the lower unit value of turned components and due to the fact that especially in the automotive industries where most multiple–FAMSs are installed, these systems are frequently used for manufacturing e.g. motor–blocks and gearbox housings [Bilderbeek and Kalff, 1985]. However, "*...there is an increasing development in flexible machining of rotational parts requiring lathes and cylindrical grinding machines...*" [Mortimer, 1984]. Examples of a combination of a prismatic machining center and a flexible automated turret lathe can be found in [Bell and Bilalis, 1982] and [Aanen, 1988]. Most multiple–FAMSs are applied in the automotive industry and in non–electrical machinery industry [ECE, 1986].

Sheet metal work
Hartley states that among processes other than machining, the automated manufacturing of sheet metal components (folding, punching and shearing) is an important area for flexible automation [Hartley, 1984]. Also Warnecke concludes that sheet metal parts manufacturers have begun to make more extensive use of flexible manufacturing systems [Warnecke, 1985]. In this field important reductions of set–up times are reported by the Japanese. Ingersoll Engineers report on a number of installed systems around the world [Mortimer, 1984]. In the Netherlands an example of a multiple sheet metal FAMS can be found at DAF Trucks (the so–called automatic sidemember manufacturing system, see e.g. [Eijkemans, 1987]). According to the Economic Commission for Europe the chief obstacles in this field are the relative short processing times of metalforming operations and the handling problems [ECE, 1986].

Welding
Most welding FAMSs are built around industrial robots. Important achievements have been realized in spot–welding operations, especially in the automotive industry. "*...All major automotive manufacturers have installed robotized spot–welding lines...*" [ECE, 1986]. The key to the successful use of robots in welding FAMSs is the development of sensors [Hartley, 1984].

Assembly
In assembly there is a huge potential for flexible automation (see e.g. [ECE, 1986]). Again industrial robots are the central pieces of equipment in these FAMSs. Examples of multiple–FAMSs in assembly can be found in [Drexel, 1982], [Hartley, 1984], [Sweeney et al., 1984], and [Vrakking, 1988].

Other
The concept of FAMS also can be applied in several other areas. The Economic Commission for Europe mentions surface treatment, inspection

and testing (systems for these processes often are included in larger FAMSs), and non-metal-manufacturing processes (like plastic and wood) [ECE, 1986]. Hartley states that even in foundry, forge and moulding shops, FAMSs are becoming more and more likely to be introduced in the manufacturing process [Hartley, 1984].

1.2.2 Application in geographic areas

As there is no generally agreed definition of F(A)MS, it is difficult to derive any accurate estimate on the number of installed FAMSs. Furthermore, not every source used for this overview uses the same kind of data. Therefore we can only provide an indication of the worldwide application of FAMSs.
Ito gives an overview of the diffusion of multiple-FAMSs up till 1984 in four geographic areas, i.e. Japan, the USA, Western Europe, and Eastern Europe ([Ito, 1988]; see Fig.1.2).

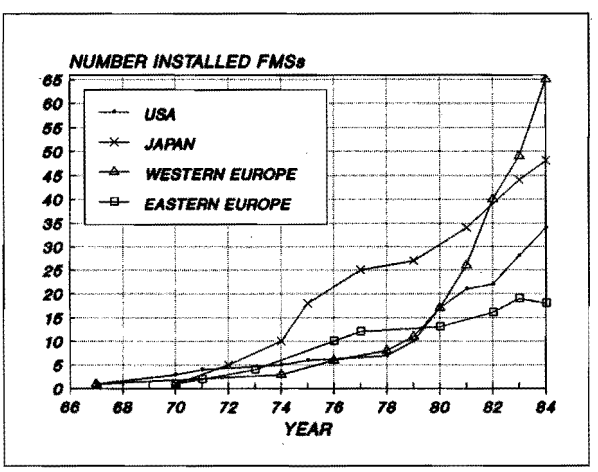

Figure 1.2:
Diffusion of Flexible Manufacturing Systems [Ito, 1988].

As we may conclude from the figures presented in [ECE, 1986], the number of installed FAMSs is (or at least was in 1986) still growing. This conclusion is supported by the estimate Spur gives of the number of cells installed in the USA (see Fig.1.3) [Spur, 1988].
Finally, in Figure 1.4 an overview is given of the world wide distribution of F(A)MSs in 1986 according to [Raju, 1988]. At that time about 370 F(A)MSs were installed worldwide.

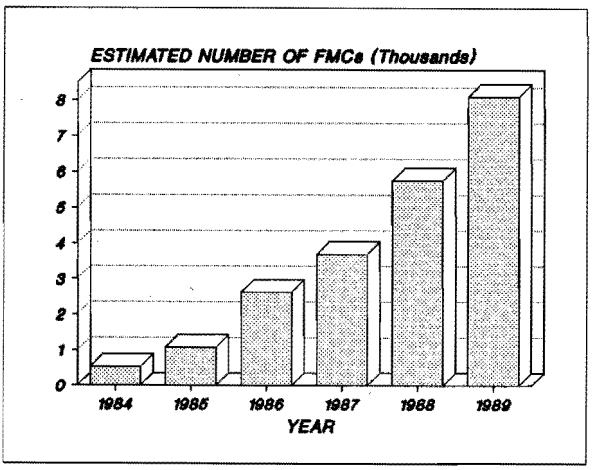

Figure 1.3:
Estimated growth in use of cells in the USA [Spur, 1988].

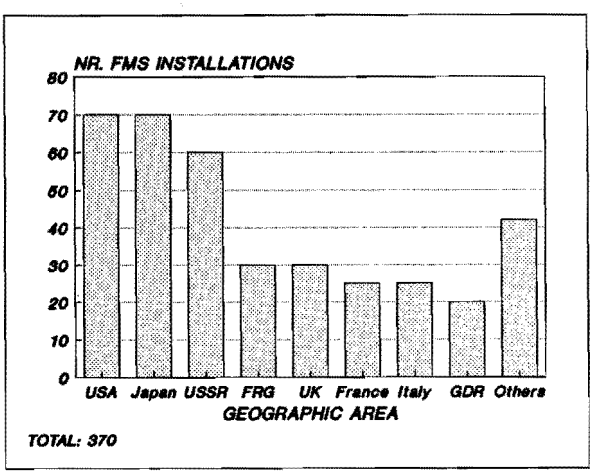

Figure 1.4:
FMS installations around the world in 1986 [Raju, 1988].

Bilderbeek and Kalff state that the marketshare of small FAMSs (single machine systems with some extra handling equipment) is growing rapidly, especially in Japan [Bilderbeek and Kalff, 1985]. According to the Economic Commission for Europe the number of single-FAMSs with extra handling equipment in 1986 was at least several tens of thousands [ECE, 1986].
Also in the Netherlands the number of installed systems is growing (see e.g. [ECE, 1986]). Krabbendam gives a description of five installed FAMSs [Krabbendam, 1988]. Vrakking also describes several projects on the introduction of FAMSs in the Netherlands [Vrakking, 1988].

1.3 Problems concerning FAMSs

There are many important research issues concerning FAMSs. This study addresses only one of these issues, i.e. the production control in case of a special type of FAMSs (viz. FAM-Stations) in low volume component manufacturing shops. The next subsection introduces this central subject. In §1.3.2, the problem will be illustrated with a case description. In the last subsection of this paragraph other important research issues will be discussed together with the contribution of our study to these issues.

1.3.1 Problem formulation

The central issue in our study is production control in case of low volume component manufacturing shops including FAM-Stations. In order to understand this central issue more clearly, we will discuss briefly the three major components of this problem formulation, i.e. production control, low volume component manufacturing shops, and FAM-Stations.

Production control
According to Burbidge *"...production control is the function of management which plans, directs, and controls the material supply and processing activities of an enterprise..."* [Burbidge, 1971]. Together with Burbidge we would like to note that production control also includes planning and directing of activities. The primary aim of production control is to achieve a specific delivery performance (see also [Bertrand and Wijngaard, 1984]).
The judgement of the total performance of a production system should be derived from the main areas of interest of the customer. Generally speaking these areas of interest are:
- the price of the product;
- the actual function(s) of the product (i.e. the quality of the product);
- the time and place of delivery (i.c. the delivery performance).

In this study, we are especially interested in the delivery performance of the production system. However, whenever the delivery performance conflicts with the performance measures concerning the other interests of customers, we will take this into account.
We assume that already decisions have been taken concerning manufacturing planning, including decisions on product design, facility planning (inclu. layout planning), and process planning. The main remaining

decision variables are the timing, volume and types of products to be produced using one or more capacity resources (see also [Bertrand and Wortmann, 1981]). One of the basic causes of production control problems is the fact that these capacity resources are scarce. Therefore, Burbidge states that the secondary aim of production control is to carry out the material supply and processing activities *"...in such a manner that the labour, plant, and capital available are used to the best advantage..."* [Burbidge, 1971].

Low volume component manufacturing shops
The production control problems in different production environments are very different. Therefore, we will restrict our study to those component manufacturing shops in which the manufacturing process of a part can be described as a single sequence of operations. In other words, we assume no major assembly operations. A further restriction will be that the number of parts produced of each type of product is assumed to be low (i.e. low volume manufacturing). As a result, production batches are small and parts are made to order. Finally, because FAMSs mainly are applied in machining processes, we will especially focus on machining shops.

FAM-Stations
In the Netherlands, only recently industry has started investment programs in FAMSs (see e.g. [Vrakking, 1988]). In many cases, these (initial) investments concern single-stage FAMSs, i.e. FAMSs in which all manufacturing processes to be performed by the system on a particular part loaded on the system, are carried out on only one machine. In other words, once the part is loaded on the FAMS, it will visit only one machine (as opposed to multi-stage FAMSs where a loaded part will visit several machines). Therefore, we will restrict our study to these types of FAMSs. In Chapter 3 we will call these single-stage FAMSs *FAM-Stations*. Often FAM-Stations are stand-alone systems, that are part of a larger manufacturing system (i.e. parts not only require operations on the FAM-Station, but also on other machines).

1.3.2 Case description: the MF-Case

In order to illustrate the problem area, we will give an example of a real life case concerning the use of two FAM-Stations in a machining shop that is part of a Machine Factory (see also [Dirne, 1989]). We will call this case the Machine Factory Case, or MF-Case.
The Machine Factory produces modules for complex products like a Multiple Chip Mounting machine and X-Ray equipment for material analysis. The factory produces to customer order, because there is no guarantee on the repeat of a demand for a particular product and because the required delivery time is equal to or longer than the time it takes the factory to produce the products. Apart from the two FAMSs, the machinery equipment in the machining shop consists of a couple of machining centres, some stand-alone CNC machine tools and several other conventional work stations.
Each FAM-Station consists of a four axes machining centre, an automated pallet changer and a pallet storage system (see Fig.1.5). Parts are loaded on a FAM-Station using positioning tools that are mounted on pallets. The pallets automatically circulate through the system. The machining centres

are capable of performing manufacturing processes like milling and drilling on parts with a maximum size of 635 by 500 by 630 (mm).

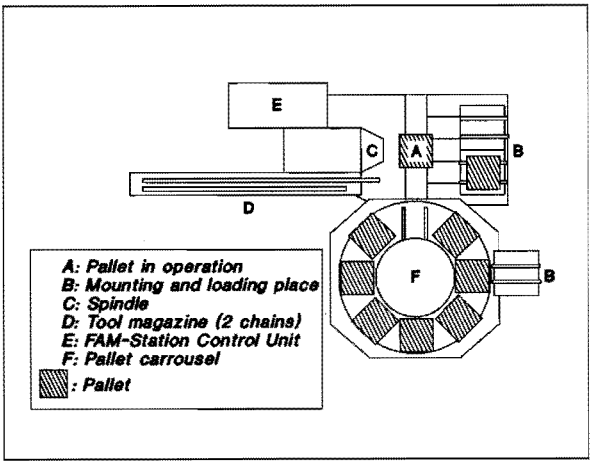

Figure 1.5:
Schematic overview of one FAM–Station in the MF–Case.

Certainly the FAM–Stations are *flexible* in some aspects. The flexibility of the systems mainly stems from the possibility to exchange parts of different part types without loss of machine productivity: exchanging parts between the machine area and the part storage area only requires a few seconds. Parts can be loaded on and unloaded from the system using the pallet mounting and loading places, thus preventing the machining centre from getting idle.
Although the FAM–Stations are flexible in some aspects, they also introduce some extra *constraints*. A 'new' constraint introduced by the manufacturing systems is a constraint on the number of available positioning tools. For instance, for most type of fixtures only one fixture is available. In case of conventional machines this constraint is not really a problem, because at any time only one part is loaded on a pallet using positioning tools. However, in case of the FAMSs at the same time more parts will be loaded on pallets using positioning tools because of the use of an automatic pallet storage system. Therefore, the number of parts on the FAM–Station using the same tool is limited. Another constraint introduced with these FAMSs is the number of tool pockets required to store all of the necessary cutting tools for all of the parts loaded on the system. Depending on the mix of parts on the system, the number of available tool pockets in the tool magazine that is attached to the machining centre, may be too small. Again, the mix of parts on the system is constrained. Therefore production control should consider the consequences of these new constraints.

These and other typical characteristics of the FAMSs made it necessary to analyse the consequences of the introduction of these manufacturing systems in the machining shop for the production control system. Some of the other questions management had concerning the production control of these systems, were:
- The FAMSs have the possibility of producing unmanned for several hours. Are there any adjustments required in the production control system in order to be able to use these possibilities?
- The FAMSs are very flexible in changing between part types. Is it possible and profitable to adjust lot-sizes because of that flexibility?
- With the introduction of the pallet carousel, management observed an *increase* in flow time. What is the cause of this increase and how should order flow times be estimated?

1.3.3 Related problem areas

Because of the (potential) complexity of FAMSs, these manufacturing systems also require many other problems to be solved in order to be able to use them properly and adequately in industry. In order to understand the contribution that we would like to make with our study, we will have a closer look at some of these other major issues concerning FAMSs, viz.:
- the technology;
- the economical justification;
- the design of the manufacturing system;
- the organizational structures;
- the infological structures.

Technological issues
A prerequisite for the introduction of FAMSs is the technological availability of these systems. In each manufacturing system we can distinguish three subsystems, each with its own technological characteristics and problems, viz. the systems for carrying out the operation processes, the handling systems, and the process control systems (see also [Sanders, 1985]). Interesting topics in each field are (among others):
- Process technology:
  - Automatic inspection systems;
  - Machine tools (speed, accuracy, rigidity of structure etc.).
- Handling technology:
  - Robotics.
- Control technology:
  - Integrating different subsystems (especially the integration of different software systems, not only horizontal integration (i.e. between software systems for the control of the different elements of the manufacturing system), but also vertical integration (e.g. between software for controlling manufacturing systems and the software for process planning));
  - Sensor and actuator technology (in order to transform quantities as pressure, temperature, light etc. into electrical signals and vice versa).

In our study we accept the manufacturing system as it is. However, as we will see, the technology used in the system will affect the nature of our problem. Therefore, from our study conclusions may be drawn regarding future research requirements in this field.

Economical issues

A second problem area is the economical justification of FAMSs. Often investments in FAMSs are high. As Meredith and Suresh state *"...the basic problem is that many advantages of these new manufacturing technologies lie not in the area of cost reduction, but rather in more nebulous, 'strategic' areas.....Yet, since these manufacturing systems are largely equipment based, and manufacturing equipment has historically been justified on the basis of cost reduction or capacity expansion, these systems are typically expected to be justified on these same measures..."* [Meredith and Suresh, 1986]. A study of the Economic Commission for Europe supports these remarks and concludes that *"...a major problem....is the quantification of these benefits and their accounting in the investment justification..."* [ECE, 1986]. Also Willenborg seems to agree with them as he states that the benefits of FAMSs are difficult to quantify and often are realised only after a long period of time [Willenborg, 1987]. More extensive remarks on similar issues are made by Kaplan and Atkinson [Kaplan and Atkinson, 1989].
In our study we assume that the FAMS already is implemented and thus also has been (economically) justified in some way. However, from our study conclusions may be drawn concerning the validity of the assumptions made in the justifications and the consequences of these assumptions for the use of these systems.

Design issues

The next problem concerning FAMSs is the design of the manufacturing system. Stecke distinguishes two categories of design decisions, i.e. the initial specification decisions and the subsequent implementation decisions [Stecke, 1985]. The first category includes decisions on the range or families of products to be produced by the system, the determination of the required manufacturing process for these products, the required types of flexibility, the type of FAMS required, and the specification of the subsystems of the FAMS (especially the material handling system and the buffers). Also the required computer configuration of the system has to be determined. Finally a selection of vendors has to be made. The second category of design decisions includes decisions like the determination of the layout of the FAMS, the number of pallets, the number and design of positioning tools, some general strategies for running the FAMS, and the software development tasks.
Van Looveren et al. make a similar distinction [Van Looveren et al., 1986]. They distinguish a technical design part and a economical design part. The technical design part includes the selection of the parts spectrum, the determination of the manufacturing requirements, and the examination of the technical alternatives. However, since the FAMS also has to perform well with respect to economic criteria, the second part of the design process includes *"...a preliminary economic evaluation of alternatives in order to identify inefficient designs. The criteria are system performance measures like utilization and production rates..."*. The above mentioned problems concerning the economic justification of FAMSs play an important role in this part of the design process. However, also problems like the determination of the number of pallets and fixtures are included in the economical design part. Van Looveren et al. also give an overview of several studies concerning (some of) these design issues [Van Looveren et al., 1986]. Other overviews concerning the use of OR-models in the design problems of FAMSs, can be found in [Kusiak, 1986] and in [Dupont-Gatelmand, 1986].
If appropriate and possible, we will discuss some of these problems in our study. Again, we assume the FAMS already to be designed and installed.

Therefore we will assume that only decisions on the selection of products, the strategy for running the system, and on (the use of) positioning tools and pallets can easily be altered, for instance in order to cope with operational problems.

Organizational issues
A fourth category of problems concerning FAMSs is the category of organizational measures and structures required for implementing and running these manufacturing systems. As Krabbendam points out, organizational measures might be necessary on the floor (i.e. concerning the manufacturing system), in maintenance, in process planning, in production control, and in quality control [Krabbendam, 1988]. A socio-technical study on the design of flexible production systems (not limited to FAMSs, but including CAD/CAPP/CAM issues as well as organizational issues) has been carried out by de Sitter et al. [de Sitter et al., 1986]. A comparison between the socio-technical approach and the *"...more critical 'labour process' perspective..."* can be found in [Jones and Scott, 1986]. They remark that both approaches tend to overemphasize the impact of technology per se. Hannam gives an interesting overview of the common practice in the organization of FAMSs in the USA [Hannam, 1985]. The conclusion is that in the USA FAMSs are operated minimally manned rather than unmanned. The reason is the high investment required to make unmanned production possible. Further, when an operator is required for one task, his presence might as well be exploited for other tasks as well. The team approach is being increasingly adopted. Hartley discusses the required training of *"...everyone who has any direct contact with an FMS in his job..."* [Hartley, 1984].
In our study, the organization around th FAMS will be taken into account if it affects the production control structure (or vice versa).

Infological issues
The last category of problems concerning FAMSs that we would like to mention, are the issues concerning the information structure required for controlling the system. The issues studied concern the architecture of information systems (both hard- and software), and often include all control functions required in a manufacturing environment (e.g. production control, process planning, process control). An interesting study in this field is being carried out by the National Bureau of Standards in the USA. They are building a laboratory that simulates a possible real production situation (the so-called Automated Manufacturing Research Facility (AMRF); see e.g. [McLean et al., 1983] and [Jones and McLean, 1984 and 1986]). Recently in the Netherlands similar studies are being carried out (see e.g. [Verver et al., 1985] and [Bakker, 1989]). Many of these issues are referred to as CIM-issues (CIM stands for Computer Integrated Manufacturing).
Our study has a different perspective. We are primarily interested in the production control aspect of the problem (see §1.3.1). For this category of control problems we will suggest control structures. These control structures could be used for the design of the overall control and information structures. However, in order to be able to build such an overall control structure also other inputs are required, such as the process control structure (i.e. the structure required to control the physical manufacturing process) and the process planning structure (i.e. the structure required to create and distribute process plans).

1.4 Study overview

In this last paragraph of Chapter 1, we will present a general overview of our study. We will start with a brief discussion on the methods used in the study. In the second subsection of this paragraph we will give the outline of this book, and introduce briefly the subjects of each chapter.

1.4.1 Study methods

As we have seen, the aim of our study is to discuss the production control issues of FAM-Stations in low volume component manufacturing. The formulation of the specific FAM-Station production control issues is based on three detailed real life case studies (one of which is the MF-Case, see §1.3.2). A further verification of these production control issues was found in several one-day visits to other companies, and in literature.
Simultaneously, the FAMS production control issues discussed in literature were reviewed. By comparing these production control issues with the production problems found in the case studies, it was possible to determine the applicability of the results described in literature. Furthermore, by studying the production control problems discussed in literature, a further and more detailed understanding of the specific control issues for FAM-Stations was obtained.
In order to study the order flow on FAM-Stations in more detail, we have developed a simulation model. The simulation program based on this model has been verified using both special problem settings already known in literature, and detailed event-based simulation output reports. Most data used in the simulation runs are derived from the detailed case studies. In order to generalize the results, sometimes also more extreme data have been used. Unfortunately, it was not possible to compare the results from the simulation experiments with real life results, since in the cases we have studied no historical data were available for comparison. However, the observations in the simulation experiments were compatible with the experiences of the people in the three companies of the case studies.

1.4.2 Outline of this book

If we take a close look at the contents of this book, we can distinguish three sets of chapters. The first set includes the Chapters 2, 3, and 4. In these chapters the central subject of our study is introduced in detail. In the second set of chapters, the production control issues typical for FAM-Stations in low volume manufacturing are addressed at. Apart from some specific capacity considerations, these typical production control issues concern the order flow times in manned and unmanned production modes. These production control issues are discussed in Chapter 5 up to and including Chapter 8. In the last set of chapters, including Chapter 9 until Chapter 11, the consequences of the production control issues studied in the previous chapters for real life situations are discussed.

Introduction of FAM-Station production control issues

In Chapter 2 an overview is given of some important production control concepts and structures, applied to component manufacturing shops. The reason for this overview is twofold, viz.:

- In many cases FAMSs are introduced gradually. Instead of the creation of an entire new production control system, the existing production control system is adapted. This requires knowledge of the concepts and structures of these systems.
- In order to be able to describe FAMSs and the related production control problems, a language is required which is applicable to production control. The overview presents such a language.

As we will see, production control is concerned especially with capacity considerations and order flow time considerations.

The third chapter gives a detailed discussion on FAMSs. Apart from a definition of an FAMS, the chapter also presents a typology of FAMSs based on production control considerations.

Most literature on production control issues for FAMSs concern multi-stage systems, i.e. FAMSs where each part after being loaded on the system, visits two or more machines before being unloaded from the system. In order to understand the applicability of the results for these systems to our problem, and to clarify from a production control point of view the important differences between these multi-stage systems and the single-stage FAM-Stations, we discuss in Chapter 4 the production control issues for both cases.

Study of FAM-Station production control issues

As we will see, not all operations on FAM-Stations can be performed in the unmanned production mode. In fact, most operations still require the continuous attendance of an operator, and therefore can only be carried out during manned shifts. In Chapter 5 we will discuss the implications for the capacity concepts to be used of the distinction in manned and unmanned production mode on the one hand, and attended and unattended operations on the other hand.

One of the major production control issues typical for FAM-Stations in low volume component manufacturing is the fact that work orders are not produced anymore one after the other, but more or less simultaneously. On top of that, apart from manned shifts, it also is possible to produce parts in unmanned shifts. In Chapter 6 we will study the impact of the simultaneous production of work orders on the flow times in the manned production mode. In Chapter 7 the flow time implications of the use of unmanned shifts are studied.

In Chapter 8 we focus on the flow time estimates required by Production Control. Clearly, the results from Chapter 6 and Chapter 7 will be frequently referred to.

Consequenses for real life situations

The implications of the results obtained in the previous chapters for all relevant production control functions, will be discussed in Chapter 9. In Chapter 10 we will extend our view and address the implications of the changes in Production Control for other production functions. Finally, we will summarize the main conclusions of our study in Chapter 11.

Chapter 2
PRODUCTION CONTROL IN COMPONENT MANUFACTURING SHOPS

In this chapter we will have a look at the production control problems and structures in component manufacturing shops. In the first paragraph we will discuss the reasons for using hierarchical production control structures. After that we will build a conceptual framework in order to describe production control problems in more general terms. As we will see, this framework is based on a bottom-up description, using aggregate terms. Finally, we will discuss the production control structure in component manufacturing shops using a top-down approach.

2.1 Reasons for using hierarchical production control

In §1.3.1 we stated that the aim of production control is to achieve a specific delivery performance by coordinating material supply and processing activities in such a manner that the available capacity resources are used to the best advantage. Often this problem is quite complex. In fact, both in practice and in theory it seldom will be solved as a single level control problem. Building a model that describes the entire production control problem is very complex (and may even be impossible). Not only the large number of variables makes it hardly possible to find such a model, but also the uncertainty on the behaviour of the variables, especially in the long run (see also [Bitran and Hax, 1977]).
Even if such a model can be found, it will be hardly possible to directly use such a model in practice. Three reasons can be mentioned for this:
- it might be hard (sometimes even impossible) to gather all data required in the model;
- the complexity of the model makes it hard to organize production control in practice (i.e. to define separate decision functions);
- it may be impossible for decision makers to interpret the (results of) calculations.

In other words, the production control problem is not how to solve the model of the problem, but how to solve the real life control problem using the strengths and capabilities of a certain organization.
Finally, even if these practical problems can be solved, it may be doubted if the marginal benefit of using such a complex model is worth the required extra effort. Often simpler models can achieve reasonable good results with far less effort.
Therefore, often a hierarchical control structure is used. In this structure several decision functions are defined, each solving a subproblem of the

entire production control problem [Bitran and Hax, 1977]. These subproblems may differ from the entire problem in the considered time horizon and in the considered (sub–)system (e.g. only department A, or work centre X; Bitran and Hax use the term 'scope of planning activity' [Bitran and Hax, 1977]). As we will see, a third important difference between the subproblems is the level of detail of the required information, i.e. the aggregation of information. The subproblems are less complicated than the entire production control problem. However, defining several subproblems instead of one main problem reduces the decision freedom of production control [Bertrand and Wijngaard, 1984]. Therefore, they should be defined in such a way that enough decision freedom remains to cope with unexpected events.
We would like to note that a distinction in decision functions does not require also a distinction in organizational functions and/or decision makers. After we have determined the necessary decision functions, we are 'free' to allocate them to one or more organizational functions. In other words: a hierarchical production control structure does not necessarily require a multi–level hierarchical organization. In fact, both from a production control point of view and from a socio–technical point of view, there are good reasons to allocate most of these decision functions as low in the organization as possible (see e.g. [de Sitter et al., 1986]). However, often some decision functions, in particular the goal setting decision functions, should be allocated to higher levels, e.g. management functions. To which organizational function a particular decision function should be allocated is highly dependent on the possibility of the organizational function to influence the decision variable(s), and on the span of control of the organizational function.

2.2 Concepts for Hierarchical Production Control

In (hierarchical) production control systems several general concepts are being used. These concepts describe the production control problem in general terms, and therefore can be used in almost any situation where hierarchical production control structures can be applied. A starting point for this description has been the research of Bertrand and Wijngaard [Bertrand and Wijngaard, 1984]. However, we have slightly extended and adjusted their concepts.

Transformations

Several *transformations* on materials and/or parts are required in the process of the production of products. We distinguish three types of transformations, i.e.:
- transformation in physical appearance (e.g. shape, size, composition);
- transformation in position;
- transformation in time.

The first kind of transformation could be a real change in physical characteristics (i.e. a physical transformation), or merely a change in the information about the physical characteristics (i.e. a testing or inspection transformation). The second type of transformations can be split up into transporting activities (between two locations) and material handling activities (at a location). Position transformations in the manufacturing

process are required to be able to perform the basic transformations (i.e. transformations in physical appearance). The last kind of transformations concerns the storage of products.

Capacity resources and types
In manufacturing one or more transformations are required to obtain the product. In order to perform these transformations we need *capacity resources*. Examples of capacity resources are an operator, a transportation vehicle, a cutting tool, and a machine. Capacity resources with identical characteristics (for our study this means identical from a production control point of view) are said to be of the same *capacity type*.
Often one of the basic causes of production control problems is the fact that in a manufacturing system capacity resources are scarce. As we have seen in §1.3.1, one of the goals of production control is the minimization of the costs involved in achieving a specific delivery performance. Therefore, one of the goal variables of production control is the capacity utilization. In order to understand this capacity utilization, we need to introduce several capacity concepts. In Fig.2.1 these capacity concepts are given.

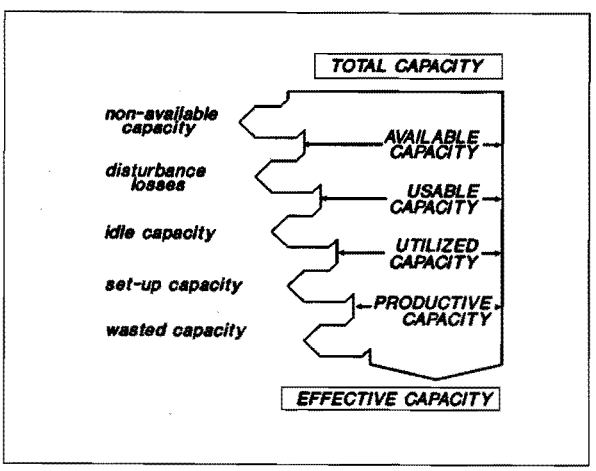

Figure 2.1:
Capacity concepts for a capacity resource.

The *available capacity* of a capacity resource can be defined as the amount of work load a capacity resource can complete in a period of time during the time the resource is planned to be available for production. The complement of the available capacity will be called the *non-available capacity*. For example, in case of a machine in two shifts of 8 hours each, five working days a week, a planned maintenance period of one week a year, and a general factory vacation period of two weeks, the available capacity per year will be 3920 hours/year.
A part of the available capacity is lost for production because of unplanned disturbances, e.g. break-downs and corrective maintenance (in case of machines), or absenteeism (in case of operators). Therefore, we define the *disturbance losses in capacity* as that part of the available capacity that is

lost due to disturbances in the availability of a capacity resource. Subtracting these disturbance losses from the available capacity gives us the *usable capacity*. In consequence, we define the *disturbance rate* of a capacity resource as follows:

disturbance rate = 1 – (usable capacity / available capacity)

Of the usable capacity some capacity may be lost because there is no work available. This lost capacity will be called *idle capacity*. If we subtract idle capacity from the usable capacity, we get what we will call the *utilized capacity*. The utilized capacity is that part of the available capacity which actually is being used for production. The *utilization rate* of a capacity resource can now be defined as the fraction of the usable capacity of the capacity resource that is being utilized. In other words:

utilization rate = utilized capacity / usable capacity

A part of the utilized capacity is used for non–productive purposes, viz. set–up activities. During the set–up time no output is produced. We will call this part of the available capacity of a capacity resource the *set–up capacity* of the capacity resource. The remaining capacity will be called *productive capacity*. The *productive use* of a capacity resource is defined as the fraction of the available capacity during which output is being produced, or:

productive use = productive capacity / available capacity

Finally a part of this productive capacity may be lost because of product quality reasons, i.e. when the output is rejected or should be repaired. We define *effective capacity* as the part of the productive capacity that results into accepted output. The difference between productive capacity and effective capacity will be called *wasted capacity*. The *effective use* of a capacity resource is defined as the fraction of the productive capacity of the resource during which accepted output is produced. In other words:

effective use = effective capacity / productive capacity

Clearly, none of the fractions given above can get larger than 1.0. Only if we compare for administrative purposes planned (e.g. budgeted) capacity with realized capacity, we may obtain a fraction larger than 1.0.

From a capacity point of view, production control is interested in two quantities, i.e.:

- the number of hours a capacity resource can be used for production. The usable capacity is regarded as the maximum capacity of a capacity resource.
- the effective capacity of capacity resources. One of the goals of production control is the minimization of the costs involved in achieving a specific delivery performance. The higher the effective use of capacity, the lower the (fixed) costs per unit of effective capacity will be. If we assume that the wasted capacity cannot be influenced by production control decisions (which is not always the case), this interest in effective capacity can be translated into interest for productive capacity, or in other words in the productive use of resources.

Server
Often a combination of capacity resources is required to perform a certain transformation. For instance, a combination of a cutting tool, a machine tool, a fixture, and an operator may be required to perform a physical transformation. To be able to perform such a transformation, the presence of all required capacity resources is equally vital. In other words, at the start of the transformation all capacity resources should be available (or known to become available if the capacity resource is not required at the start of the transformation, but at some time during the transformation). However, often not all capacity resources are equally scarce. Therefore, in order to evaluate the possibility of executing a transformation a considerable time before the start of the transformation, checking the availability of the scarce capacity resource(s) will be sufficient. In that case it is assumed to be possible to organize the availability of the other required capacity resources later on (by lower levels of control). This is the reason why, instead of modeling each capacity resource separately, an aggregate concept is being used. In accordance with queueing theory, we will use the concept of a *server*. In this text a server is defined as a set of (scarce) capacity resources that from the point of view of a particular production control function can be modeled as a unit of capacity. Examples of a server can be a single man/machine system, but also a complete manufacturing line, and even a complete factory. In other words, we can model a production system as a hierarchy of servers. In Fig.2.2 an example of such a hierarchy is given.

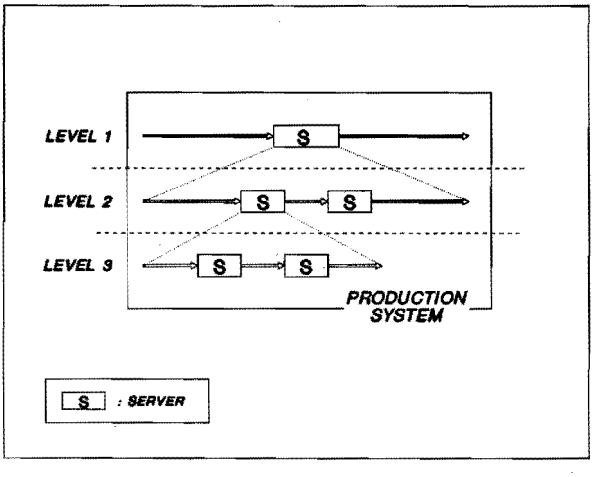

Figure 2.2:
A production system modeled as a hierarchy of servers.

For the concerning production control function the server is a black box with certain operational characteristics, being:
- time required to perform all transformations (i.e. transformations in physical appearance, in position, and in time);

– capacity constraints of the server (if any);
– state of server input and output.
The manufacturing process itself is a responsibility of the server. The production control function at hand is only interested in the output of the server. As long as the server constraints are not violated, the production control function may assume a certain delivery performance of the server, expressed in the mean time spent in the server, and in the reliability of the predicted time. Therefore, a prerequisite for the use of this concept is the possibility to predict the time required by the server for all transformations required.

Server characteristics
A server can be single– or multi–dimensional, depending on the number of server constraints. In case of a *single–dimensional* server, checking the capacity of one capacity resource will be sufficient. In other words, one scarce capacity resource is dominant. This capacity resource is called the *bottleneck* of the server. In many non–automated situations the bottleneck capacity will be the operator capacity. In case of a *multi–dimensional* server the (expected) usable capacity of more capacity resources should be checked. In many cases the same capacity resources remain the bottleneck capacities of the server for a long period of time. In some cases bottlenecks may shift from one capacity resource to another. From a production control point of view, a single–dimensional server is the most simple server.
Frequently servers share a particular capacity resource. This creates interactions between servers. As long as this capacity resource is not scarce, production control will neglect these interactions. However, sometimes the capacity resource that is being shared among servers, is scarce (e.g. operator capacity in the case of a dual constraint capacity system; see e.g. [Fryer, 1973]). In that case these servers are said to be *coupled.* The shared capacity resource (often an operator) is said to have a *multi–functional* nature [Bertrand and Wortmann, 1981].
Servers may show *set–up states.* A server in a set–up state can be defined as a particular set of capacity resources combined in such a way that the set is suitable for the production of a particular set of product types. Within a set–up state, some minor adjustments might be necessary in order to be able to produce a particular product type belonging to the set of product types mentioned. However, these adjustments require far less time and effort than the changes between set–up states.
If a server is able to process more than one product simultaneously, it may face *mix problems.* A mix problem means that a particular server can only produce products at the required speed if the mix of products satisfies certain constraints [Dirne, 1987].

Production orders
Orders for a particular server concerning the production of a batch of products, are called *production orders.* The level of control generating a production order will be called the *order–generating level,* whereas the level of control receiving the production order will be called the *order–receiving level.* The order–generating level of control usually considers the set of products belonging to the same production order to be a unity. This means that the production order is considered to be completed as soon as the last transformation on the last product belonging to that order is finished. Creating a set of products belonging to the same production order is known as *lot–sizing.* Often this set of products is determined by:
– the product requirements: if a certain quantity of a product is required at the same time, production control should not be focused on the

delivery of single products, but in the delivery of the entire quantity;
- the operational characteristics of the servers: if the servers show set–up states, combining a number of products (very often of the same type) in one production order is a way to avoid as much as possible the loss of usable capacity due to required set–up capacity.

What is regarded as a production order by one particular production control function, might be different from the relevant production orders for another production control function. Sometimes production orders for a higher level (i.e. more aggregated) server are split up into several sub–orders or are combined for lower level servers. The reason for this split up or combination is that due to specific characteristics of the lower level server, the products are processed by the lower level server in a combination different from the production orders. An example of such a split up is given in Fig.2.3.

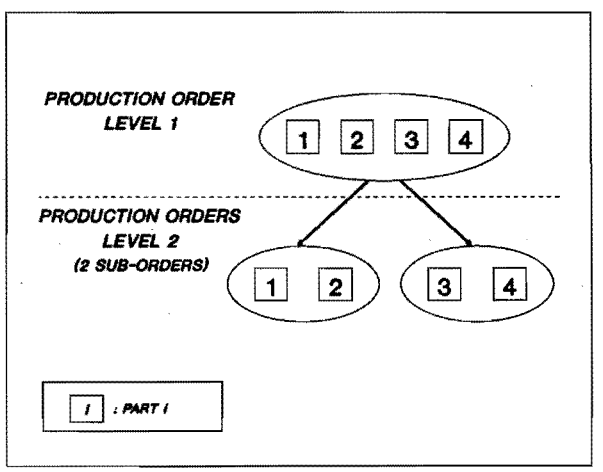

Figure 2.3:
A production order split up into several sub–orders.

In that case the lower level of control is focused on the progress of these sub–orders. If a split up is made, the lower levels of control should be aware of the fact that the higher levels of control often are not interested in the completion of one sub–order, but only in the completion of the entire production order.

Operations
Very often a particular sequence of transformations on a machine (or another scarce capacity resource) is considered to be fixed (i.e. these transformations are always performed subsequently in a given sequence on the capacity resource, without the interference of another transformation). Not only technical, but also production control considerations may cause such a sequence (e.g. because the change–over time between the transformations of this sequence is small compared to the change–over time

required to interrupt this sequence, change to other transformations and then return to the sequence). We will call such a sequence of transformations a *basic operation.* For production control the basic operation is the smallest entity considered; individual transformations are not considered.
The set of basic operations that according to the production control function at hand is to be carried out on the same server on a production order, will be called a *server operation* (or shortly: an *operation*). An operation is considered to be a unity by the production control function at hand; it is not subject to internal manipulation. For instance, in the manufacturing line of Fig.2.4 each machine performs a certain basic operation (o_j). If we model each machine as a server, every single basic operation will be defined as an operation. However, if the entire line is modeled as one server, the whole set of basic operations (O) will be defined as one operation.

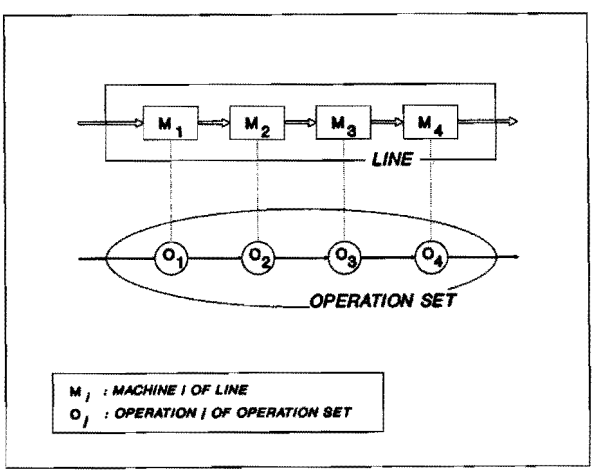

Figure 2.4:
The definition of operations on a manufacturing line containing several machines.

In order to complete a certain production order, often more than one operation is required. Such a sequence of operations is called the *process plan* of the production order. The sequence of servers required to perform this process plan, is called a *routing.*

Order flow time
Generally speaking, an order will have to wait in front of a server, because the server is occupied by other production orders. The time involved in this waiting will be called the *server waiting time* of the order. The time it takes the server to complete a certain production order is called the *service time* (see Fig.2.5).

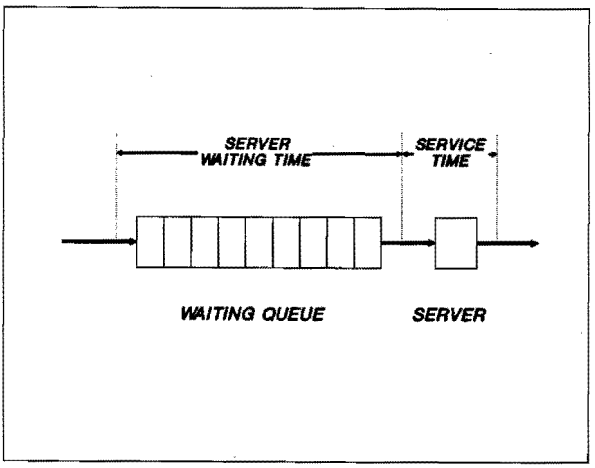

Figure 2.5:
Server waiting time and service time of an order.

The service time of a server may consist of:
- service time of sub–servers
- waiting time at sub–servers
- server set–up time
- transportation time to and from sub–servers.

Often these various time components can only be characterized by a probability distribution (especially in case of waiting time). The reason for this fact is that frequently one or more capacity resources may not be available (e.g. unexpected operator absenteeism, a machine break–down, a missing fixture), or that we simply are not able to control all of the important factors that influence these time components (e.g. the characteristics of the materials used, the accuracy of operator activities, wear and breaking of cutting tools). In other words, for a particular operation, servers may be *deterministic* or *stochastic* by nature. Of course deterministic servers are the most simple servers to control.

The time it takes to complete the entire production order (the *order flow time*) can be determined by adding up the several waiting times, transportation times and service times at each of the required servers. An exception should be made in case of operation overlapping, i.e. if it is not required to complete the entire production order at one server before the first part of the order is transported to the next server (see Fig.2.6).

Usually, production control problems are *dynamic* problems, i.e. during each production period new production orders may arrive that also have to be produced (as opposed to *static* problems, where all production orders to produce are available at the beginning of a certain production period). We know from queueing theory that in case of a stochastic dynamic production control problem, both the utilization rate and the service time are important for estimating the waiting times.

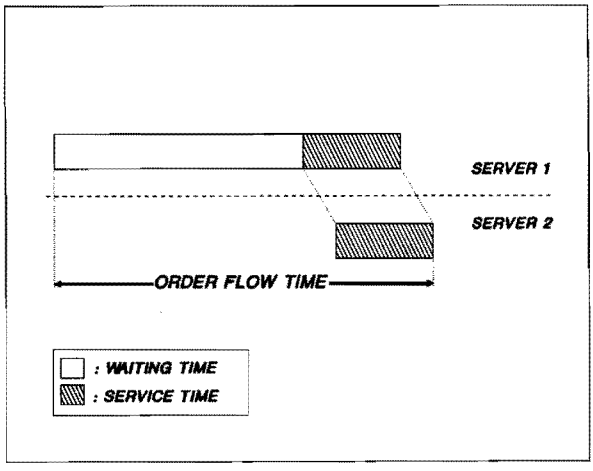

Figure 2.6:
Flow time consequence of operation overlapping.

Often a relation exists between utilization rate and waiting time that resembles the curve drawn in Fig.2.7. The average waiting time can be expressed as a multiple of the average service time of a server.

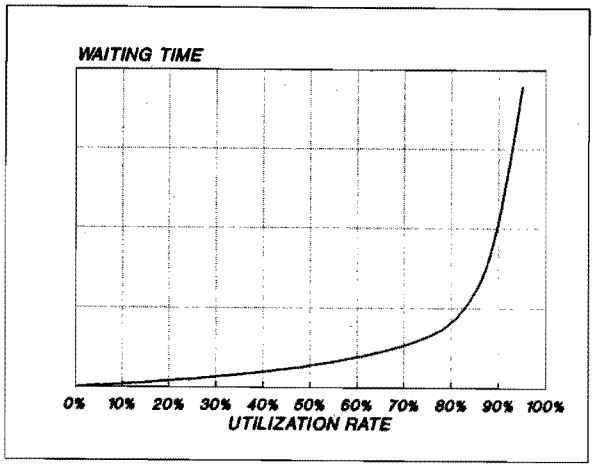

Figure 2.7:
Nature of relation between average waiting time and utilization rate.

For instance, assuming:
- a Poisson arrival process (i.e. the time between two arrivals of work orders at the server is negative exponentially distributed),
- a First Come First Served (FCFS) sequence,
- one server,

the expected waiting time of work orders can be determined with the so-called Pollaczek-Khinchin formula [Kleinrock, 1976]:

$$E(\underline{w}) = \frac{\rho E(\underline{x})(1+C^2(\underline{x}))}{2(1-\rho)} = \frac{\lambda E(\underline{x}^2)}{2(1-\rho)}$$

where:

$\underline{x}$:	service time at server;
$C^2(\underline{x})$:	variation coefficient of service time ($= \sigma^2(\underline{x})/E(\underline{x})^2$);
ρ:	utilization rate of server;
λ:	arrival rate of orders.

In many cases the order flow time is determined to a large extent by waiting time. A waiting time of more than 80% of the flow time is not uncommon in component manufacturing shops. As we can see in the Pollaczek-Khinchin formula, these waiting times and thus the flow times can be reduced by reducing the utilization rate. However, from a economical point of view, assuming that:
- the available capacity, the disturbance rate, and the effective use of a capacity resource are independent of the utilization rate,

and:
- the productive capacity is linear related to the utilized capacity,

a high utilization rate is desirable in order to produce parts at low costs. Therefore, a trade-off is required between utilization rate and order flow time.

Inventory

As we recall, we distinguish three types of transformations, viz. in physical appearance, in position, and in time. The transformation in time is being realized by *inventory*. Inventory has the function of decoupling the goods flow between two servers (see Fig.2.8). Reasons for decoupling the goods flow may be an unbalance in the availability or working speed of the two servers, or a difference in required lot-sizes. All the inventory inside servers is called *server inventory*.
The total inventory of a production system can be split up into two parts. First of all, inventory is being used to decouple production orders on a particular level of control (or vice versa: production orders are considered to be inventory replenishment orders). This inventory, of which both input and output can be controlled by production control, will be called *(controlled) stock*. Stock is stored in *controlled stock points* and may be kept for an indefinite time, since no production order exists (yet) that requires the inventory. In production control literature controlling this kind of stock is known as inventory control. As Bertrand and Wijngaard state *"...in practice we prefer to locate controlled stock points at places in the production structure where a substantial change occurs in the demand or production uncertainty..."* [Bertrand and Wijngaard, 1984]. For instance, we may create controlled stock points in case the lot-sizes required by the 'customers' are smaller than the lot-sizes required by the server. Other

reasons for controlled stock are for example output uncertainties like waste and flow times (safety stock), variations in the capacity demand (capacity stock), and convergency or divergency in the product structure (i.e. resp. when two or more components are required to create the product, or when out of one component several products can be created). A more extensive discussion on controlled stock can be found in [Bertrand and Wijngaard, 1984].

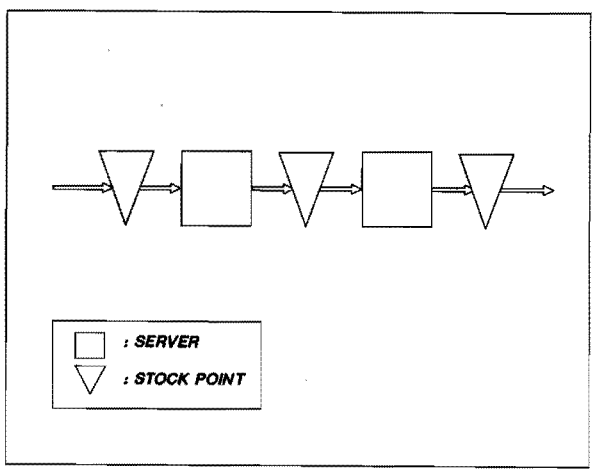

Figure 2.8:
Inventory decoupling servers.

The second part of the total inventory is called *Work–In–Progress* (or WIP–)inventory. Usually WIP–inventory just occurs undeliberately due to an unbalance between two subsequent servers (also known as queueing). Sometimes WIP–inventory is to some extent deliberately created to decouple two subsequent servers (e.g. in a transfer line). In both cases, for every part in the WIP–inventory a production order exists which is competing for capacity of the next server. In case of parts in controlled stock points, there are no production orders requiring these parts.

Production Control Levels

Each production control function is responsible for the progress of production orders requiring a particular set of servers (see e.g. Fig.2.9). The most simple situation to control is the situation where these servers are positioned in line; a complex situation to control is the case where servers are positioned in a network (see also [Burbidge, 1971]).
Using the concepts 'server' and 'production orders', we can define several levels of control. Each lower level of control (i.e. each order–receiving level) is responsible for the progress of production orders on the sub–servers of the server considered by the higher level of control (the order–generating level). As we have seen, both the order–generating level of control and the order–receiving level of control face the problem of controlling a set of

servers (see Fig.2.10). In other words: each order–receiving level may be at the same time an order–generating level.

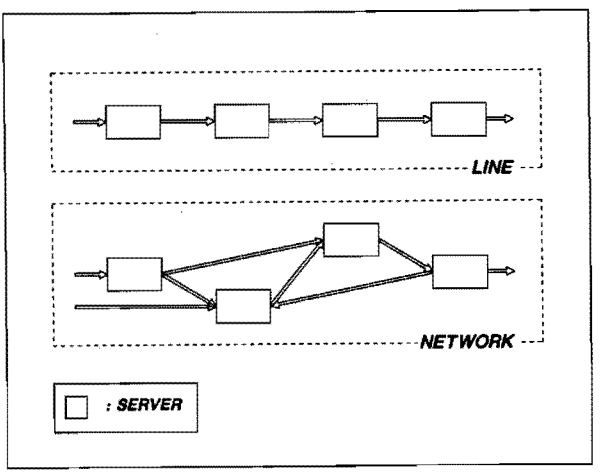

Figure 2.9:
A set of servers to be controlled by a production control function, resp. in line and in a network.

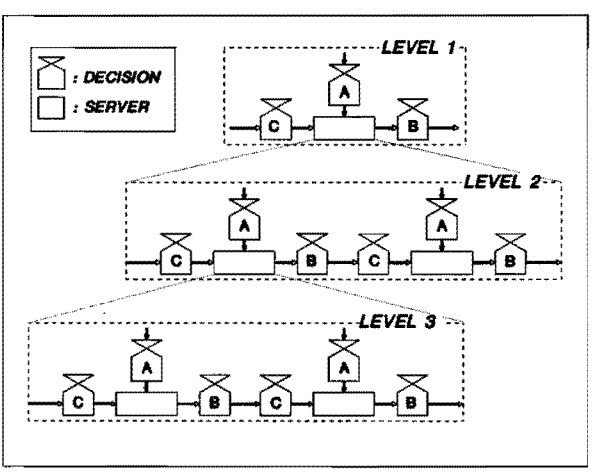

Figure 2.10:
Hierarchical production control
using the concepts of servers and production orders.

As is clarified in Fig.2.10, for each server three decisions are to be taken by production control. The exact procedures used to solve each of these decision problems, depend on the particular characteristics of both the servers and the environment of the production system.
The first decision concerns the *allocation of capacity resources* to servers (valves A in Fig.2.10). This decision is particularly important in case the set of capacity resources used in the system varies a lot, in case capacity resources have a multi-functional nature, or in case the demand for server capacity varies a lot.
Once an operation of the production order is completed, the next decision to take concerns the *allocation of the next operation* in the process plan to a particular server (valves B in Fig.2.10). Often there is only little freedom, if any, in this choice.
Finally, each order-generating level and order-receiving level of control are interconnected by a *order transfer* decision (valves C in Fig.2.10). As long as the production orders still are waiting in the queue in front of the server, the order-generating level of control is responsible for the order progress. As soon as the decision is taken to transfer the production order to the order-receiving level (and thus the production order is taken out of the waiting line), the responsibility for the progress of the production order is transferred also. The main goal of the order-receiving level of control is to behave according to the agreements and assumptions made with and by the order-generating level of control. In other words: as long as the server constraints are not violated, the lower level of control should be able to complete all activities within the given time.

2.3 Structure of Hierarchical Production Control

Bertrand and Wijngaard distinguish two levels of production control, i.e. Goods Flow Control (GFC) and Production Unit Control (PUC), using the concept of a *Production Unit* [Bertrand and Wijngaard, 1984]. As we will see in the first subsection of this paragraph, this concept can be described as a special kind of server. In the next subsection we will discuss the first level of control (i.e. GFC). The third subsection will discuss the PUC (especially in component manufacturing shops), while in the last subsection an overview of the entire production control structure will be presented.

2.3.1 Production Units

Bertrand and Wijngaard define the concept of a *Production Unit* (PU) as *"...a combination of a set of capacity types, a set of operations and a set of materials with the following properties:*
- *for each set of operations to be performed, it is only required to use materials from the set of materials, and to use capacity from the set of capacity types;*
- *each capacity type in the set of capacity types and each material item in the material item set is only used for performing operations belonging to the operations set...".*

They state further that *"... an ideal Production Unit is self–contained from a manufacturing point of view. Also from a production control point of view the Production Unit is self–contained, but it generally is constrained with respect to the amount and timing of its production..."*. In other words, a PU can be regarded as a specific kind of uncoupled server. Usually the constraints of this server are expressed in terms of required batch sizes, sequence constraints, work load constraints and constraints on the variation of the available capacity.
With the introduction of PUs, the overall production control problem can be split up into two distinct production control problems, i.e.:

- The *PUC–problem*, being the achievement of an agreed delivery performance given the fact that the environmental conditions of the PU are and will be in accordance with the norms. These norms are selected by management and are based on the server constraints of the PU. Production orders for PUs are called *work orders* (see also [Bertrand and Wijngaard, 1984]). For each work order a due date is given. Assuming that the utilization rates, especially of the bottleneck capacity resources, are kept at the required level (see Fig.2.7, §2.2), and that the mix of work orders does not violate possible mix constraints, it is the task of PUC to meet these due dates. In single–stage manufacturing systems, work orders usually are the lowest level of production orders taken into account by production control.
- The *GFC–problem*, being at the same time the achievement of the overall production control objectives, and the realization for each PU of the agreed environmental conditions (e.g. a certain work load in order to achieve the required utilization rates, and a certain mix of operations). The overall production control objectives usually refer to the customer order delivery performance and to the productivity of the (expensive) bottleneck capacity resources.

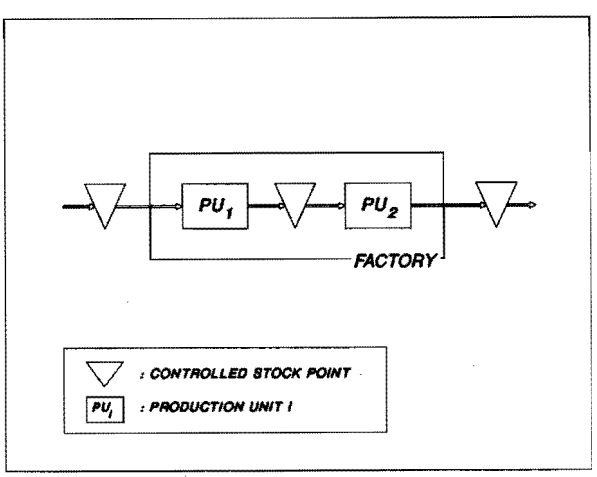

Figure 2.11:
Break–down of goods flow into production units, decoupled by controlled stock points.

The PUs are decoupled by controlled stock points (see Fig.2.11). Assuming a delivery performance of the PU according to the agreements, these stock points are controlled by GFC by releasing work orders to the PUs. The server inventory of a PU is called WIP–inventory. Such a decomposition of the overall production control problem in a set of hierarchical ordered subproblems, is only worthwhile if it reduces the complexity of the problem (see §2.1). To achieve this reduction of complexity for the Goods Flow Control problem, the following three guidelines are useful:
- the goods flow considered by GFC should be uni–directional;
- loops in the goods flow should be avoided;
- the number of PUs should be limited.

Also in other research concepts similar to a PU have been mentioned, using terms like 'shops' (see e.g. [Meal, 1978] and [Jones and McLean, 1984]) and 'processing departments' (see e.g. [Burbidge, 1971]). However, most of these concepts stem from organizational or infological considerations, not from production control considerations. We would like to stress that a PU not necessarily has to be identical to one separate department in an organization (although some kind of separate organizational identity seems to be logical).

2.3.2 Goods Flow Control

In the previous subsection we have seen that the Goods Flow Control (GFC–)problem is how to realize for each PU the agreed environmental conditions, while at the same time the overall production control objectives should be achieved. For GFC the PUs are servers, decoupled by controlled stock points.
As Bertrand and Wijngaard have pointed out, often GFC itself can be decomposed into four distinct control functions, being:
- Master Planning;
- Materials Coordination;
- Work Load Control;
- Work Order Release.

As we will see, these last two control functions are not entirely GFC–functions, but lie at the interface of GFC and PUC.
Master Planning is concerned with decisions on the available capacity in the PUs, the effective capacity stored in controlled stock points (as capacity stock), and often, due to the relation with order flow times, also on norms concerning the capacity utilization (see Fig.2.12). At this level only capacity aggregates are used as variables: *"...Demand, production and inventory are all aggregated to capacity..."* [Bertrand and Wijngaard, 1984]. Therefore, Master Planning is also known as 'aggregate production control' (see e.g. [Silver, 1972], [Meal, 1978]). Vollmann et al. distinguish at this level of control capacity decisions ('Resource Planning') from aggregate production level decisions ('Production Planning') [Vollmann et al., 1984].
Within the aggregate limits set by Master Planning, *Materials Coordination* coordinates the goods flow between the PUs such that the final inventories of the various products are balanced (in that case work orders can be regarded as stock replenishment orders), and/or the individual due dates of production orders are met. In the latter case, material coordination includes decisions on the utilization of capacity by means of capacity allocation [Bertrand and Wijngaard, 1984]. In other words, the Materials Coordination function initiates the goods flow in a production system (see Fig.2.12). As

such, it includes Master Production Scheduling decisions and Material Requirements techniques (see e.g. [Vollmann et al., 1984]).

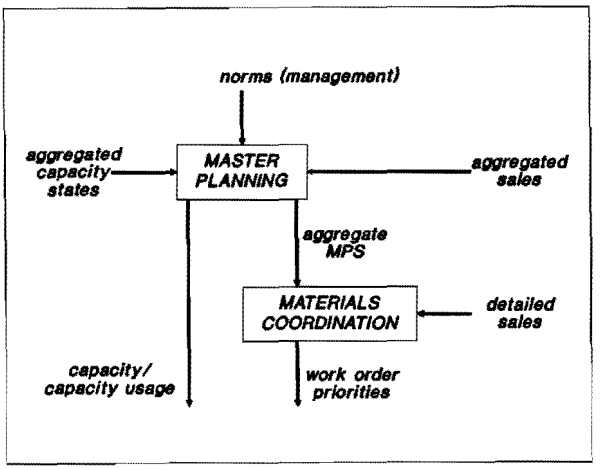

Figure 2.12:
Master Planning and Materials Coordination as part of GFC.

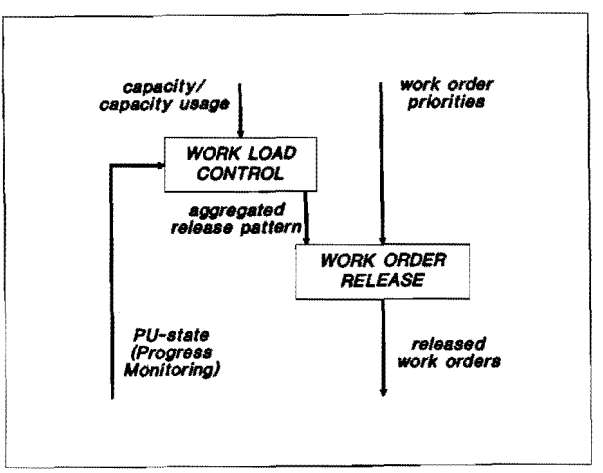

Figure 2.13:
Work order transfer decisions connecting GFC with PUC.

The task of *Work Load Control* is to determine for a particular PU the aggregate work order release patterns or release opportunities. Usually these aggregate release patterns should be based on the actual work load and usable capacity of the PU, and on the work load norms translated from the capacity utilization norms set by Master Planning. By controlling the work load of the servers inside the PU, the average work order flow times are controlled also (see e.g. [Bertrand and Wortmann, 1981], [Wiendahl, 1987], and [Bechte, 1988]). The Work Load Control function is the first part of what we in §2.2 have called the order transfer decision function (see Fig.2.13), connecting the order-generating level (i.c. GFC) with the order-receiving level (i.c. PUC).
Finally, the *Work Order Release* function is concerned with the acceptance and release of work orders according to the aggregate release pattern or release opportunities, the work order priorities set by Materials Coordination, and the actual state of the PU. This production control function is the second part of the order transfer decision function (see Fig.2.13). Once a work order has been released, it is not the responsibility anymore of GFC to control the progress of the order.
The detailed structure of GFC must depend on the characteristics of both the environment and the PUs. A more extensive discussion on GFC-structures can be found in [Bertrand and Wijngaard, 1984].

2.3.3 Production Unit Control

Since each Production Unit consists of a number of lower level servers, PUC faces the problem of how to control the progress of work orders through the PU (and thus on the servers inside the PU) in such a way that the PU delivery performance is optimal, i.e. according to the norms.

In case there is freedom in the *allocation of capacity resources* to servers, PUC will have to take decisions concerning this allocation. Often the allocation is merely an organizational and administrative issue and can be made together with or even after the sequencing decision (e.g. in case of tools). However, in case of multi-functional capacity resources and coupled servers, the allocation will be an important and distinct production control issue (e.g. in case of a multi-functional operator). In that case it is possible to allocate the capacity resources to servers based on the work loads of servers in the PU. Simulation experiments of Fryer have shown that a re-allocation of multi-functional operators at servers of which the sum of the flow times of the jobs waiting at the server is low, reduces both the average and the variance of the order flow time considerably [Fryer, 1974].
In many job shop like production situations there is some freedom in the *allocation of operations* to servers. Studies of Wayson have shown, that a small increase in the freedom of this allocation (e.g. one alternative server for each possible operation on each server) already has a large impact on the average flow times of work orders [Wayson, 1965]. Neimeier has shown that in case of some flexibility in the sequence of operations, similar but smaller effects can be achieved [Neimeier, 1967]. Usually the operation allocation as studied in literature, is based on the actual queue of work orders in front of each server. In real life often a preferential server is determined, usually based on economical considerations. Only in case of exceptional situations (e.g. machine breakdown, or an extremely high work load) the operation will be allocated to the alternative server.

The production control function which determines the sequences of operations on the PU-servers (see Fig.2.10), is called the *sequencing* function (also known as the dispatching decision; see e.g. [Burbidge, 1971], [Vollmann et al., 1984]). To determine the sequence of operations on work orders in a particular queue, in most component manufacturing shops some kind of priority rule is used. Using such a rule implies that the next operation is chosen according to a priority based on a particular characteristic of the operation, the status of the work order, and/or the status of the PU. Well known priority rules are 'Shortest Processing Time first (SPT)' and 'Operation Due Date (ODD)' (for an overview on priority rules and their characteristics, we refer to [Bakker, 1965] and [Baker, 1975]). Due to the positive effect the ODD priority rule has on the variance of due date deviations of work orders [Kanet and Hayya, 1982], and due to the clarity and meaningfulness of the rule for the decision maker, in most real life cases the ODD-rule (or a similar rule) is used.
In case of sequence dependent set-up times, the required set-up time should be included in the sequencing decision. In such a case the required set-up capacity can be limited by giving priority to work orders requiring the same server set-up.
Sometimes a combination of priority rules is used. An example of these combined priority rules is the so-called two-class priority rule: a first priority rule determines the division into an urgent and a non-urgent class of operations, while a second rule determines the priority of operations within each class (see e.g. [Bakker, 1965] and [Bertrand and Wortmann, 1981]).
In case of a deterministic server (see §2.2) and a deterministic environment, a predetermined schedule might be used, i.e. the sequencing decisions can be taken a considerable time before the operation is started.

The Work Load Control and the Work Order Release function at the GFC-level determine to a large extent the work load of the servers in the PU, and thus also the work order flow times (see e.g. [Bertrand and Wortmann, 1981] and [Wiendahl, 1987]). Therefore, in order to be able to predict the flow time (i.e. the service time of an entire PU) and to assign due dates in case of varying work loads, or to keep the work load of the servers and thus also the flow times on an acceptable level, at least the work load of the bottleneck capacities of the PU should be monitored. It has been shown that in many cases, release opportunities can be determined by observing the Remaining Work Load (RWL) of the capacity types ([Bertrand and Wortmann, 1981], [Bertrand and Wijngaard, 1984], [Wiendahl, 1987], [Bechte, 1988]). This RWL is defined as the amount of work (expressed in hours) to be carried out by a certain capacity type, that is already released to the PU, but not yet completed. The function that monitors the progress of work orders in a PU (and thus also the RWL in the PU), is called *Progress Monitoring.*

At the PUC level very often the operations are identical to the basic operations as defined in §2.2 (e.g. in case of single man-machine systems). However, sometimes even these operations are aggregate operations. For example, in case the PU includes a transfer line connecting several machines, usually the whole line is regarded as one server. Consequently, in such a case the set of all operations of a work order performed one after the other on machines in the line is regarded as one operation.
Since in these cases the operations are regarded at the PUC level as aggregate operations, the sequence of the basic operations is to be determined at a lower level of control, and the allocation and sequencing of

operations (in the example the 'transfer line operation') can be regarded as another order transfer decision.

2.3.4 Overview of complete control structure

In Fig.2.14 the complete production control structure in case of component manufacturing shops is given. The GFC–function coordinates the goods flow between the PUs. As we have seen above, the GFC–function can be split up into a Master Planning function and a Material Coordination function. Master Planning is responsible for the more aggregate (capacity) coordination together with the coordination with management. Materials Coordination coordinates the material flow between the PUs using work

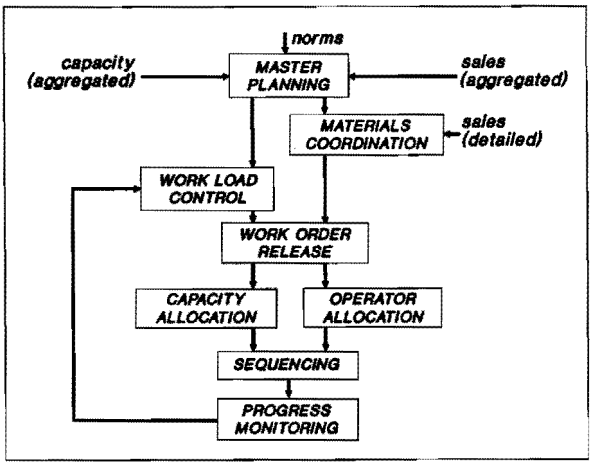

Figure 2.14:
Hierarchical production control structure for component manufacturing shops.

orders. Based on the actual work load and capacity state of the PU, the capacity and flow time norms set by Master Planning, and the work order priorities set by Materials Coordination, work orders are accepted and released to the PU. The PUC–function is responsible for the coordination of the production activities inside the PU. Often it is possible for PUC to (re–)allocate multi–functional capacity resources to servers. Sometimes also operations have to be allocated to servers. The sequence of operations on a server is determined by the sequencing function. Finally, feedback information on the remaining work load is required, especially for the Work Load Control function.

The aim of our study is to determine:
- how FAM–Stations should be described using the concepts introduced in this chapter;
- whether a control structure as given in Fig.2.14 will still be applicable in case of component manufacturing shops using FAM–Stations;
- whether specific control functions require new information on and/or insights in the capacity and flow time behaviour of FAM–Stations;
- whether new control principles are required for production control.

Chapter 3
FLEXIBLE AUTOMATED MANUFACTURING SYSTEMS

In this chapter we will have a closer look at the concept of Flexible Automated Manufacturing Systems. First we will discuss the concept of flexibility, especially in the context of manufacturing systems. In §3.2 we will give a formal definition of a Flexible Automated Manufacturing System. In the last paragraph a typology based on production control characteristics is presented and several types of FAMSs are discussed.

3.1 Flexibility of manufacturing systems

In the first subsection of this paragraph the flexibility of manufacturing systems will be discussed in a more general way. After a definition of flexibility, some characteristics of changes, the flexibility required by a system, and the importance of the flexibility of sub– and aspect–systems will be explained. In §3.1.2 we will discuss the types of flexibility that are important for manufacturing systems. As we will see, these flexibility types can be grouped into two sets.

3.1.1 The concept of flexibility

We define the *flexibility* of a system as the ability of the system to respond effectively to changes (cf. the definition of Mandelbaum; see [Buzacott, 1982a]). A similar definition is given by Zelenović as he defines the flexibility of a production system as *"...a measure of its capacity to adapt to changing environmental conditions and process requirements..."* [Zelenović, 1982]. The ability to respond effectively to changes can be expressed both in the range of changes the system is capable to respond to, and in the time required to respond. However, if a system is unable to respond to a certain change, we could say that the time required to react is infinitely large. In other words, the ability to respond to changes can also be measured by the time required to respond to changes. Therefore, we conclude that the most important measure of flexibility is the time required to respond to changes.

Changes
Changes may have a temporary and a permanent effect on the system. After temporary changes, the system returns to the original situation (e.g. an incidental increase in demand). In case of permanent changes the situation will stabilize at a point different from this original situation (e.g. a change in the demand level due to a shift on the product life cycle).
Furthermore, we can make (artificially) a distinction between two ideal typical classes of changes, i.e. minor and major changes. In case of minor changes the relative 'distance' between the situation before the change and the situation after the change is small (for instance: a minor product modification like a change in the diameter of a hole). A major change may create a new situation which is totally different from the original situation. Therefore, the relative 'distance' between the situation before the change and the situation after the change is large (for instance the introduction of an entire new product).
Finally, we can distinguish expected and unexpected changes at expected or unexpected times. In case of expected changes we know that the change will occur, but it might be unknown when it will occur (e.g. the break-down of machinery equipment). In case of unexpected changes at an expected time we know when something will happen, but we don't know (exactly) what (e.g. in case of a special marketing action). The most difficult changes to live with are the unexpected changes at unexpected times (e.g. a sudden collapse in demand).

Required flexibility
The amount of flexibility required in a certain system heavily depends on the probability of the occurrence of changes, the period of time during which an effective reaction is required, and the consequences of not being able to react (in time) on the changes. As long as the system is functioning in a very stable environment, flexibility is of no use to the system. The actual amount of flexibility of the system should depend both on the flexibility required and on the costs of this flexibility. In other words, a comparison should be made between the costs (and benefits) of systems containing different amounts of flexibility in equal circumstances. This requires an evaluation of the performance of the production system (i.e. of quality, delivery performance and costs) taking into account possible changes. For instance, in case we have to build a new manufacturing system, we have to consider not only the present situation (including the present set of product types to be produced), but also the situation in the future. If there is a reasonable chance that the life-time of (one of) the manufacturing system options will be longer than the product life-time, we have to include in our decision the future costs (and benefits) due to the changes in the set of products.

System flexibility
The flexibility of a system is determined by the flexibility of all of the elements of the system, and the flexibility of the relations between these elements. For instance, in a manufacturing system the required flexibility may be achieved at the machine level by increasing the capabilities of a machine, or at the system level by distributing the required capabilities among a variety of machines (see also [Buzacott, 1982a]). In the latter case it should be possible to visit several machines in a flexible way, thus requiring a flexible transportation system with interfacing flexibility to all machines.
The flexibility of a system is determined also by the flexibility of all aspects of the system. For instance, in case of a production system, the

flexibility of the entire system depends on the flexibility of the hardware of the manufacturing system and on the flexibility of other aspects of the production system, like the information system and the production control system.

3.1.2 Flexibility types

Although the concept of flexibility is general, there are many different types of flexibility. Examples of different flexibility types can be found in [Buzacott, 1982a], [Browne et al., 1984], [Kusiak, 1985], and [Ashayeri and Gelders, 1989]. Following van Amelsfoort, we distinguish two sets of flexibility types [van Amelsfoort, 1984], i.e. functional flexibility and executable flexibility.

Functional flexibility

The first set encloses the flexibility types concerning functional flexibility. This *functional flexibility* of a system refers to the required variability in the output of the system. Functional flexibility has a direct linkage with the sources of variability (i.e. the changes). We would like to stress that changes may stem from variability sources outside the system, but also from sources within the system itself due to a change in (the behaviour of) one of the elements or relations in the system ([Buzacott, 1982a] and [van Amelsfoort, 1984]). Important types of flexibility for manufacturing systems due to external variability sources are the types concerned with variations in demand, i.e.:

- Product flexibility, i.e. the flexibility of the manufacturing systems in producing different types of products;
- Mix flexibility, i.e. the flexibility of the manufacturing system in producing different mixes of products (assuming a product flexibility that is sufficient for the production of each of the products in the mix);
- Volume flexibility, i.e. the flexibility of a manufacturing system to produce at different capacity levels (assuming a sufficient mix flexibility).

Important internal variability sources of manufacturing systems are the absence of capacity resources (e.g. because of a temporary or definite machine break-down, or operator absenteeism) and quality or process control problems.

Executable flexibility

The second set of flexibility types concerns the executable flexibility of a system. The *executable flexibility* of a system refers to the way the system tries to achieve the required flexibility. There are three ways of reacting on changes:

- Operational flexibility:
  First of all the system may be designed in such a way that it is capable of dealing with changes without the need for system alterations. In other words: these changes can be dealt with within the existing system structure. We will call this kind of flexibility *operational flexibility* (cf. [Wortmann, 1989]; Buzacott uses the term 'state flexibility' for this kind of flexibility [Buzacott, 1982a]]). Examples of operational flexibility in case of manufacturing systems are routing flexibility, i.e. flexibility in the sequence of machines to visit, and set-up flexibility, i.e. flexibility in the set-up of a manufacturing system.

- Structural flexibility:
  Sometimes changes can be dealt with by changing the structure of the system, e.g. by adding a new element in the system or changing the relations between the elements of the system. This kind of flexibility will be called *structural flexibility* (cf. [Wortmann, 1989]; also known as 'action flexibility' [Buzacott, 1982a]). Examples of structural flexibility in case of manufacturing systems are the introduction of a new machine and a change in the layout of the transportation system.
- Rigidity:
  Finally, changes may be 'ignored' by the system; the time required by the system to react is infinitely large. The only way to cope with these changes is to build a new system. Therefore the existing system is said to be *rigid* within the scope of these changes. The range of changes in which the system is not rigid, will be called the *flexibility range*. The relation between flexibility range and reaction time of a system is drawn in Fig.3.1.

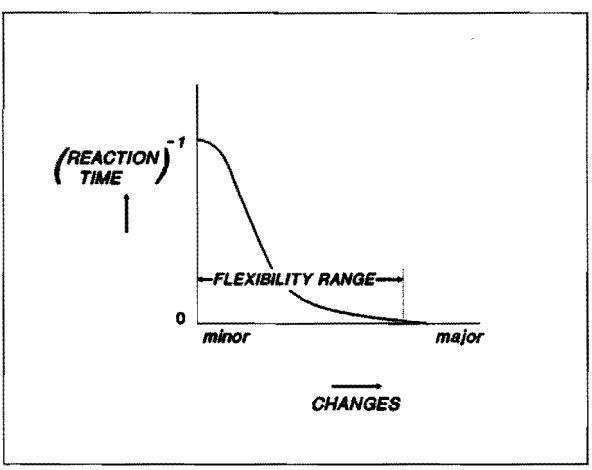

Figure 3.1:
Nature of the relationship between
reaction time and flexibility range of a system.

Often the reaction time in case of operational flexibility is shorter than the reaction time in case of structural flexibility. For instance, in case of an increase in required capacity of a manufacturing system, the time to react will be negligible if the manufacturing system already has more capacity than actually required. However, if we have to change the manufacturing system by adding a new machine, the reaction time will be considerable, even if provisions (like reserved floor space) have been made.
Also the costs involved in changing are likely to be lower in case of operational flexibility. In the example just given, the costs of changing in case of operational flexibility are low, since no extra machine is required, nor are any adaptations required in the existing manufacturing system.

However, often the costs of implementing this kind of flexibility in a manufacturing system are higher than the costs of implementing structural flexibility, or implementing no flexibility at all. It is clear that the manufacturing system already containing the extra machine is the most expensive system. In case of structural flexibility, we may have to reserve floor space, or we may have to invest in a more expensive flexible transporting system in order to be able to add a new machine to the manufacturing system. In case of rigidity, no provisions are required at all.

3.2 Defining Flexible Automated Manufacturing Systems

In §1.1 some definitions have been given of what is commonly known as 'FMS'. We concluded, that many manufacturing systems may have flexible characteristics, but only a subset of these systems is called 'FMS'. This subset has the specific characteristic that all of the manufacturing systems that are part of the subset, are fully automated. This was the reason why we introduced the term *'Flexible Automated Manufacturing Systems'* (FAMS). In order to give a proper definition of an FAMS, we will first have a look at the basic elements of this term, i.e. a manufacturing system, automation and the type of flexibility.

Manufacturing system

In the APICS-dictionary a 'manufacturing process' is defined as *"...the series of activities performed upon material to convert it from the raw or semifinished state to a state of further completion and a greater value..."* [APICS, 1984]. In this definition, the term 'material' not only refers to raw materials, but also to parts and subassemblies. Several transformations on material may be required in this process (see §2.2). A manufacturing system is the technical system required to transform the physical appearance of material and possibly perform also position and time transformations, in order to obtain the required product. The system may consist of machine tools, operators, transportation vehicles, testing equipment, handling devices, buffer stations etc. Both a single man/machine system and an entire transfer line can be regarded as a manufacturing system.

From a logical point of view, each transformation is carried out by a subsystem of the manufacturing system. Such a subsystem consists of both a controlling unit and a executing unit (see Fig.3.2). The executing unit merely performs the required transformation. It consists of two functions, i.e. energy transmission and physical operation. The controlling unit gives the required information on the transformation to be performed. It controls the energy flow, the movements of tools (if required), speed of execution, etc. We will refer to this type of control as *process control.* The described subsystem will be called a *transformation unit.* Physically, the distinction between controlling unit and executing unit is not always as clear-cut as shown in Fig.3.2.

Automated manufacturing system

A manufacturing system will be called (fully) automated if all of its transformation functions are automated, i.e. if all transformation tasks can be fulfilled without the interference of (human) operators.

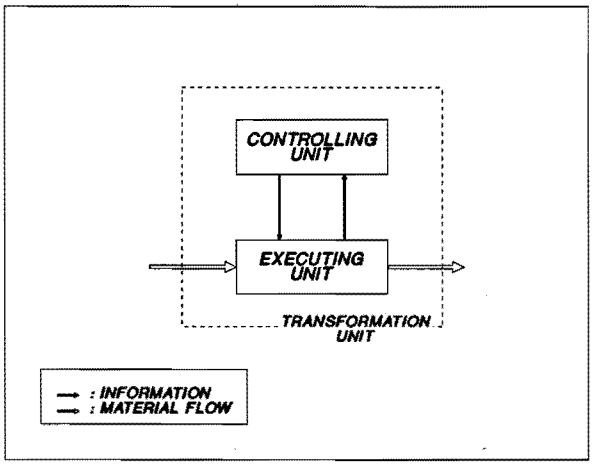

Figure 3.2:
A transformation unit as basic subsystem of a manufacturing system.

In mechanical engineering often three degrees of automation are distinguished (see e.g. [Stal, 1977]), i.e.:
- the self–working system;
- the self–working and self–inspecting system;
- the self–working, self–inspecting, and self–correcting system.

A self–working system is capable of performing a set of actions without the presence of a human operator. This can be achieved not only with numerical control units, but also with e.g. mechanical constructions (in which case also the term 'mechanization' is being used; see e.g. [ECE, 1986]). The system becomes self–inspecting if it is capable of inspecting the result(s) of the actions (e.g. taking size–measurements). Often such a system is also capable of comparing these measurements with pre–determined norms; as soon as these norms are violated, the system stops automatically. A self–correcting system not only inspects the results of its actions, but also is capable of taking corrective actions or reject–decisions. As we may conclude from Fig.3.2, in all cases it is required that not only the executing unit of the transformation unit is automated, but also at least a part of the controlling unit. The higher the degree of automation of the controlling unit, the higher the degree of automation of the whole system. For our study the first degree of automation is sufficient for a manufacturing system to be called automated.
The automation of manufacturing systems can be flexible or dedicated. In case of flexibly automated manufacturing systems the automation is re–programmable, i.e. it is possible to adapt the automated functions to new circumstances (especially new products). Note that in this case the term 'flexibly' refers to the automation, not necessarily to the system itself. An automated manufacturing system is called dedicated, if the system can handle only one type of product (or a small range of variants) [de Sitter et

al., 1986]. To make such a system suitable for the manufacturing of other products, the system must be rebuilt. As we will see, *Flexible* Automated Manufacturing Systems are a specific type of *flexibly* automated manufacturing systems.
As Stal has pointed out, automation can be realised both by hardware solutions and by software solutions [Stal, 1977]. Nowadays most often manufacturing systems are automated using electronic and computer–based systems. Groover for example defines automation as *"...the technology concerned with the application of complex mechanical, electronic, and computer–based systems in the operation and control of production..."* [Groover, 1980].

Flexible Automated Manufacturing System
Finally, an automated manufacturing system will be called flexible (and thus an FAMS), if the system is capable of dealing with changes in demand. In the previous section we have seen that demand changes may require product flexibility, mix flexibility and volume flexibility. This means at least, that the automation should be re–programmable. In other words, FAMSs are flexibly automated manufacturing systems with mix and volume flexibility.

3.3 Typology of flexibly automated manufacturing systems

In [van Rijn, 1985] some methodological issues on typologies are discussed, based on the definition of the term 'typology' given by Grosse–Oetringhaus. He defines typology as *"...das Gesamt aller Denkprozesse und Denkergebnisse ...., das die realen Erscheinungsformen eines Untersuchungsbereiches im Hinblick auf ein Untersuchungsziel durch Abstraktion und Differenzierung in eine Ordnung bringt..."*. Important in this definition is the fact that a typology depends on its application in a particular area of research, and on the research objectives. In other words, when a typology is given, it should be clear in what kind of research the typology is or could be used for what purpose.

In the next subsection we will present a basis for distinguishing types of flexibly automated manufacturing systems according to characteristics that are relevant from a production control point of view. The main purpose of this typology is to identify first of all those flexibly automated manufacturing systems that can be called FAMSs, and secondly the relevant types of FAMSs.
Changes in the characteristics of the manufacturing system may influence two important aspects of production control. First of all, the characteristics of the manufacturing system may change such, that the flow time characteristics of work orders requiring the manufacturing system change considerably. Secondly, the system characteristics may change such, that the capacity characteristics of the server change.
In both cases, the models used by production control may be affected in two ways. Sometimes these characteristics merely influence the value of the parameters used in the production control models, not the models themselves. However, often it is necessary to change the models, and maybe even the concepts used in these models.

As we will see, the resulting typology contains types that appear to be similar to some of the types presented in literature. In §3.3.3 a comparison between these typologies will be made and a discussion will be given on these typologies.

3.3.1 The typology

Because we have defined a flexibly automated manufacturing system as a technical system, the typology used in our study should be based on some description of the hardware of the system. However, since our study focuses on production control issues, the typology should also consider capacity and flow time characteristics of these systems in order to distinguish different types of flexibly automated manufacturing systems. As we will see, the transformations in the manufacturing process introduced in §2.2 give the opportunity to combine these different points of view. In that subsection, we distinguished three types of transformations in the manufacturing process, i.e.:
- transformation in physical appearance;
- transformation in position (material handling or transportation);
- transformation in time (controlled stock or WIP-inventory).

In a manufacturing system some of the transformations may be automated in a programmable way. Depending on the number of transformations that are integrated in the system, we can distinguish several types of programmable automated manufacturing systems. As we will see, each of these types also has some interesting characteristics from a production control point of view.
We will start the discussion with an introduction on conventional non-automated machines. In order to illustrate each type of flexibly automated manufacturing system, we will use a reference work order. Without changing the characteristics of this work order, we will show for each type of manufacturing system what the consequences are both for the transformations required and for the flow time of the work order.

Conventional non-automated machine

The starting point of our typology will be the manufacturing process as presented for the reference work order in Fig.3.3, assuming that no transformation in this process is automated. As we can see, the reference work order requires three operations on three different conventional machines. In case of machining operations, usually pallets and positioning tools are used to handle parts. The set of tools required and prepared to position and hold one or more (identical) parts in a particular way, will be called a *product set-up*. In many cases, especially in low volume manufacturing, a part-specific fixture is used. In other cases product set-ups are built up from several positioning tools like standard fixtures with ancillary devices as clamps and location pegs. On non-automated machines, a product set-up usually contains only one product. Sometimes not all required transformations on a part can be performed in one product set-up, e.g. because the number of axes of the machine tool is insufficient to complete all transformation in one set-up, or a particular side of the product cannot be reached due to the positioning tools. Therefore, a product might require more than one type of product set-up per operation

in order to be completed.
Usually product set–ups are mounted on pallets. We will call a combination of product set–ups on one pallet a *pallet set–up*. In case of non–automated machines, the pallet is fixed on the machine and usually contains only one product set–up.

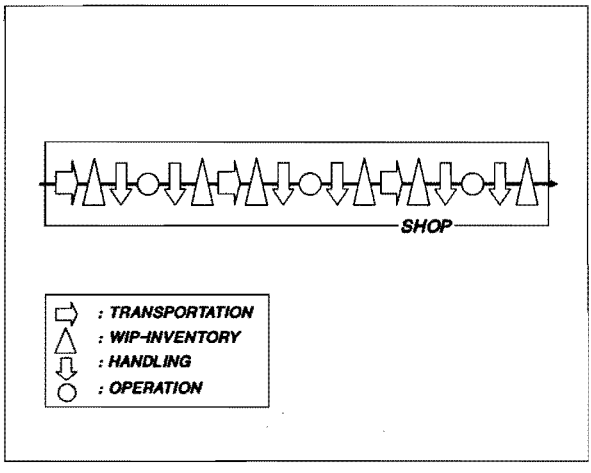

Figure 3.3:
Transformations in a simplified manufacturing process
on the reference work order in a component manufacturing shop.

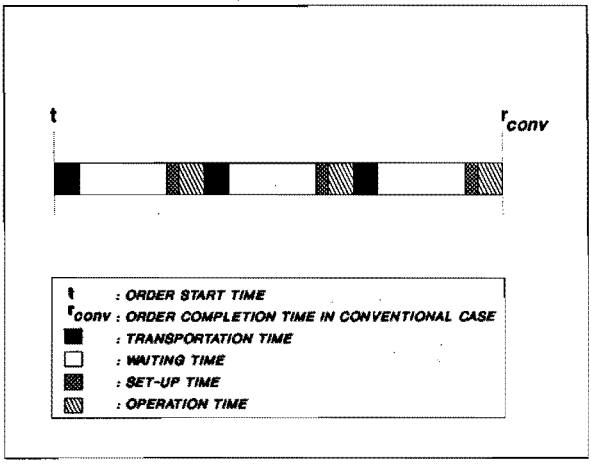

Figure 3.4:
Flow time of reference work order in case of non–automated machines.

In many cases, especially in case of a job–shop environment, a work order will have to wait at each machine before the required operation can start. In that case, the flow time of work orders is estimated using a model like is shown for the reference work order in Fig.3.4. This model is based on the relation given in Fig.2.7 (§2.2). The waiting time of a work order can be expressed as a multiple of the average service time (i.e. set–up time and operation time) on the machine considered (cf. the Pollaczek–Khinchin formula, see §2.2). Usually the assumption is made, that once an operation on a work order has started, no other work orders will be taken into operation before the operation on that particular work order is completed. We will call this the *sequential production* of work orders.
Often it is assumed that the server required to perform a particular operation, can be modeled as a single–dimensional server (see §2.2). Therefore, no distinction is made between machine capacity and operator capacity. In case such a distinction is made, usually it is assumed that the required capacity of each of the two resources equals the operation time.

Stand alone (C)NC–machine

Stand alone (computer) numerical controlled machines are the basis of manufacturing systems using programmable automation. A stand alone (C)NC–machine can carry out several different, but similar physical transformations without human intervention (see Fig.3.5). If different tools are required for each of these transformations, an Automatic Tool Changing system (ATC) is used, consisting of a tool magazine mounted on the side of the machine and a robot arm. In many cases NC–machines are able to perform more accurate operations and operate at a higher speed than conventional machines.

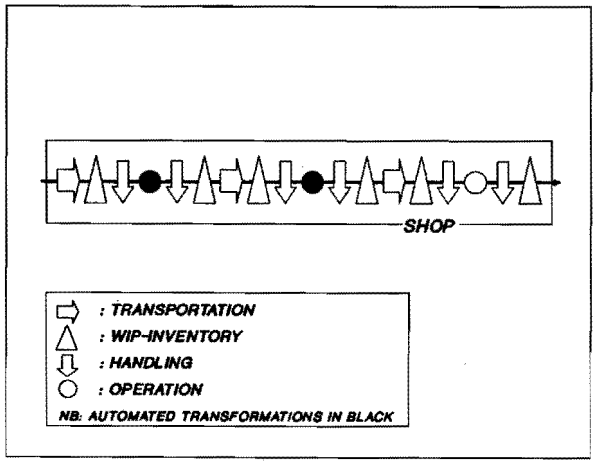

Figure 3.5:
Automated transformations on the reference work order in case of two subsequent stand–alone NC–machines.

Due to the higher speed of NC–machines, the operation times are reduced (e.g. in the MF–Case presented in §1.3.2, an average reduction of 33% was established). Consequently, the flow time of work orders will be reduced proportionally (see Fig.3.6 for the flow time consequences for the reference work order). Although the pallet set–ups may be different from the pallet set–ups at conventional machines, still work orders are produced in a sequential way. Therefore, the model used for estimating the flow time remains the same.

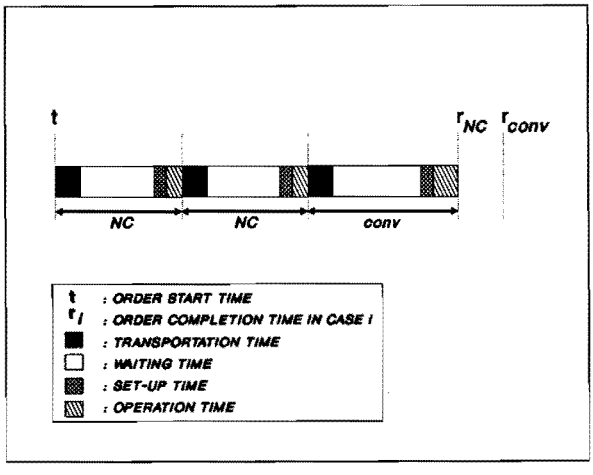

Figure 3.6:
Flow time of reference work order in case of stand alone NC–machines.

The main difference for production control with non–automated conventional machines is the fact that during the operation the presence of the operator may not be required anymore. In theory an operator could perform another task, while the machine is carrying out the operation(s). In other words, for each operation the use of machine capacity differs from the use of capacity of the operator. In many production control systems, this distinction in required capacity can not easily be made.

Manufacturing Centre (MC)

A Manufacturing Centre can be defined as a computer controlled machine capable of performing several distinct operation types. An MC enables the reduction of the number of operations in a process plan. This is illustrated for the reference work order in Fig.3.7. As we can see, the MC is capable of performing two 'conventional' operations on the work order, thus reducing the number of operations from three to two.

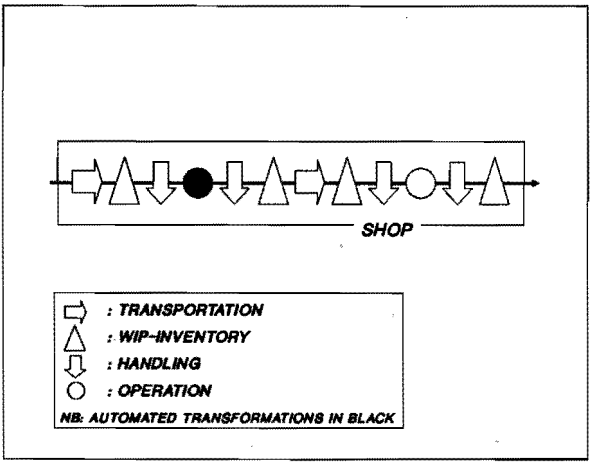

Figure 3.7:
Automated transformations on the reference work order in a Manufacturing Centre.

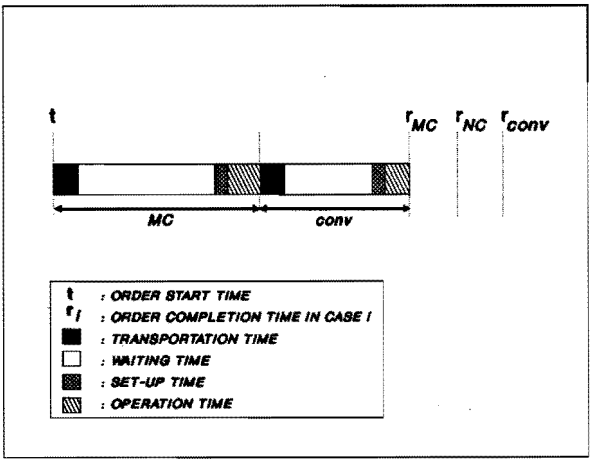

Figure 3.8:
Flow time of the reference work order in case of an MC.

It is very likely that the number of product set-ups to be made per work order will be reduced, especially in case of an MC with many axes. In most cases such a reduction will lead to a reduction in the total time machines are occupied due to set-ups for work orders. Assuming no change in the total available capacity, this 'extra' time can be used either for a reduction in the utilization rate and thus for a flow time reduction (see Fig.2.7, §2.2), or for an increase in the productive use. Also in the latter case it may be possible to reduce flow times. Assuming an equal utilization rate, work order flow times may be reduced due to the reduction in total service time. In Fig.3.8 the flow time reduction for the reference work order is shown. Notice that work orders still are produced in a sequential way.
In case of a job-shop environment, both the number of operations in a process plan and the number of distinct routings will decrease. Because of that, the production control problem will be simplified. On top of that, in order to maintain the same usable capacity, it might be necessary to invest in a second (identical) MC. As we know from queueing theory, this will reduce flow times in a job-shop considerably. In case of a flow-shop environment often investment in a second MC is required to maintain the speed of the flow. This second parallel MC also reduces the sensitivity of the flow to capacity disturbances.

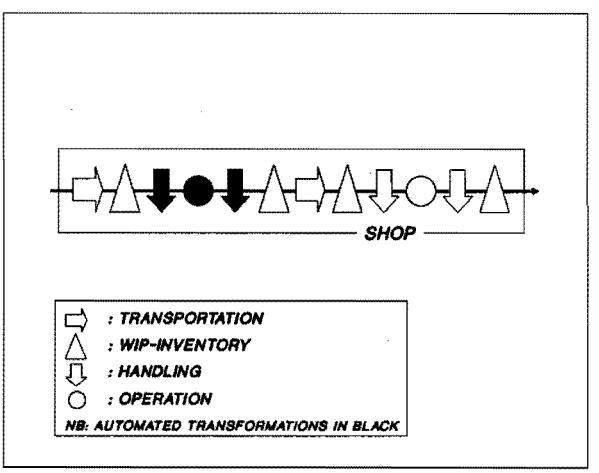

Figure 3.9:
Automated transformations on the reference work order in a Manufacturing Centre with Automatic Part Changer.

Manufacturing Centre with Automatic Part Changer (MC&APC)

If the configuration of an MC is expanded with an Automatic Part Changer (APC), some handling activities are automated as well (see Fig.3.9). Because of the APC it is possible to prepare pallet set-ups in front of the machine instead of on the machine itself. Also the (un)loading

of parts in (from) product set-ups can be performed in front of the machine. On top of that, if it is required to inspect the first product of a new work order, the machine tool can proceed with the processing of parts of another work order. The result is that the machine set-up time is reduced considerably. An example of an APC is a pallet changer. While the machine is processing a set of parts in a particular pallet set-up, another pallet set-up can be prepared on the pallet changer (using another pallet). As soon as the machine has completed the operation process, the two pallets containing the set-ups will be interchanged. The machine can start the operation process on the parts in the second pallet set-up, while the operator is unloading the parts from the first pallet set-up and loading the parts to be produced next.
Due to the machine set-up time reduction, the flow time will be reduced (see Fig.3.10) and it may become possible to reduce the work order lot-size. This lot-size reduction again will cause a further order flow time reduction at the MC&APC. Furthermore, an MC&APC has the capability of pre-emptying work orders without loss of productive capacity: each time a pallet is moved from the machine, a pallet containing parts of an urgent work order can be taken into operation.

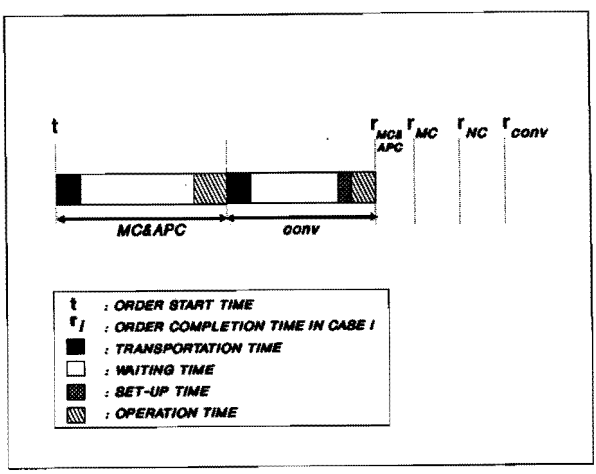

Figure 3.10:
Flow time of reference work order in case of an MC&APC, assuming no restrictions in the number of identical product set-ups.

With the introduction of an APC also some new constraints may have to be introduced to be considered by production control. First of all, the number of identical product set-ups concurrently on the manufacturing system might be limited, e.g. due to a limitation in the number of identical fixtures. If this number is limited to only one, the machine may alternately operate on parts of two work orders, in particular due to the mechanism of the changing of pallets as described above. In other words, work orders are no longer produced one after the other, but more or less

simultaneously. If that is the case, the flow time of a work order will be different from the flow time as given in Fig.3.10. In Fig.3.11 the flow time of the reference work order is given in case of the simultaneous production of two work orders. Not only are the values of parameters used in the flow time estimating model changed, but also the model itself may have to be changed. The model presented in Fig.3.4 may not be applicable anymore.
In case two work orders are in operation at the same time, the number of tool pockets available in the tool magazine may be a limitation too, thus creating a new constraint, viz. on the mix of orders in operation (see also [Stecke, 1983]).

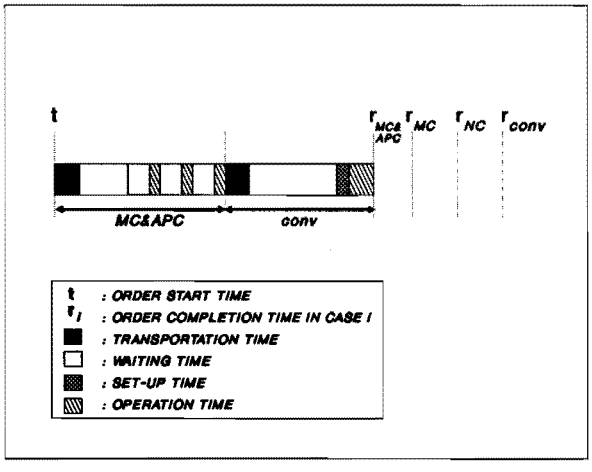

Figure 3.11:
Flow time of reference work order in case of an MC&APC, assuming a limitation in the number of identical product set–ups.

Flexible Automated Manufacturing Station (FAM–Station)

A Flexible Automated Manufacturing Station can be defined as one or more MCs&APCs connected with a (common) pallet storage (see Fig.3.12). This enables the storage of several pallets on the manufacturing system. Each pallet visits only one MC, after which the parts can be unloaded (so–called single–stage manufacturing). A single FAM–Station contains only one MC, a multiple FAM–Station more. The two FAMSs described in §1.3.2 are examples of single FAM–Stations. In [Swinkels, 1986] an example is given of a multiple FAM–Station.
This manufacturing system is less dependent on the continuous presence of an operator. In fact, it is able to produce unmanned for several hours (depending on the amount of work loaded on the system), thus increasing the available capacity of the system. This increase in available capacity per day also reduces the order flow time expressed in calendar time. Furthermore, the above mentioned phenomenon of the simultaneous

production of work orders becomes more important, since the number of orders in operation at the same time may grow considerably (see Fig.3.13).

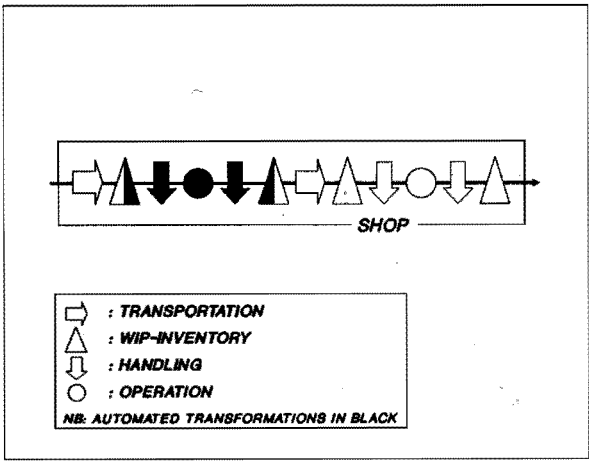

Figure 3.12:
Automated transformations on the reference work order in a Flexible Automated Manufacturing Station.

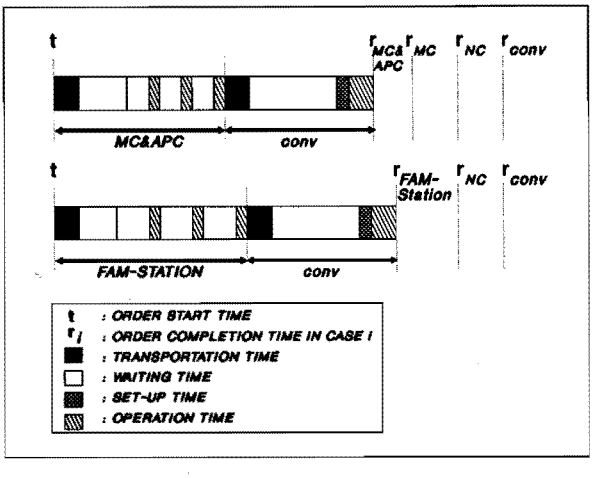

Figure 3.13:
Flow time of reference work order in case of an FAM–Station, assuming a limitation in the number of identical product set–ups.

Finally, the machine set–up times may become sequence dependent. An example of sequence dependent set–up times could be the case of a multiple FAM–Station with the possibility of exchanging cutting tools between the machine tools automatically. These tool exchanges may take some time, thus possibly causing the machine tools to get idle (see also [Gaalman et al., 1986]). Another example of sequence dependent set–up times can be found in [Aanen, 1988], where a description is given of a turret lathe with sequence dependent set–up times. In §2.3 we have seen that in case of sequence dependent set–up times at least the priority rules used by the sequencing function should be changed.

Flexible Automated Manufacturing Shop (FAM–Shop)

The last type of manufacturing system considered in this typology is the Flexible Automated Manufacturing Shop. This manufacturing system consists of a number of numerical controlled machines with APC– and ATC–devices, connected by part storage equipment and transportation devices in such a way that several operations on different machines can be performed without loading and unloading activities (so–called multi–stage manufacturing; see Fig.3.14).
There are three distinct sub–types, i.e.:
- Flexible Automated Transfer Line (FATL), where the number of different internal routings (i.e. the sequence of servers to visit on the manufacturing system) is limited to one, due to the strict connection of the transportation system with the (flexible) machines;
- Flow FAM–Shop, where the number of internal routings is limited due to a uni–directional flow;
- Random FAM–Shop, where no limitations exist on internal routings.

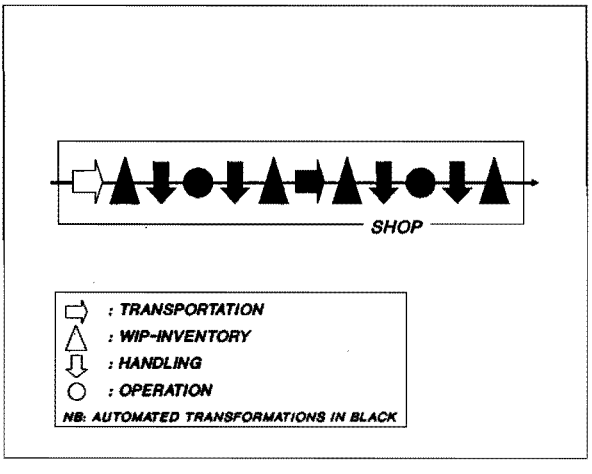

Figure 3.14:
Automated transformations on reference work order in a Flexible Automated Manufacturing Shop.

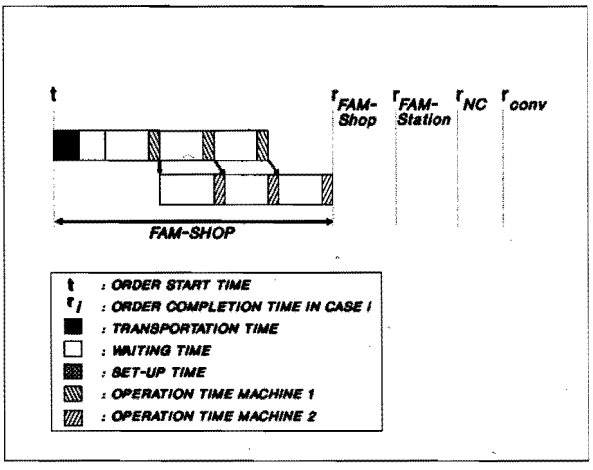

Figure 3.15:
Flow time of reference work order in case of an FAM–Shop.

FAM–Shops have the potential of finishing a work order completely. Each machine in the FAM–Shop may have characteristics similar to FAM–Stations, MC&APCs, or NC–machines with APCs. Furthermore, in a FAM–Shop it is not necessary to finish the first operation for all parts of a work order in order to be able to start the second operation on the first part (see Fig.3.15).
Often FAM–Shops have severe mix–constraints (see e.g. [Stecke, 1983] and [Buzacott and Shanthikumar, 1980]). First of all, the mix of product set–ups on the system should be such that idle capacity is avoided as much as possible. In other words, a certain mix of routings may be required. This problem is known as the balancing problem. Also, a machine may 'starve', in which case the machine is idle because it is not able to perform a particular operation due to the temporary absence of a part (for instance because the part is waiting for the transportation system to be transported to the concerning machine; see also [Tempelmeier et al., 1988]). On top of that, the mix of parts on the system might be limited due to limitations in the number of pockets available for tool storage. Finally, the storage capacity for pallets might be limited, thus possibly causing so–called blocking problems. A machine is said to be blocked when it is impossible to remove the pallet with finished parts due to the fact that no usable buffer or next machine is available [Tempelmeier et al., 1988].

3.3.2 Literature review

In literature several other typologies are used. In this subsection we will present some of these typologies, and compare them with the typology presented in the previous subsection.

Both in [Spur and Mertins, 1982] and in [Cziudaj and Pfennig, 1985] a typology of Flexible Automated Manufacturing Systems is presented consisting of three types, i.e.:
- Flexible Manufacturing Cell (FMC), containing an automated stand-alone machine tool, an automatic tool storage and exchange system, and an automatic part storage and exchange system. The system is only capable of single-stage manufacturing. In our typology this type of manufacturing system is called a single FAM-Station.
- Flexible Manufacturing System (FMS), containing several automated machine tools, an automatic tool storage and exchange system, and an automated work-piece storage and exchange system. The machine tools are externally interconnected (no transportation through the operation area) by a non-cyclic automated work-piece transportation system, thus enabling the system to perform multi-stage manufacturing. We call this type of manufacturing system a random or flow FAM-Shop.
- Flexible Transfer Line (FTL), containing several automated machine tools, an automatic tool storage and exchange system, and an automated work-piece storage and exchange system. The machine tools are internally interconnected (transportation through the operation area) in a fixed sequence by an cyclic automated work-piece transportation system, thus enabling the system to perform multi-stage manufacturing. This system seems to be identical to the FATL in our typology.

A similar, but extended typology is given in [Browne et al., 1984] and [Stecke and Browne, 1985]. Apart from the three types already mentioned, they distinguish a fourth type of FAMS, i.e.:
- Flexible Transfer Multi-Line (FTML), consisting of several interconnected Flexible Transfer Lines;

Furthermore, in [Stecke and Browne, 1985] the last three types (i.e. FMS, FTL, and FTML) are further subdivided according to the type of Material Handling System (MHS).

Based on the number of numerical controlled machines and their arrangement, Kusiak distinguishes five classes [Kusiak, 1985], i.e.:
- Flexible Manufacturing Module (FMM), which can be defined as an NC-machine with a part buffer, a tool changer, a pallet changer etc.. This FMM seems to be identical to the above mentioned FMC and to the single FAM-Station in our typology.
- Flexible Manufacturing Cell (FMC), consisting of several FMMs. It is not clear to us where this FMC should fit in our typology, since Kusiak does not give a detailed definition of this type. Presumably, an FMC merely is a set of FMMs under common computer control, but not interconnected by an automated transport system (cf. [ECE, 1986]).
- Flexible Manufacturing Group (FMG), being a collection of FMCs and FMMs in the same manufacturing area (fabrication, machining or assembly), interconnected by an MHS under common computer control. Although also a multiple FAM-Station satisfies this definition, we assume that Kusiak refers to specific random and flow FAM-Shops.
- Flexible Production System (FPS), containing several FMGs in different manufacturing areas. In our typology, also this type of manufacturing

system would be called a random or flow FAM–Shop.
- Flexible Manufacturing Line (FML), defined as a set of dedicated machine tools. Presumably these machine tools are arranged in a fixed sequence (cf. an FATL), although this aspect is not included in the formal definition.

Finally, depending on the degree of programmable automation, Herroelen defines several types of programmable automated manufacturing systems [Herroelen, 1985], being:
- NC–, CNC–, or DNC–machines.
- Machining centres (MC), being NC–machines capable of performing several operations. MCs also use automatic tool changers and automatic part changers.
- Flexible Manufacturing Module (FMM), consisting of a stand–alone MC, a pallet carousel, a system for self–inspection, and a automatic system for self–correction. This type of manufacturing system is capable of producing several hours without the presence of an operator. We would call this type of manufacturing system a single FAM–Station.
- Flexible Manufacturing Cell (FMC), containing several independent NC–machines or MCs under the control of one central computer. This FMC seems to be a mixture of the FMM and the FMC defined by Kusiak.
- Flexible Transfer Line (FTL), being a set of NC–machines arranged in a (fixed) sequence according to the required operations on a part.
- Flexible Manufacturing System (FMS), consisting of a group of work stations (NC–machines or MCs) interconnected by an automatic internal transportation system, all under the control of a computer. We would call this type a random or flow FAM–Shop.

The typology of Herroelen seems to be very similar to our typology.

If we compare these four typologies, some remarks can be made:
- For similar types of manufacturing systems different terms are used. Especially the word 'cell' is used in different meanings. On top of that the term 'cell' is also widely used in Group Technology literature, but in that context it again has a different meaning. In order to avoid confusion, we have chosen not to use this term.
- In all typologies the label 'system' is reserved for manufacturing systems containing several machines in a non–fixed arrangement. In our definition in §3.2 also a single–machine manufacturing system is regarded as a (manufacturing) system.
- Most typologies make a distinction between systems using a (central) computer and systems not using such a computer. From a software point of view this might be an important characteristic. However, for our purpose the computer control structure only becomes relevant in the discussion of implementation, not in the identification of production control issues.
- As our typology, most typologies are based on a description of the (hardware) configuration of the manufacturing system. However, for none of the typologies given in literature it is clear in what kind of research the typology could or should be used. On top of that it is not very clear why the several types are distinguished as they are.

3.3.3 Flexibility of flexibly automated manufacturing systems

In this subsection we will discuss the flexibility of the several types of flexibly automated manufacturing systems. We will start with a discussion on the structural flexibility of these systems, and continue with a discussion on their operational flexibility. Based on these flexibility considerations and on the definition of FAMS given in §3.2, we will conclude this chapter with the identification of the types of FAMSs included in the typology of §3.3.1.

Structural flexibility

When transformation units are automated, often several assumptions have to be made regarding the interfaces with other transformation units and regarding the characteristics of the transformations to be performed in the future. In case these assumptions are violated, the system may have to be rebuilt. In §3.1.2 we have called the flexibility required to be able to rebuild a system, the structural flexibility of the system.

In our study we focus on demand flexibility, expressed in product flexibility, mix flexibility and volume flexibility (see §3.1.2). Therefore, the structural flexibility of a manufacturing system is to a large extend determined by the assumptions made regarding these characteristics at the time the system was built. The more integrated the system is, the more assumptions are required (e.g. regarding the set of products to be produced by the manufacturing system; see e.g. [Stecke, 1985]). However, the more assumptions made when designing the system, the more likely that one of these assumptions will be violated in the future. Therefore, the more integrated a system is, the higher the need for structural flexibility will be. Unfortunately, introducing new elements in a highly integrated system often creates much more problems than introducing new elements in a non-integrated system. Experience at the Cincinnati Milacron Plastics Machinery Division shows that *"...the more extensive the amount of integration of a new system, the more problems there will be. As additional elements were included in the new system, the amount of trouble went up much faster..."* [Meredith, 1989]. For instance, introducing a new machine in a manufacturing system consisting of several conventional man/machine systems takes far less time than introducing a new machine in a FAM-Shop. In the former case, a change in the lay out of the plant will be sufficient. In the latter case, additional adjustments may be required regarding for instance the part transportation system, the tool transportation system, and the software of the FAM-Shop. On top of that, some assumptions are to be regarded as constraints which may never be violated. An example may be the maximum size of the parts to be produced on the system. If these assumptions are violated, the system will not function anymore (see also [Bertrand and Wortmann, 1981]). The more elements and relations are integrated in the system, the more basic assumptions may be required.

Therefore, we conclude that the structural flexibility of manufacturing systems depends on the number of transformation functions integrated in the system. The structural flexibility can be extended slightly if during the design phase of the manufacturing system the capability of changing the structure of the manufacturing system is carefully taken into account. In Fig.3.16 the structural flexibility of the different types of manufacturing systems is schematically given.

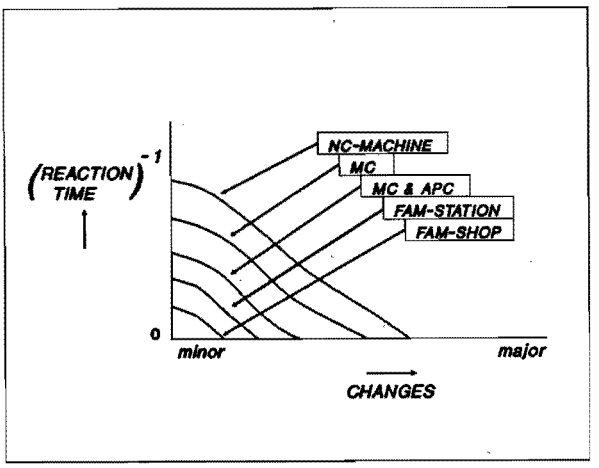

Figure 3.16:
The structural flexibility of manufacturing systems.

Operational flexibility
As we have discussed in §3.2, an FAMS typically incorporates three types of functional flexibility, viz. product flexibility, mix flexibility and volume flexibility. As long as the assumptions made when designing the system, are not violated, an FAMS is supposed to be very flexible regarding these changes in demand. FAMSs are designed in such a way that a range of products, mixes of products, and volumes of products can be produced without large reaction times. As Buzacott states, the emphasis on the term 'flexibility' in FAMSs implies operational flexibility [Buzacott, 1982a].

- Product flexibility:
  Every type described in the typology in §3.3.1, contains machines that are flexibly automated. Therefore, each type can be said to be product flexible by means of machine flexibility. However, in case of the more automated types, the number of constraints on the products to be produced is higher than the number of constraints imposed by the less automated types. Apart from the hardware and possibly software constraints of one machine, also constraints imposed by the transportation system (e.g. on the weight of the product), the handling system (e.g. on the shape of the product), the storage system (e.g. on the size of the product), and the overall computer system should be considered. In other words, assuming similar machining capabilities, the less automated types have a larger product flexibility range (see §3.1.2). Moreover, often even if none of the constraints is violated, it takes less effort and time to introduce the new product in a less automated system. The reason for this is twofold, i.e. the number of interfaces that may create problems, is smaller (see e.g. [Meredith, 1989]), and the number of (automated)

subsystems that require special attention, is smaller. For instance, in the MF–Case described in §1.3.2, products were only prepared for operation on the FAM–Stations if the demand for the product was repetitive to some extent. Otherwise, the time and effort required for this preparation were regarded as wasted. Only in case the new product is a variant of an existing product (e.g. an identical product except for the diameter of a hole), the more automated systems may be faster in taking the product into production due to the higher set–up flexibility. To summarize: the product flexibility range of less automated systems usually is larger (i.e. these systems can cope with more changes), whereas within a small range of only minor product changes the more automated systems may be more flexible.

- Mix flexibility:
  The mix flexibility of a system heavily depends on the number of mix constraints of the system. Generally speaking, the larger systems have more mix constraints. For instance, the number of pallet set–ups to be stored on the manufacturing system may be limited in such a way that blocking or starving may occur, or the number of pockets still available in the tool magazines of one of the required machines may be insufficient. We conclude that the mix flexibility range of less automated systems is larger. However, as long as these constraints are not violated (in other words, in case of minor changes in the mix, and thus in a small flexibility range), the larger systems have a higher mix flexibility due to shorter set–up times.

- Volume flexibility:
  Usually the usable capacity of a manufacturing system can be increased by increasing the available capacity. Unfortunately, this volume flexibility of conventional manufacturing systems is limited due to the time it takes to organize working overtime or an extra shift, and due to the often limited social acceptability of working during night shifts. Therefore, the more automated the system is, the easier it is to fluctuate the capacity of the manufacturing system (e.g. with an unmanned shift). With the introduction of an automated pallet storage system the potential volume flexibility increases rapidly. In fact, with an automated storage system, the manufacturing system may work for as long as it takes to finish all operations on all loaded and stored pallet set–ups. However, the range of the volume flexibility depends on the number of hours the manufacturing system normally is utilized. If due to high investment costs the system is fully utilized for 24 hours a day, 7 days a week, there is no volume flexibility left at all. In other words, FAM–Stations and FAM–Shops have a much higher potential operational volume flexibility, but the actual volume flexibility of the manufacturing system in real life depends on its normally utilized capacity.

We conclude that the operational product flexibility and mix flexibility of the manufacturing systems described in §3.3.1, change gradually with each type of system. Usually the flexibility range of the less automated systems is larger. However, within a small range of product and mix changes, the more automated systems often have a shorter reaction time. This relation between flexibility range and reaction time is drawn in Fig.3.17.

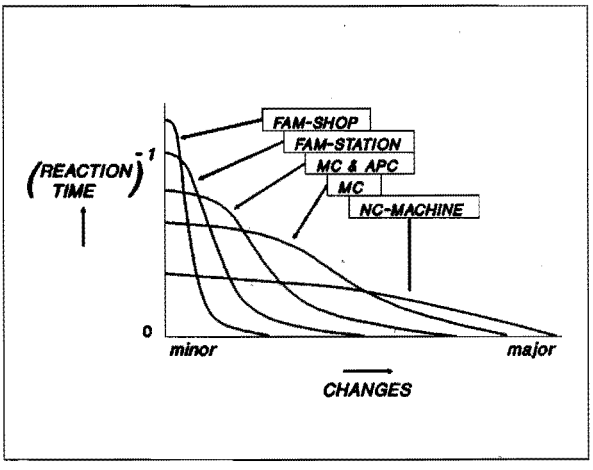

Figure 3.17:
The operational flexibility of manufacturing systems.

The volume flexibility of the manufacturing system depends heavily on the inclusion of an automated part storage system. Assuming an equal normally utilized capacity, the manufacturing systems including such a storage system require far less time to extend this utilized capacity.

Types of FAMS

In §3.2 we have defined a FAMS as an automated manufacturing system capable of dealing with changes in the products, in the mix of products, and in the volume of products to produce. As we have seen, every type has to some extend product flexibility and mix flexibility. However, due to the drastic change in operational volume flexibility with the introduction of an automated part storage system, we will call a flexibly (i.e. programmable) automated manufacturing system only a FAMS if such a part storage system is included. In other words, only FAM–Stations and FAM–Shops will be called FAMSs. Therefore, we may conclude that the FMSs as described in §1.1 indeed are FAMSs, but that an FAMS not necessarily satisfies the definition of an FMS. In the definition of an FAMS it is not necessary that transportation equipment is included, nor that more than one machine is required.

Chapter 4
PRODUCTION CONTROL ISSUES IN CASE OF FAMSs IN COMPONENT MANUFACTURING SHOPS

As we have seen in Chapter 2, the main concepts used by production control are capacity resources (modeled as servers or Production Units), work orders and operations. If these concepts do not change, the basics of the production control problem remain the same, even though the procedures used by production control to solve the problem may differ for each production system. Therefore, we first have to investigate whether the existing concepts are sufficient to describe the production control problem in case of FAMSs. After these production control concepts are identified, the changes required in the production control structure as presented in §2.3, and in the procedures used by the production control functions will be analysed.
Although in the remaining of this work we will focus on FAM-Stations as part of a component manufacturing shop, we also discuss some production control issues in case of FAM-Shops. The reason for doing so is the fact that FAM-Shops are discussed most in literature. In order to understand the applicability for our problem of the majority of the results for FAM-Shops, it is required to study these results more carefully. On top of that, a discussion on the production control issues in both cases also clarifies the important differences of both problems.

4.1 Production control issues in case of FAM-Stations

We will start the discussion on the production control issues in case of FAM-Stations with an overview of the required production control concepts. As we will see, some new concepts are required to describe the production control problem. In §4.1.2 we will have a closer look at the specific production control problems.

4.1.1 Production control concepts

In this sub-section, we will discuss the concepts concerning the capacity resources, the operations, and the work orders.

Capacity resources

Production Unit

In some cases, all operations on a part are performed on the FAM-Station. In these cases we may speak of 'stand-alone' FAM-Stations. Usually, these FAM-Stations replace several conventional machining tools. However, often FAM-Stations are part of a larger manufacturing system. In these larger manufacturing systems various types of machines may be available. For example, in the machining shop of the MF-Case (see §1.3.2), apart from two single FAM-Stations, also several MCs, CNC machine tools, and conventional machine tools were used. In these cases, completing all operations on a certain part usually requires several machines, the FAM-Station being only one of them. As we know from §2.3.1, the introduction of a PU should reduce the complexity of the production control problem. However, creating a PU especially for any of these machines, would increase the complexity of the GFC-problem, both because it would introduce extra PUs and because it would introduce loops in the goods flow considered by GFC (see Fig.4.1). On top of that, usually none of these machines is located at a place in the production structure where a substantial change occurs in the demand or production structure. In other words, only limited advantages may be obtained by creating such a PU (if any). Therefore, in these cases the entire set of machining tools is regarded as one Production Unit.

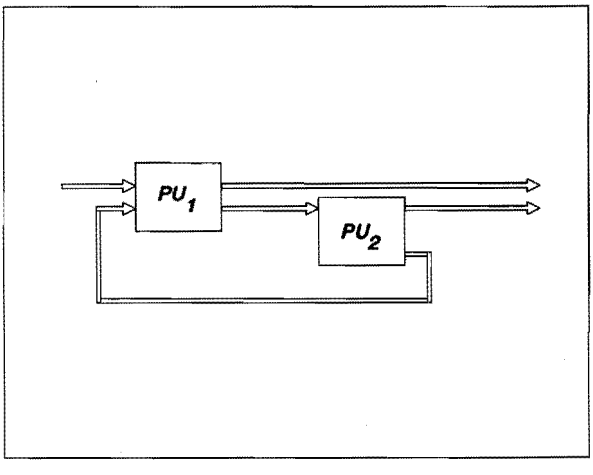

Figure 4.1:
Goods flow considered by GFC
when creating a PU especially for the FAM-Station.

Manned production versus unmanned production

One of the most striking characteristics of a FAM-Station (or FAMSs in general), is the ability to produce unmanned for several hours (see §3.3.1). Often this capability is considered to be an important advantage of FAMSs

over all other flexibly automated manufacturing systems. Using an unmanned shift, e.g. during the night, may create volume flexibility (see §3.3.3) in a socially acceptable way. In many cases the possibility of such an unmanned shift is used in the economical justification of the FAMS. From case studies we know that for FAM-Stations it is not uncommon to assume an average unmanned production of two to four hours a day (see also [Slomp and Spijkerman, 1988]).
During the *unmanned shift* no operator is available for loading and unloading activities. Therefore, all the loading and unloading activities of parts and tools should take place before the start and after the end of the unmanned shift. As a consequence, at the start of each unmanned shift several pallet set-ups are required in order to utilize the available unmanned capacity as much as possible. During the *manned shift(s)* operators may change system set-ups, pallet set-ups, and the set of loaded parts at any time during the shift. As long as for each machine in the FAM-Station at least one pallet set-up with one or more parts is ready for operation and all the required cutting tools are loaded, there will be no loss of machine capacity.

Operations

Attended operations versus unattended operations

The basic element in FAM-Stations is the NC-machine or Manufacturing Centre. Often in conventional machining shops it is assumed that no production is possible without the presence of an operator. In that case, the operator capacity required for a certain operation equals the required machine capacity. The work load for both capacity resources due to a certain operation, equals the set-up and operation time of the operation.

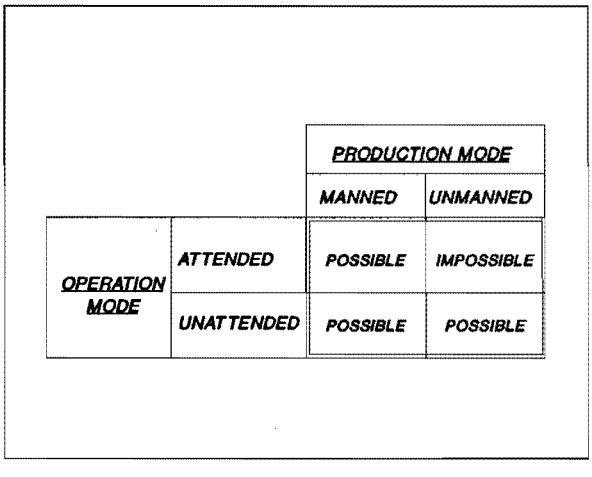

Figure 4.2:
The relation between attended/unattended operations and manned/unmanned shifts.

Also in case of automated machines the presence of an operator during the operation may still be required. In fact, in many real life situations, most operations require the continuous attendance of an operator. The reason for this fact is that often the automatic process control is insufficient to control the entire operation process. We will call these operations *attended operations*. However, as we have seen in §3.3.1, one of the differences of NC–machines with non–automated conventional machines is the fact that for some operations, the presence of the operator during the operation is not required anymore. These kind of operations will be called *unattended operations*.
During the unmanned shift only unattended operations can be performed, while during the manned shift, both attended and unattended operations are possible (see Fig.4.2). In case of unattended operations during the manned shift, the operator may perform other tasks, like deburring or testing of parts, preparing set–ups for other parts, or attending operations on other machines. Also in case of most attended operations, usually the operator may perform some other tasks as long as these tasks are performed at the FAM–Station. In other words, usually attended operations do not require a strict attendance, but merely the presence of the operator in case something goes wrong.

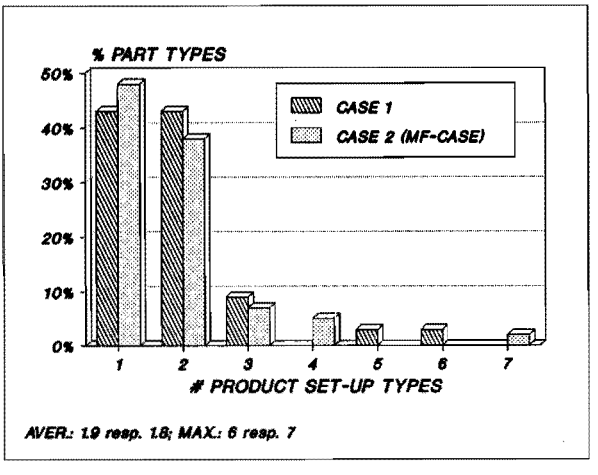

Figure 4.3:
The number of product set–up types required in two cases.

Product set–up types
In §3.3.1 we have mentioned the fact that not always all operations required on a workpiece on a FAM–Station can be performed in one type of product set–up. In Fig.4.3 the number of product set–up types required in two of the cases we studied (including the MF–Case), are given.
Assuming that the FAM–Station is regarded by PUC as a server, one way of looking at these set–up types is to regard them as separate operations to be performed on the same FAM–Station (in short: a FAMS–operation). The

alternative to this option is to regard all product set–up types together as one FAMS–operation. For instance, let us assume that the parts of a particular work order require two different product set–ups in order to be completed. In the first case, these product set–ups are regarded as two distinct subsequential operations in the process plan. In the latter case, only one operation is mentioned in the process plan, thus simplifying the PUC–problem. Also, in the first case, we have to estimate the flow time for each product set–up separately, while in the second case only one flow time estimate is used (see also Fig.4.4).

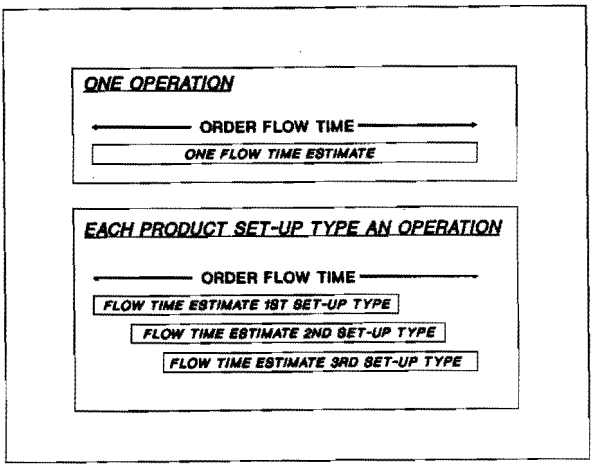

Figure 4.4:
Flow time estimates
in case each product set–up type is defined as an operation,
resp. in case all product set–up types are defined as one single operation.

Work order

Order contents

In many cases, a work order lot–size of one part will not be applicable for FAM–Stations. There are several reasons for this.
First of all, the contents of a work order should not only be determined by the characteristics of the operations on the FAM–Station, but also by the characteristics of the other operations on other work stations. In many cases, due to higher set–up times these other work stations are less flexible than the FAM–Station concerning lot–sizes. In other words, often the lot–size of a work order is determined by other work stations, not by the FAM–Stations.
Besides, often not all processes on the FAM–Station are controlled sufficiently to be regarded as unattended operations. Often it is difficult to achieve the required position and tool measure accuracy. Sometimes the first product is regarded as a test–product, and the measures of this

test–product are used to correct the offset values of the cutting tools. Therefore, once the required accuracy is achieved, it is desirable to produce several parts instead of one.
On top of that, although machine set–up times are reduced, they often have not disappeared completely. In Table 4.1 an example is given of some estimates of the time spent by several capacity resources and departments on the preparation of a new work order, depending on the familiarity with the product to be produced. These estimates are made in cooperation with FAM–Station operators. As we can see, there are three sets of capacity resources that may be involved in the preparation activities for FAM–Stations. First of all, usually an operator is required for mounting positioning tools on pallets, for loading and unloading of parts and cutting tools, for taking some measurements on the test–product, and for attending the operation on the test–product in order to validate the NC–program. Secondly, also other departments and operators may be involved in

Table 4.1:
An estimate of the time required to prepare a FAM–Station for a new work order (in hours).

Capacity resource	Activity	Product category New	Changed	Old
Machine	– changing cutting tools	0.2	0.2	0.2
	– changing NC–progr./offsets	–.–	–.–	–.–
	– dry run	1.5	–.–	–.–
	– reduced speed first part(s)	1.5	1.0	–.–
	– measuring first part(s)	1.3	0.8	0.3
	– gauging pallet set–up	1.5	1.0	1.0
	total preparation time:	6.0	3.0	1.5
Operator	– machine set–up time	6.0	3.0	1.5
	– inspecting first part(s)	1.0	0.5	–.–
	– preparing pallet set–up	2.0	1.0	1.0
	total preparation time:	9.0	4.5	2.5
Other	– inspection department	1.5	0.8	0.3
	– programming department	?	?	?

N.B.: Negligible times are denoted as '–.–'

preparing the operation on a particular part type. For instance, tools may have to be prepared by a tool management department, and extra capacity may be required from the measuring department for measuring the test–product. Also, NC–programs may have to be checked and/or downloaded to the FAM–Station by the programming department. Finally, although the machine set–up time will be reduced considerably, still there may be some time left that should be regarded as set–up time. In case of a new product, a dry run may be required. In case of changes in a product design or in the tools used, some measurements may be required while the

pallet set-up remains on the machine, or the operation may be carried out on half speed. Also, the use of the first part as a test part requires extra time.
Therefore, we will assume a work order lot-size larger than one.

Order structure
Usually, in single-stage manufacturing systems work orders are the lowest level of production orders taken into consideration by production control (see §2.2). Although each work order consists of several items, the order is treated as a unity, because it is assumed that the operation to be performed by the manufacturing system on a work order, is completed before the operation of other work orders are started. In that case, the way in which the operation is carried out, is not relevant for production control. Only the total operation time is of interest to production control. The operation is considered to be a basic operation (see §2.2).
In case of a FAM-Station this may not be true anymore. Due to:
- the ability to store several pallet set-ups on the system,
- the ability to exchange pallet set-ups containing parts belonging to different work orders, without a loss in productive capacity,
- and the possible limitation in the number of identical product set-ups concurrently on the system,

several work orders may be in operation at the same time. If that is the case, the way in which the FAMS-operation is carried out, becomes relevant for production control.
In order to be able to describe the FAMS-operation in more detail, first of all we require the concept of a 'cycle'. We define a *cycle* as a set of parts belonging to the same work order, that always are loaded together in a product set-up during the entire FAMS-operation. A cycle will be re-loaded once or several times in case more than one product set-up type is required to complete the FAMS-operation. The number of cycles required to complete all parts of a work order in all required product set-up types will be called the *cycle-size* of the work order.
In case only one product set-up type is required to complete a part, the entire set of parts loaded in one product set-up can be regarded as a cycle. For instance, let us assume that a work order *A* contains six identical parts (*p1,..,p6*). Also, let us assume that it is possible to load two parts together in a product set-up. In that case, the set of the first two parts of the work order (i.e. {*p1,p2*}) is called a cycle; likewise both the set {*p3,p4*} and {*p5,p6*} are called cycles. The cycle-size of the work order is 3.
Fig.4.5 presents two more complex cases. In both cases two product set-up types are required to complete a part of work order *A* (i.e. *ProST1* and *ProST2*). In other words, every part has to be re-loaded once in a different product set-up in order to be completed. In the first case, 2 parts are loaded together in a product set-up of the type *ProST1*. Since also 2 parts can be loaded together in the product set-up of type *ProST2*, *p1* and *p2* remain together during the entire FAMS-operation. Therefore, we can regard the set {*p1,p2*} as one cycle (*c1*). Likewise, we can regard each of the sets {*p3,p4*} and {*p5,p6*} as a cycle (*c2* resp. *c3*). Consequently, the cycle-size of work order *A* in case I is 3. In the second case the number of parts loaded together in a product set-up of type *ProST1* is 3 instead of 2. In other words, first *p1,p2,* and *p3* are loaded together in a product set-up of type *ProST1*. After the operation on these parts is completed, only the first two parts are re-loaded together in a product set-up of *ProST2*. The third part will be re-loaded some time later together with part *p4*. Clearly, it is not possible to regard {p1,p2,p3} as one cycle. Instead, the number of parts belonging to one cycle should be chosen equal to the greatest

common divisor of the numbers of parts loaded together in the product set-ups of all product set-up types required to complete the work order. In this case, the greatest common divisor is one; consequently each individual part should be regarded as one cycle (*c1* till *c6*). In this second case, the cycle-size equals the lot-size of work order *A* (viz. 6).

CHARACTERICS WORK ORDER A

- Lot-size: 6
- Product Set-up Types: ProST1 and ProST2

CHARACTERICS PRODUCT SET-UP TYPES

set-up type	# parts/set-up case I	# parts/set-up case II	# available set-ups
ProST1	2	3	1
ProST2	2	2	1

CYCLE-STRUCTURE OF WORK ORDER A

PARTS	CYCLES CASE I	CYCLES CASE II
p1	c1 (p1,p2)	c1 (p1)
p2		c2 (p2)
p3	c2 (p3,p4)	c3 (p3)
p4		c4 (p4)
p5	c3 (p5,p6)	c5 (p5)
p6		c6 (p6)

Figure 4.5:
Example of cycle-structure of a work order in two cases.

Preferably, the number of parts loaded together in one product set-up is equal for all types of product set-ups required for a work order (see case I in Fig.4.5). In such a case, cycles that are completed in the first product set-up type, can be re-loaded immediately in a product set-up of the second product set-up type. If such is not the case, it will be necessary to unload parts from the FAM-Station and store them temporarily, because it is not possible to re-load them immediately in a product set-up of the next type (e.g. part *p3* in the second case of the example of Fig.4.5, which has to wait for the completion of the first operation on part *p4* before it can be re-loaded in a product set-up of type *ProST2*). As a result, two parts stored at the FAM-Station may belong to the same work order, but their 'status' may be completely different. This will require extra handling activities and may impose additional organizational, scheduling and lay-out problems. Especially if more than two product set-up types are required, the situation at the FAM-Station may become quite complex.

Unfortunately, the introduction of the concept of a cycle is not sufficient to describe a FAMS-operation in the required level of detailness. We also have to describe the way cycles are combined on pallets. Therefore, we will introduce the concept of a 'run batch'. A *run batch* is defined as the set of cycles loaded together on one pallet (thus also in the same pallet set-up). Usually these run batches contain cycles belonging to the same work order (but possibly in a different type of product set-up), or cycles belonging to

work orders that always come together (e.g. because both part types are required at the same time for assembly).
In the example of Fig.4.6 (based on the cases of Fig.4.5), each pallet set-up of the pallet set-up type *PalST1* contains two product set-ups of type *ProST1* resp. *ProST2*. We assume that the number of identical product set-ups of each product set-up type is limited to one. As a result, also the number of pallet set-ups of type *PalST1* is limited to one. In case I the first run batch (*rb1*) contains only one cycle (viz. *c1*, loaded in the product set-up of type *ProST1*) since no cycle is available yet that can be loaded in the second product set-up. After *rb1* is completed and unloaded from the pallet set-up, the second run batch can be loaded. This second run batch (*rb2*) contains the second cycle of order *A* (loaded in the first product set-up) and, again, the first cycle (re-loaded in the second product set-up). The last run batch (*rb4*) contains only the last cycle (loaded in the second product set-up). In case II, the first run batch contains the first

CHARACTERISTICS PALLET SET-UP TYPES

# Product set-ups / pallet set-up	ProST1	ProST2
PalST1	1	1

STRUCTURE OF WORK ORDER A

PARTS	CYCLES		RUN BATCHES	
	CASE I	CASE II	CASE I	CASE II
p1	c1	c1	rb1 (c1,--)	rb1 (c1/c2/c3,--/--)
p2	(p1,p2)	c2		
p3	c2	c3	rb2 (c2,c1)	rb2 (c4/c5/c6,c1/c2)
p4	(p3,p4)	c4	rb3 (c3,c2)	rb3 (--/--/--,c3/c4)
p5	c3	c5		
p6	(p5,p6)	c6	rb4 (--,c3)	rb4 (--/--/--,c5/c6)

NB: ORDER- AND PRODUCT SET-UP CHARACTERISTICS: SEE FIG.4.5

Figure 4.6:
Example of cycle- and run batch-structure of a work order in two cases.

three cycles, all loaded in the first product set-up. The second run batch contains the last three cycles (loaded in the first product set-up) and the first two cycles (loaded in the second product set-up). Clearly, in both cases the number run batches required to complete the work order is 4.
At FAM-Stations, sequencing decisions have to be made between the run batches, not between work orders. For instance, decisions have to be made on which run batch should be loaded next, and which of the loaded run batches should be taken into operation next. In other words, work orders are split up into 'sub-orders' (i.e. cycles), and these 'sub-orders' may be combined with other 'sub-orders' to a new set of parts, called a run batch (in [Zeestraten, 1989] such a 'sub-order' concerning the loading, operating, and unloading of a run batch is called a 'task'). Interrupting an operation on a run batch would create the problem of keeping track of the status of

each run batch and of starting the NC-program at an arbitrary point. Usually, the automatic process control is not capable of doing so. Therefore, once the operation on a run batch is started, it will be completed before another run batch is taken into operation. As a result, it is not required to consider the operation on each part, or on each cycle separately. Consequently, we can call each operation on a run batch a basic operation. At least the production control functions concerned with the work order progress at the FAM-Station should be able to model this more complex order structure. If the complex order structure is required to comprehend the characteristics of the FAM-Station (e.g. in order to estimate flow times), also other control functions should be able to model the structure.

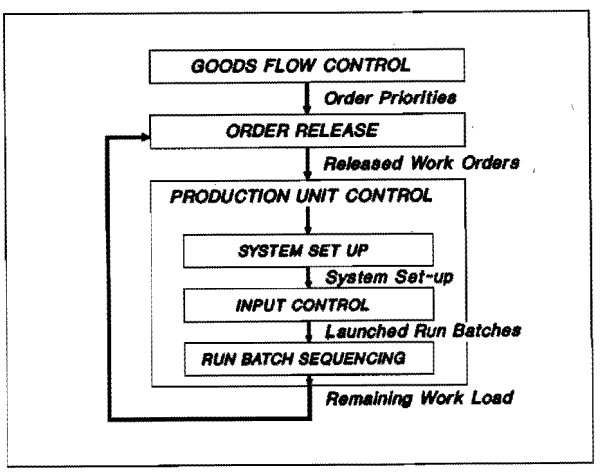

Figure 4.7:
Production control functions in case of FAM-Stations.

4.1.2 Production control functions

In Fig.4.7 an overview is given of the production control functions in case of FAM-Stations. As we can see, especially Production Unit Control requires some additional control functions as compared to the traditional PUC (cf. §2.3.3). In this subsection we will discuss these control functions.

Goods Flow Control

Usually FAM-Stations face set-up problems, as described in §2.2. In theory, a part of the set-up time required may be sequence-dependent, i.e. the time required to change the set of tools. However, in low volume component manufacturing often the positioning tool(s) required for a certain part type are unique for that part type. Therefore, it hardly will be

possible to create a work order sequence in which the pallet set-up mounting and dismounting time is reduced considerably. Also, the overlap in the set of cutting tools required for each work order is rather small. In Fig.4.8 an example of this overlap is given for two cases we studied (including the MF-Case). The real overlap in cutting tools between NC-programs may be even smaller than in the example given. Frequently the offset values of a cutting tool not only compensate for the tool measures, but also for measure deviations due to e.g. the bending of the cutting tool and/or spindle. These measure deviations are part-specific. For other part types other offset values are required. In many cases, the automatic process control of the FAM-Station is not capable of coupling different offset values to one cutting tool. Therefore, such a cutting tool can only be used for one specific type of part at a time.

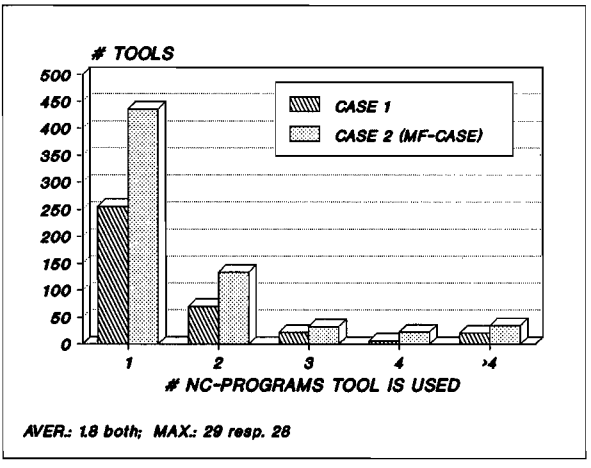

Figure 4.8:
Example of the number of times a cutting tool is required in an NC-program in low volume component manufacturing.

As we can see, also from the point of view of the cutting tools it hardly will be possible to reduce the set-up times.
Given the fact that the entire set of tools loaded in the tool magazine is limited due to a limited number of tool pockets, the FAM-Station also faces a mix problem. However, due to the fact that FAM-Stations are single-stage manufacturing systems, these problems are not very complex. For example, it is easy to change the set of tools in a tool magazine in a flexible way (i.e. every time a work order is completed). All it takes is to review the contents of one tool magazine and to check whether the required tools can be loaded and, if necessary, which tools should be unloaded. Also, the utilization of the machine capacities is guaranteed as long as for each machine in the FAM-Station at least one run batch is loaded that still requires an operation on that machine.

On top of that, the Goods Flow Control function is not permitted to influence the progress of work orders inside the PU. Therefore, in case the FAM-Station is only a subset of the set of capacity resources that are part of the PU, the mix of orders at the same time present at the FAM-Station cannot be pre-determined by GFC. In such a case, it would be difficult for GFC to consider the special set-up characteristics of the FAM-Station. Therefore, it can be expected that the set-up and mix problems can be solved at a lower level of control. The FAM-Station, if it is a bottleneck, will be modeled as any of the other bottlenecks of the PU, i.e. in aggregate capacity terms. Of course, the capacity terms that should be used by GFC, will depend on the required capacity concepts. Especially the fact that not all operations can be performed in both production modes (i.e. manned or unmanned production) will impose new capacity constraints. Therefore, the relation between the production mode and the operation mode (attended and unattended) requires a further analysis.

Order release

The problem of releasing work orders to the PU usually is a dynamic problem. It is very unlikely that the PU will be empty (i.e. no work load remaining) at the moment of order release. Since the order release function releases work orders based on the work load of the bottleneck capacity resources of the PU (see §2.3.3), the first prerequisite for this production control function is the availability of information on the work load of each relevant capacity type. In case the (concepts for modeling the) relevant capacity types change (e.g. due the difference between attended and unattended operations), also the requirements on work load information may change.

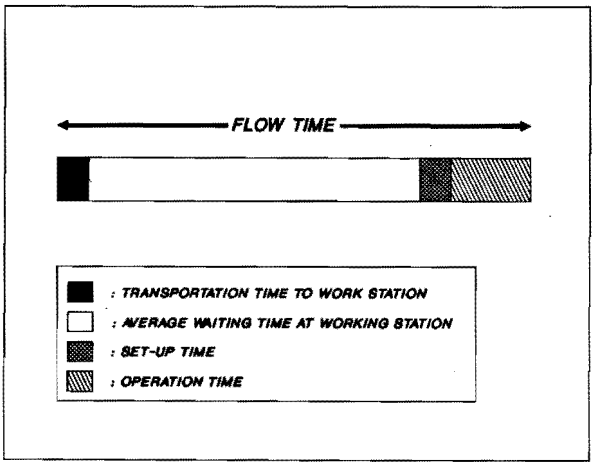

Figure 4.9:
Expected flow time at conventional stations.

Also, usually the work orders and even the operations are given due dates, either based on the release date and the norm flow times, or on the order due date and the norm flow times (see §2.3.2). Therefore, a second prerequisite for this production control function is the availability of flow time estimates for each server. A typical flow time estimate used at conventional stations in many component manufacturing shops, is given in Fig.4.9. The estimated flow time per work station is equal to the sum of the estimated transportation time to the station, the estimated waiting time at the station, the set-up time, and the operation time. In this estimate it is assumed that all operations on all parts of a work order are completed before operations on parts of a next work order are started.
An important question to be answered is, if there is any difference between the flow time behaviour of work orders at conventional work stations and the flow time behaviour of work orders at FAM-Stations. If there is no difference at all, we can use existing models for estimating flow times. Only the values used in the models are likely to change, as is the case when for instance Machining Centres are applied (see §3.3.1). However, we know from §3.3.1 that in case of a FAM-Station, not only the set-up time required for each work order changes, but possibly also the sequence in which work orders are completed. As we know from queueing theory, both aspects are likely to influence the waiting times, and therefore also the flow times.

Production Unit Control

As we have seen in §2.3.3, the objective of PUC is to meet the work order due dates. In order to achieve this objective, several decisions have to be made by PUC.

System set-up
Once a work order has arrived at the FAM-Station, two decisions have to be made before the operation on the first cycle of the work order can be started. First of all, we have to decide on the timing of the preparation of the required pallet set-ups. Usually not only pallets and/or positioning tools must be prepared, but also the required cutting tools. After the preparation of a pallet set-up, the operation(s) must be allocated to the machines. This decision is only relevant in case of a multiple FAM-Station without an automatic central storage of cutting tools. Physically this allocation results into the loading of the cutting tools into the local tool magazines.
Also, decisions have to be made concerning the unloading and/or dismounting of cutting tools and pallet set-ups. These decisions may be linked in such a way that the tools always are dismounted immediately after unloading. However, if it is possible to store mounted tools after being unloaded from the FAM-Station, the dismounting decision can be made more or less independent of the unloading decision.

Input Control
Once the required set-up decisions have been made, we have to decide on the time the run batches should be launched to the system. Pallet set-ups not containing launched run batches may be kept in a separate storage that is not automatically linked to the FAM-Station, or on the system, e.g. on the load/unload places. However, usually the automatic control system will regard all loaded pallets containing a non-completed run batch as 'active' pallets, i.e. as pallets competing for machine capacity. Therefore, in case non-launched run batches are stored on the station, it should be possible

either to withdraw pallets located on the system from the automatic control system, or to give the pallets a special status ('passive').

Run Batch Sequencing
Given a set of launched run batches still requiring an operation, a decision has to be made on the operating sequence of run batches. In component manufacturing shops often work order or operation due date information is used for determining operating sequences, sometimes combined with set-up considerations (see §2.3.3). In FAM-Stations, often the run batch sequence is determined by the automatic control system. Due to hardware and software reasons, this control system may be limited in its freedom of allocating priorities. For example, the material handling system may only be capable of applying the FCFS-rule due to hardware constraints. Also, the software may be designed in such a way that run batches can be taken into operation only according to a pre-fixed sequence. On top of that, also due to the special way work orders are completed on the FAM-Station, it is to be questioned if the same priority rules can or should be used.

Progress Monitoring
The last production control function that might be influenced by the introduction of FAM-Stations, is the Progress Monitoring function. The main purpose of this function is not only to monitor the progress of work orders, but also to monitor the remaining work load for a particular server (see §2.3.3). Since several work orders may be in operation at the same time, the total time a work order is in operation will increase compared to the situation where only one work order is in operation at the same time. As a result, the registered status of the work order may differ more from the real status of the order than in case of sequential production.

4.2 Production control issues in case of FAM-Shops

Most literature on FAMSs concerns FAM-Shops. At first sight, it may appear that if the production control problems of these FAM-Shops are solved, the solutions will also be applicable to FAM-Stations, for FAM-Shops include all the characteristics of FAM-Stations (see §3.3.1). However, as we will see, often this will not be the case.
We will first discuss the production control concepts required to describe the production control problems in case of FAM-Shops, and compare these with the concepts required in case of FAM-Stations. In § 4.2.2 the control problems studied in literature and the proposed solutions will be discussed.

4.2.1 Production control concepts

As we have done in §4.1.1, we will discuss the concepts concerning the capacity resources, the operations, and the work orders.

Capacity resources

Production Unit

Often a FAM-Shop comprises all capacity resources required for completing all operations on a certain part. Therefore, in literature, usually a FAM-Shop is considered as a Production Unit as defined in §2.3.1. Because of that, in order to solve the PUC-problem, it is possible to use a production control structure specially designed for FAM-Shops (see e.g. [Bakker, 1989] and [Zeestraten, 1989]). As we have seen in §4.1.1, this is not the case for many FAM-Stations.
Sometimes the FAM-Shop is sub-divided into several Production Units. For instance, Kusiak suggests to group the machines in a FAM-Shop into several uncoupled servers (called 'cells') in order to reduce the size of the loading problem [Kusiak, 1985]. These cells are logical cells, as opposed to the physical cells used in traditional Group Technology. Each of these cells manufactures a particular set of part types. In other words, each cell is regarded as a separate PU with its own PU-Control problem. Because of this more flexible cell concept, the machines can be regrouped easily into new cells if the set of part types to be produced changes.

Manned production versus unmanned production

In most studies concerning the production control problems of FAM-Shops, no explicit assumption is made regarding the production mode. However, as we will see in the next subsection, the proposed solutions to the system set-up problems solved by Order Release are likely to be based on an implicit assumption on the production mode.

Operations

Operation characteristics

Generally, it is assumed that all processes to be performed on the FAM-Shop are controlled sufficiently by the automatic process control. Therefore, no operator is required to attend operations; all operations are regarded as unattended operations. Only recently, Zeestraten suggested to introduce an attribute to the set of operations to be performed on the FAM-Shop, which specifies whether the set can be performed during an unmanned shift [Zeestraten, 1989]. His consideration to include this attribute was that it may be decided not to perform certain types of operations during an unmanned shift in order to prevent machine failures.
A further assumption often made, is that all operations required to produce a part can be performed in one product set-up. Therefore, no re-loading of parts is required (see e.g. [Hwang, 1986]). Again, an exception to this assumption can be found in [Zeestraten, 1989].

Process plan and routing

A FAM-Shop is a multi-stage manufacturing system. Therefore, as opposed to FAM-Stations, parts have to follow a routing on the FAM-Shop. Because of the flexibility of the FAM-Shop, one out of four distinct assumptions is to be made regarding the process plan and routings of parts inside the FAM-Shop.
First of all, the process plan may be considered as fixed. All operations of the process plan are known, and the sequence of the operations is fixed. The only flexibility left, is the machine that will perform the operation. However, the time required to perform the operation is independent of the machine. An example of such a case is given in Fig.4.10.

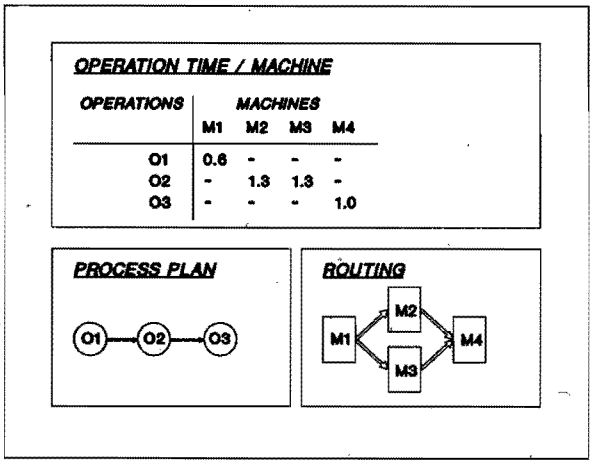

Figure 4.10:
Routing flexibility due to parallel machines.

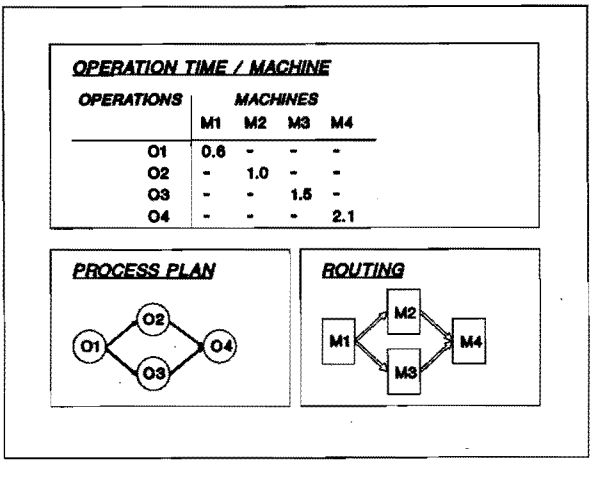

Figure 4.11:
Routing flexibility due to alternative operations.

Secondly, the result of a particular operation may also be obtained by one or more other operations. The sequence of operations before and after these

operations is equal for all operations. However, the time required for the alternative operation(s) differs from the original operation time, because the operations are carried out on different machine types (see Fig.4.11).
Thirdly, all operations required are known, but in the process plan the fixed part of the sequence of operations is strictly limited to the sequence required from a technical point of view. In other words, the process plan only gives the strict precedence relations between the operations. Alternative sequences are possible (see Fig.4.12).

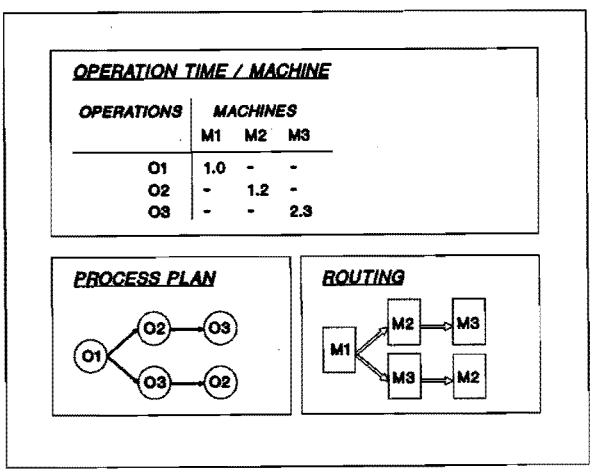

Figure 4.12:
Routing flexibility due to alternative sequences.

Finally, instead of having only one process plan, several process plans may be applicable (see Fig.4.13). In such a case, the set of operations to be performed depends on the process plan chosen.

In most literature on production control of FAMSs the first type of routing flexibility is assumed; sometimes also the second routing flexibility is considered. Only recently, production control in case of process plan flexibility has become a research topic (see e.g. [Lin and Solberg, 1989]). A prerequisite for this kind of research is the availability of alternative process plans, which in many organizations is not the case yet. On top of that, due to the versatility of the machine tools used in FAM-Shops, often it is not required to have alternative process plans in order to create a high level of routing flexibility.
In low volume manufacturing usually only one process plan is available. Also, for each operation, often only one NC-program is available. Therefore, we will assume only the first type of routing flexibility, e.g. in case of a multiple FAM-Station with identical machine tools.

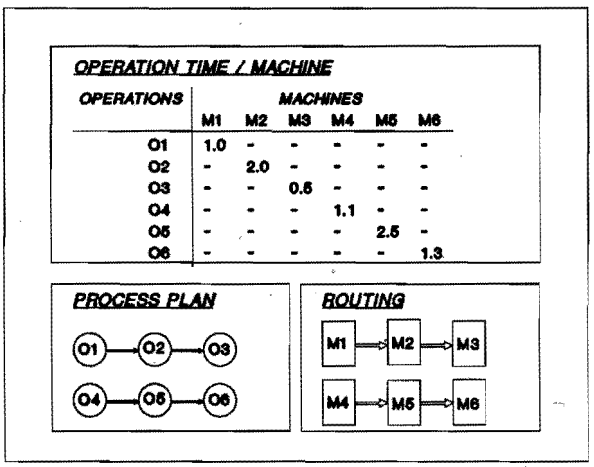

Figure 4.13:
Routing flexibility due to alternative process plans.

Work order

Order contents and structure

In literature it is assumed that the set of parts to be produced by the FAM-Shop during the next production period is selected by a higher level of control (e.g. the Master Production Schedule in an MRP-environment; see for instance [Kimemia and Gershwin, 1983], [Suri and Whitney, 1984], [Bakker, 1989] and [Mazzola et al., 1989]). We would call this higher level of control the Goods Flow Control level. The selected set of parts is known as the *production order* (see e.g. [Hwang, 1986]). In order to distinct this specific meaning of the term 'production order' from the more general meaning introduced in §2.2, we will denote the specific term as 'production program'.

In case of FAM-Shops, as opposed to FAM-Stations, often a lot-for-lot production is assumed, because of the following considerations:

- The FAM-Shop is considered to be a PU (as opposed to many FAM-Stations) which delivers parts to an assembly department that requires no batches. Therefore the lot-size can be determined entirely by the characteristics of the FAMS.
- The machine set-up time is reduced considerably, as is the case for FAM-Stations.
- The production output is assumed to be independent of the lot-size, due to the fact that the automatic process control is capable of achieving the required accuracy at once.

In other words, usually each work order is supposed to contain exactly one part. Even if work orders contain more than one part, usually it is assumed that the cycle size of the work order is one (see e.g. [Millar, 1986]). Also, each run batch is supposed to contain only one cycle. As a

result, each run batch covers exactly one work order. Therefore, there is no need to introduce the concepts of a cycle and a run batch in order to describe the production control problem. Only in [Zeestraten, 1989] concepts similar to a cycle and a run batch can be found.

4.2.2 Production control functions

In the discussion on the production control functions in case of FAM–Shops, we will distinguish the two levels of production control as described in §2.3, including the interface between these two levels (the Order Release level; see Fig.4.14). The relevant relationships of the FAM–Shop with its environment are controlled by what we have called the Goods Flow Control function. The Order Release function especially focuses on the FAM–Shop set–up problem, i.e. on the loading and unloading of the required tools. As we will see, most literature is concerned with this system set–up problem. Finally, Production Unit Control should determine the sequence and timing of the (un–)loading of parts, and should control the progress of parts on the system. As we can see in Fig.4.14, PUC again consists of several production control functions.
Each discussion on a production control function for FAM–Shops will be concluded with a discussion on the applicability to FAM–Stations.

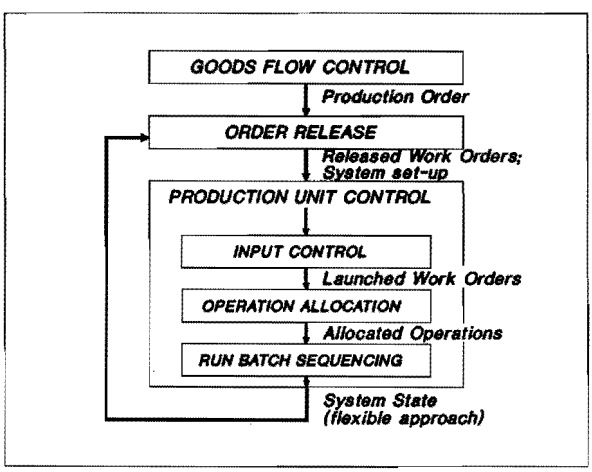

Figure 4.14:
Production control functions in case of FAM–Shops.

Goods Flow Control

As we have seen in the previous subsection, usually the Goods Flow Control (GFC) level selects a production program. Often it is assumed that

existing methods used at the GFC-level which are not specifically designed for FAM-Shops, can be applied. The only difference may be the versatility of the machines in the FAM-Shop, which may result in less distinct capacity types and/or different operation times for different capacity types (see e.g. [Kusiak, 1985] and [Chakravarty and Shtub, 1986]).
In most studies, this production program is supposed to cover exactly one production or planning period. In an MRP environment such a production period may cover exactly one time bucket. In that case, the production program is supposed to be completed at the end of the time bucket [Mazzola et al., 1989]. Once the order has been selected, individual work order due dates and flow times are not important, for the remaining problem is to complete the entire production program during the production period. However, if the production program covers several time buckets, individual work order due dates may become important in order to be able to determine the priorities among the work orders (see also [Bakker, 1989] and [Zeestraten, 1989]). Because of the small lot sizes on the FAM-Shop, and the limited WIP-inventory, also in this case individual flow times are considered to be of minor importance. A survey of nineteen FAM-Shops in the U.S.A. seems to underline the validity of this assumption [Smith et al., 1986].

Applicability to FAM-Stations
Only in case of stand-alone FAM-Stations with small lot-sizes a concept similar to the production program covering exactly one production period will be applicable. However, in case the FAM-Station is part of a larger manufacturing system, or in case of larger lot-sizes, it would not be wise or possible to select a production program covering exactly one production period. In other words, we will assume at any time there will be some work load left in the Production Unit.

Order Release

Given a selected production program, the remaining production control problem is static by nature, viz. what should be the sequence in which the parts mentioned in the production program should be completed. In that case, the Order Release function mainly is concerned with the decision on the set-up of the FAM-Shop [Kiran and Tansel, 1986]. This set-up problem also is referred to as the (pre-release) planning problem ([Buzacott and Shanthikumar, 1980], [Stecke, 1985], [Kuhn, 1989]).
The work of Stecke has had a major impact especially on research on these FAM-Shop planning problems. She defines the FAM-Shop planning problems as *"...those decisions that have to be made before the FMS can begin to produce parts..."* [Stecke, 1985]. The planning problems include the following issues:
- Determination of a subset of *part types* for immediate and simultaneous manufacture (also called the part type selection problem); the FAM-Shop will be set up for the production of these part types.
- Partition of the set of machines in the FAM-Shop into machine groups in such a way that each machine in a particular group is able to perform the same set of operations. In other words, each machine in a machine group is identically tooled. This problem is known as the *pooling* problem. Pooling of machines reduces the flexibility of the FAM-Shop, since the routing flexibility of a particular operation will be limited to the set of machines belonging to the same machine pool. However, it also reduces the complexity of the production control problem.

- Determination of production ratios of the selected part types (the *part selection* problem). This decision determines the relative production rates of parts for each part type that is selected in the part type selection. As a result of this part selection, it is possible to determine the machine capacity required to complete the production program.
- Allocation of (limited) *tools* like pallets and fixtures among part types.
- Allocation of cutting tools among the pooled machines. This problem is also known as the (machine) *loading* problem (see e.g. [Stecke, 1983], [Van Looveren et al., 1986], [Kuhn, 1989]).

The emphasis in literature lays on the part (type) selection problem and the machine loading problem. Furthermore, usually it is assumed that the system cannot be set up for the entire production program at once. In other words, in order to complete the production program, one or more changes in the system set-up are required. More specific, two important assumptions are made [Hwang, 1986], i.e.:

- The system has limited capacity resources (particularly the tool magazine capacity) such that not all parts belonging to the production program can be produced simultaneously.
- No tool transfer between tool magazines (and central tool storage) is possible during the time the FAM-Shop is in operation. If automatic tool transfer is possible, the total tool magazine capacity would be virtually infinite.

If these assumptions are not valid, there is no need for a part (type) selection in order to set up the system. Examples of such a case can be found in [Bakker, 1989] and [Zeestraten, 1989].
Given the production program and the two assumptions described above, two solution approaches to the planning problems are being proposed, viz. a *batching* and a *flexible* approach.

Batching approach
Usually the FAM-Shop planning issues are regarded as a *batching* problem (see e.g. [Suri and Whitney, 1984], [Hwang, 1986], [Kusiak, 1986], [Van Looveren et al., 1986], [Stecke and Kim, 1988]). In order to solve the FAM-Shop set-up problems, the set of parts to be produced is divided into *set-up batches* [Dirne, 1987]. Each part belonging to a set-up batch will be produced without a change in the FAM-Shop set-up state. Between two set-up batches the system set-up state will be changed, in particular the set of cutting tools loaded into the tool magazines.
As Suri and Whitney state, *"...the main criterion the batching procedure should satisfy is to minimize the total time it takes to produce all parts..."* [Suri and Whitney, 1984]. In other words, only the makespan of the production program is considered, not the flow times of individual parts. They transform this criterion into two sub-criteria, i.e. minimization of the number of set-up batches required, and minimization of the makespan for each set-up batch through balancing of work load on the FAM-Shop. Mazzola et al. notice that at least in an MRP environment the minimization of the makespan of the entire production program should satisfy the time bucket constraint, i.e. all parts belonging to the production program should be completed within the time bucket [Mazzola et al., 1989]. If that is not possible, the due dates of the parts should be take into account. In fact, in these cases *"...the primary objective .... is to meet due dates..."* [Zeestraten, 1989].
Rajagopalan distinguishes two batching approaches [Rajagopalan, 1986]. First of all, the batching problem may be solved at the beginning of every change in the set-up state to obtain an optimal part mix only for the next set-up period. Once the set-up batch is completed, the batching problem is

solved again, thus facilitating possible alterations in the production program. Essentially this approach is a greedy method. Parts that are unfavourable from the point of view of the objective, will be selected late. Therefore, there is a danger that the objective described above concerning the minimization of the makespan of the production program, may not be achieved. Examples of this approach can be found in [Stecke, 1983], [Hwang, 1986], and [Kiran and Tansel, 1986].
In the second approach, the batching problem is solved for the entire production program. In other words, several set–up batches are created, with a tool change–over between two batches. This approach aims at avoiding poor schedules over the rest of the plan period. In [Rajagopalan, 1986] a typical goal function in this approach is given, i.e.:

$$\text{Minimize} \quad \Sigma_i(z_i S + h_i) \tag{4.1}$$

where:
z_i : $\{1,0\}$, if there is a i^{th} set–up batch or not;
S : time required for changing the set–up of the system;
h_i : total time required for completion of i^{th} set–up batch.

Often this objective function is transformed into a function minimizing the number of set–up batches required to complete the production program, or into a function balancing the work load. Examples of this approach can be found in [Rajagopalan, 1986] and [Mazzola et al., 1989].

Flexible approach
In the *flexible approach* it is assumed that when the production requirements of some part type are fulfilled, space in the tool magazine(s) is freed up. At that moment we can consider to change the system set–up to facilitate the introduction of one or more new part types, or to update the ratios of the set of part types already on the system (see e.g. [Stecke and Kim, 1988] and [Chung and Doong, 1989]).
The main difference with the batching approach is that no specific set–up periods exist anymore. Although the total set–up time remains the same, the idle time of the machines due to a change in the system set–up reduces considerably. Only those machines where cutting tools are changed, get idle; all the other machines may remain in operation. In [Stecke and Kim, 1988] an example is given of a FAM–Shop containing eight to ten machines, each with a tool magazine capacity of 60 tools. Assuming a change–over time per cutting tool of one minute and a batching approach, the replacement of tools may take as much as one shift.
Furthermore, in case the presence of operators is required to attend the processes and to change worn and broken cutting tools, the flexible approach has the advantage that the operator capacity is better used. On top of that, instead of a peak in the required operator capacity (and ATC–capacity), the use of capacity is leveled. On the other hand, if no operators are required to attend the system, the batching approach reduces the required operator capacity, and may concentrate the required operator capacity in a shift during daytime. However, this last potential advantage of the batching approach depends on the formulation of the planning problem. If the makespan per set–up batch is variable, there is no guarantee that the tool change–over period will correspond to a shift during daytime.

In [Stecke and Kim, 1988] a simulation experiment is used to compare the batching approach with the flexible approach. The conclusion is that for the type of systems studied, the use of the flexible approach tends to make the system more highly utilized and requires less positioning tools. Furthermore, the flexible approach can cope more easily with dynamic situations than the batching approach.

Applicability to FAM-Stations
As we have seen in §4.1, the system set-up problem for FAM-Stations is not solved at the Order Release level. Usually it is possible to change the set-up of the FAM-Station during the manned shifts in a flexible way. Sometimes this system set-up can be changed without the machine tool spindle getting idle. Therefore, every time the set of work orders to produce changes or priorities change, a reconsideration of the system set-up is possible. Especially in case the FAM-Station is not a stand-alone system, the environment will be dynamically. As a result, if possible, the flexible approach should be applied at FAM-Stations. Only in case of unmanned shifts some kind of batching approach is required. However, also in this case we assume that the production requirements will change in time.

Production Unit Control

Once the system set-up problems are solved, and all the cutting tools have been loaded into the tool magazines, production can begin. In literature, the PUC-problems are called the *FMS scheduling and sequencing problems* and are concerned with *"...running the FMS during real time once it has been set up during the planning stage..."* [Stecke, 1985]. Important scheduling and sequencing issues are:
- determination of loading sequence and time of parts from the selected part types, also known as *input control* or the dispatch decision (see e.g. [Buzacott and Shanthikumar, 1980], [Shanthikumar and Stecke, 1984]);
- determination of a schedule specifying the machine(s) on which the next operation(s) should be performed (we will call this issue the problem of *operation allocation*);
- determination of priorities among the parts waiting to be processed by the same machine (the problem of *run batch sequencing*).

Input Control
In case of a batching approach to the planning problems, sometimes not all parts of the same set-up batch are or can be loaded at the same time, e.g. because of a limited operator capacity. In such a case, the input control problem can be split up into a problem concerning the initial entry in an empty system and a problem concerning the general entry into a loaded system. A study of Nof et al. indicates that in this case initial entry effects cannot be neglected, since they appear every time a new set-up batch is loaded [Nof et al., 1979]. In the case they studied, the differences in production rate (i.e. parts per hour) due to the initial entry effects were as large as 10%. However, if loading times are small compared to the operation times, the effect of the initial entry will be small.
Several general entry strategies are suggested in [Nof et al., 1979], [Bell and Bilalis, 1982], [Buzacott, 1982b], [Denzler et al., 1987], and [Bakker, 1989]. Denzler et al. and Nof et al. agree on the preference of loading those parts with the largest proportion of requirements left. This rule aims to achieve a steady part mix on the FAM-Shop similar to the mix of all selected parts. Denzler et al. notice a similar performance of a rule which aims at

re-loading an unloaded pallet with a new part of the same part type. Again, this rule tries to achieve a steady part mix on the system. Buzacott stresses the importance of taking into account a possible limitation of buffer space in the FAM-Shop. In that case, blocking may occur, which may result in a dramatic decrease in throughput (see also [Tempelmeier et al., 1988]). In case of a limitation in buffer space, a random FAM-Shop containing two machines, and the First Come First Served priority rule at the machines, Buzacott suggests to use the idle machine rule, i.e. never load a part unless a machine is idle and the first operation of that part is at the idle machine.

Applicability to FAM-Stations
In case of a FAM-Station, there hardly are any initial entry problems. Especially in case of a single FAM-Station, or a multiple FAM-Station with identical tooled machine tools or an automated central tool magazine, the machine tools may start with any operation. Therefore, the effects of special initial entry strategies will be negligible. Also, it is very unlikely that the system will get blocked, unless a multiple FAM-Station is considered with a number of pallets that exceeds to a large extent the number of buffer places in the system. Finally, many of the entry policies studied aim to minimize the makespan of the selected production program. However, in a dynamic environment as in case of most FAM-Stations, the objective of PUC should be to meet the operation due dates of a work order. Minimizing the makespan of a subset of work orders selected in a production program, will not necessarily accomplish this.

Operation allocation
One of the remaining decisions concerns the choice of a machine to perform an operation. Generally it is assumed that the operations should be allocated as late as possible, thus leaving open all options still available after the system set-up (see e.g. [Nof et al., 1979], [Buzacott, 1982b], and [Lin and Solberg, 1989]). This could mean that operations are allocated to machines no sooner than the time at which the machine selects its next operation. In that case the operation allocation decision is at the same time the operation sequence decision. However, this may not always be possible, for instance because the buffer spaces in the FAM-Shop are located at the work-stations instead of at a central space.
Murotsu et al. studied three machine selection criteria in combination with transport device selection criteria [Murotsu et al., 1983]. In their study a FCFS-priority discipline is assumed at the individual machine tools. Furthermore, they assumed the second type of routing flexibility. They conclude that the rule which selects the machine on which the operation will be finished as soon as possible, is effective in minimizing both the makespan and the mean flow time. Apart from the operation time required, this rule also considers the work load present at each machine at the time of selection. The utilization rate of the machines during the makespan is maximized using the rule which selects the machine which becomes available at the earliest time. However, since the output rate is not increased nor the number of capacity resources decreased, we see no need to maximize this utilization rate. Finally, Murotsu et al. notice that selecting the machine which requires the shortest time to complete an operation, performs worst, both in mean flow time as in utilization rate. In this rule, the work load of the machines at the time of selection is not considered. Therefore, the possible routing flexibility will not be used. As a result, the work load per machine at a particular time can be very unbalanced, thus creating unnecessary long waiting times.

In other studies, often an allocation rule is assumed which aims at balancing the work load among the machines (see e.g. [Nof et al., 1979], [Denzler et al., 1987], [Bakker, 1989]).

Applicability to FAM–Stations
In most FAM–Stations in low volume component manufacturing there hardly will be any freedom in selecting a particular machine tool to perform an operation on a loaded run batch. Usually the number of identical cutting tools with identical offset values is low. Therefore, frequently operations are already allocated to a machine tool once the system has been set up to perform the operations. Changing this system set–up requires time, even if an automatic tool change system is used, and therefore may cause idle time on the machine tools. Therefore, we will assume that routing flexibility is only used at the system set–up level.

Run Batch sequencing
Stecke and Solberg state that sequencing using a pre–determined schedule has no advantages in case the system is subject to many random disturbances, and results in a mathematical intractable scheduling problem [Stecke and Solberg, 1981]. Co et al. studied the impact of different sequencing rules on the flow time of work orders in case of FAM–Shops with queues of short lengths [Co et al., 1988]. Their conclusion is that if there are any differences in performance between sequencing rules, these differences are small. The reason for this relative small impact of sequencing rules on system performance is that the number of options for each sequencing decision is limited. In a comment on the paper of Co et al., Hutchinson stresses the fact that in many FAM–Shops the use of sequencing rules is limited not only due to the relative small impact on the system performance, but also due to the possible inability of the system to apply a particular rule. For instance, the hardware of the FAM–Shop can make it impossible to apply a priority rule other than FCFS. Also the software of a FAM–Shop may impose limitations on the number of rules that can be applied.
However, as we know from many studies on job shops, in case the number of parts waiting for processing is not small, sequencing rules do have an impact on system performance. For examples of studies on sequencing rules assuming larger queues in FAM–Shops, we refer to [Nof et al., 1979], [Stecke and Solberg, 1981], [Bell and Bilalis, 1982], and [Co et al., 1988]. An interesting observation on sequencing rules is made by Bakker [Bakker, 1989]. He notices that if tools in a central tool magazine are to be allocated and transported to a local tool magazine of a machine in order to perform an operation, this will take time. Therefore, in order to prevent the machine tool from getting idle due to absence of cutting tools, the decision on which tools are to be transported to which machine tool, should be made some time before the actual operation is supposed to be started. Furthermore, once a decision has been made on the sequence of run batches, the run batches already sequenced shouldn't be delayed too much due to the arrival of new run batches. Otherwise the set of cutting tools stored in the tool magazine of the machine tool may have to be changed all over again. As a result, it only may be possible to apply a pre–determined schedule or a priority rule like the FCFS–rule.
Finally, Zeestraten stresses that *"... a better solution to the sequencing problem can be found if both the problem of assigning operations to work–stations* [i.e. the operation allocation problem], *and the problem of finding the near optimal sequence of operations on each work–station* [i.e. the run batch sequencing problem] *are solved concurrently ..."* [Zeestraten,

1989]. He suggests a so-called look ahead procedure, based on Branch and Bound techniques.

Applicability to FAM-Stations
The sequencing rules studied for FAM-Shops are evaluated on the flow times of individual cycles, since each work order contains exactly one cycle. However, the impact of a particular sequencing rule in case of a FAM-Station should not be measured on the flow time of one cycle (nor on the makespan of a set-up batch). Instead, the flow time of the entire work order should be considered. Therefore, one should be careful in applying a sequencing rule that performs well in FAM-Shops.

4.3 Conclusions

From the above comparison of the production control issues in case of FAM-Stations and those in case of FAM-Shops, the following conclusions can be drawn.

- First of all, the set-up problems of FAM-Stations are less complex than in case of FAM-Shops due to the fact that these systems are single-stage manufacturing systems. Therefore, the algorithms used by higher levels of control are less likely to be influenced by the introduction of these systems as compared to FAM-Shops.
- In most production control literature concerning FAM-Shops, usually the distinction between attended and unattended operations and manned and unmanned production is neglected. It is questionable if that is also possible in case of FAM-Stations, since both operation modes and production modes will appear.
- In case of FAM-Stations, work orders are likely to have a larger lot-size than in case of FAM-Shops.
- In case of FAM-Stations, the problem of a limited tool magazine capacity is not very complex. However, instead, due to the larger lot sizes, the limitation in the number of identical product set-ups concurrently on the system will have a larger impact.
- In case of FAM-Shops, individual work order flow times are considered to be negligible. Due to the work order lot-sizes this will not be true for FAM-Stations. Especially the effects of the simultaneous production of work orders requires a more detailed study.

In the next chapter we will concentrate on the models required by production control to cope with the capacity constraints of FAM-Stations due to the distinction in production modes and operation modes. In the following two chapters we will focus on the flow time behaviour of work orders on FAM-Stations, taking into account the specific characteristics mentioned in §4.1. Based on the results of Chapter 6 and 7, in Chapter 8 conclusions will be drawn regarding the estimators required by production control on the flow times of individual work orders. In Chapter 9 we will discuss the production control functions mentioned in §4.1.2 in more detail.

Chapter 5
FAM-STATION CAPACITY CONCEPTS

In Chapter 4 we have introduced some new concepts required to describe the production control problems of FAM-Stations. As we have seen, the most striking differences between FAM-Stations and conventional work stations on the one hand, and FAM-Stations and FAM-Shops on the other, are the distinction in production mode (manned or unmanned) and the distinction in operation mode (attended or unattended). In this chapter we will have a closer look at the concepts required to model the capacity of a FAM-Station.
In the first paragraph we will start with a discussion on the normative capacity of such a system, i.e. the capacity that may be utilized according to the norms set by Master Planning (see §2.3.2). With these norms it should be possible for Production Unit Control to achieve the required delivery performance (see also §2.3.1). In paragraph §5.2 we will study the capacity constraints of FAM-Stations. In the last paragraph we will draw some important conclusions from the discussion in the previous paragraphs.

5.1 Normative capacity

Both in case of a manned production mode and in case of an unmanned production mode, there is a limitation on the amount of work that can be completed on a FAM-Station during a certain time period. As usual, the absolute maximum is determined by the usable machine capacity in each time period. Due to a conflict between short flow times and a high productive use (see §2.2), the normative capacity to be utilized (or shortly: the normative capacity) is less than the usable capacity. The normative capacity of the machine tools of an FAM-Station (in short: the normative capacity of the FAM-Station) is the sum of the normative capacity in the unmanned production mode and the normative capacity during the manned production mode. Thus:

$$C_{n,t}(t) = C_{n,m}(t) + C_{n,u}(t) \qquad (5.1)$$

with:
$C_{n,t}(t)$: total normative capacity of FAM-Station during period t
$C_{n,m}(t)$: normative capacity in manned production mode during period t
$C_{n,u}(t)$: normative capacity in unmanned production mode during t

In Fig.5.1 this capacity structure is schematically drawn.

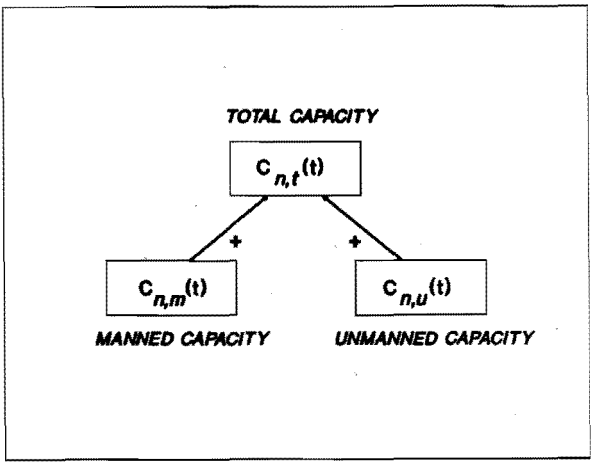

Figure 5.1:
Capacity structure of FAM–Station.

Before we determine the normative capacities in the manned and unmanned production mode, let us have a closer look at the storage of WIP–inventory at FAM–Stations. In Fig.5.2 it is shown that we can distinguish two parts

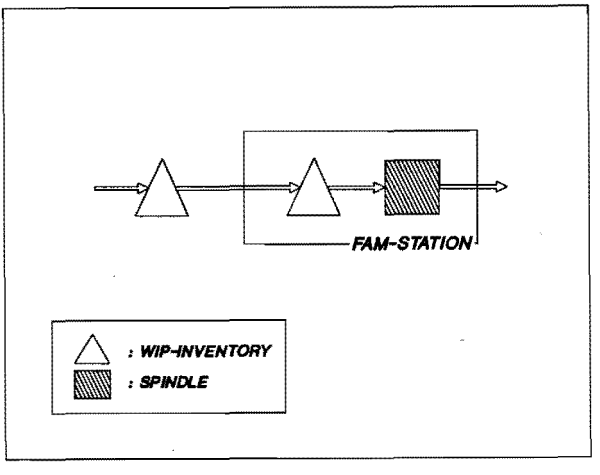

Figure 5.2:
WIP–inventory in front of and on a FAM–Station.

of WIP-inventory at a FAM-Station.
First of all, in front of the FAM-Station WIP-inventory is stored that is waiting to be loaded. The second part of the WIP-inventory is already loaded on the FAM-Station. Several system hardware or software characteristics will limit the amount of WIP-inventory stored on the FAM-Station. For instance:
- the maximum number of pallets that can be stored on the system, may limit the work load that can be loaded on the system at the start of an unmanned shift;
- the maximum number of tool pockets in the system may limit the number of cutting tools that can be stored in the tool magazine(s) of the system, and therefore also may limit the number of different parts on the system;
- there may be a maximum number of cutting tool offset values that can be stored in the computer control system, e.g. because a only a limited number of memory addresses is reserved for this purpose; this limitation creates again a limitation on the number of cutting tools that can be loaded, and therefore also on the a number of different parts.

The machine tools of the FAM-Station can only work on run batches that are loaded on the system. During the manned shifts the mounting/loading place will be manned continuously. Therefore, for the manned production mode we may assume that always enough run batches will be loaded to keep the machine tool(s) running, at least as long as work orders are available at the FAM-Station. As a result, the capacity of FAM-Stations in the manned production mode can be determined as explained above: the maximum capacity is the usable capacity, while the normative capacity is a compromise between high productive use and short flow times.
However, during the unmanned shift the mounting/loading place is closed. As a result, the machine tool(s) will run idle as soon as all run batches loaded on the FAM-Station at the start of the unmanned shift are completed. Thus the maximum capacity that can be utilized during the unmanned shift, is the minimum of the usable machine capacity and the maximum work load on the FAM-Station at the start of the shift. As we have seen above, the maximum work load loaded on the FAM-Station can be limited. In other words, usually the maximum utilization rate for the unmanned shift will not be 100%. Therefore, the utilization rate considered when determining $C_{n,u}(t)$ should not only be based on the usable capacity, but also on the set of products to be produced, and on the characteristics of the FAM-Station itself. Since these characteristics generally are not subject to frequent changes, a standard norm can be derived for the capacity utilization, expressing the number of hours that is likely to be produced on the FAM-Station during every unmanned shift (for instance four hours in stead of eight hours).

5.2 Capacity constraints

As we have seen in §4.2.1, generally not all operations that are performed on the FAM-Station, can be performed in both production modes. Therefore, we have distinguished attended from unattended operations (see also Fig.4.2, §4.1.1). Attended operations can be performed only in manned shifts. Unattended operations can be performed in both production modes.

Consequently, the capacity required in each production mode in order to perform operations, depends on the type of operation. In Fig.5.3 an example is given, showing a detailed overview of the use of machine and operator capacity during the flow time of a work order at a FAM–Station.

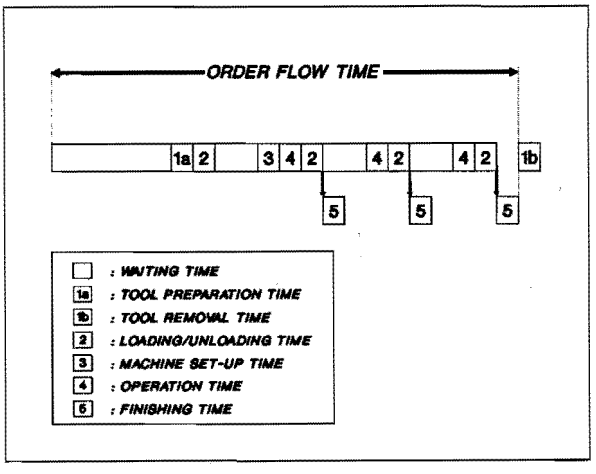

Figure 5.3:
Detailed overview of activities at FAM–Station during flow time of work order.

The first activities considered here are the tool preparation activities, which require only operator capacity. Usually, these activities concern the preparation of a pallet set–up (e.g. mounting a fixture on a pallet, denoted as activity 1a in Fig.5.3). Often these activities also include some change of the FAM–Station set–up, viz. when it is possible to download the required NC–program or change the set of cutting tools in the tool magazine without the spindle getting idle. Sometimes some of the tool preparation activities are performed by others than the FAM–Station operators. For instance, in the case mentioned in §1.3.1, fixtures are mounted on pallets, cutting tools are assembled, and the initial tool offset values are determined in a special preparation corner with specialized equipment. In this case, the tool preparation activities require capacity from resources other than the FAM–Station operators (i.e. the preparation corner).
Although it does not influence the flow time of the order itself, the removal and dismounting of the tools required for an order also takes time, especially of the FAM–Station operator. These tool removal activities may take place immediately after the completion of the order (activity 1b in Fig.5.3), or at the time the pallets, tool pockets, or memory places are required by other orders.
We will refer to the time required by the operator of the FAM–Station for the preparation and removal of tools for all operations on parts belonging to a work order i as the *mounting and dismounting* time ($t_m(i)$).

After a pallet set-up is mounted, parts can be loaded on the pallet. Also, every time a run batch is completed, this run batch can be unloaded and a new run batch may be loaded using the same pallet set-up. These activities are known as the loading/unloading activities (activity 2 in the figure) and usually are performed by the FAM-Station operator(s). The time required to perform these activities will be called the *loading and unloading* time ($t_l(i)$).

Once the first cycle of an order is taken into operation, usually some extra time is required, e.g. for a dry-run, a machining process at low speed, or measurements of the part. Also, in some FAM-Stations it is not possible to change the set of cutting tools in the tool magazine without the spindle getting idle. All of these activities require both operator and machine capacity. We will call the time required for these activities the *machine set-up* time ($t_s(i)$; see activity 3 in Fig.5.3). At conventional work stations, the sum of (a part of) the tool preparation time, the loading/unloading time, and the machine set-up time is known as the order set-up time.

Once the machine is set up, the processing of parts can begin (activity 4 of Fig.5.3). The time required to perform these machining processes, is called the *operation* time ($t_o(i)$). In case of unattended operations, only machine capacity is required. During attended operations, the operator should remain close to the FAM-Station. However, usually during the machining process he can perform other tasks like deburring and inspection of completed parts. We will call the time involved in these tasks the *finishing* time ($t_f(i)$; see also activity 5 in Fig.5.3). In case of unattended operations, these tasks are to be performed during the manned shift(s).

As we can see, apart from machine capacity, also operator capacity is required to perform the required operations. In the previous subsection we have denoted the normative machine capacity in the manned production mode and in both production modes resp. as $C_{n,m}(t)$ and $C_{n,t}(t)$. Similar to these notations, we denote the normative operator capacity as $C_{n,o}(t)$. The capacity required during a period t for the activities tool (dis-)mounting, (un-)loading, machine set up, operation, and finishing, will be denoted resp. as $c_{m,j}(t)$, $c_{l,j}(t)$, $c_{s,j}(t)$, $c_{o,j}(t)$ and $c_{f,j}(t)$, where the subscript j refers to the operation mode ($j=a$ if capacity is required for attended operations; $j=u$ if capacity is required for unattended operations). The sum of the capacity required for a certain activity will be denoted without the subscript j. In other words, for a certain activity 'y' we get:

$$c_y(t) = c_{y,a}(t) + c_{y,u}(t)$$

The operator and machine capacity constraints of a FAM-Station can now be expressed as follows:

$$c_s(t) + c_{o,a}(t) \leq C_{n,m}(t) \qquad (5.2)$$

$$c_s(t) + c_o(t) \leq C_{n,t}(t) \qquad (5.3)$$

$$c_m(t) + c_l(t) + c_s(t) + c_f(t) \leq C_{n,o}(t) \qquad (5.4)$$

Although it should be possible for an operator to attend more than one machine at a time, often this will not be case. Due to the attention required for the manufacturing process, usually only one machine is being attended by each operator. Only in case of a multiple FAM-Station the number of operators may not equal the number of machine tools. Therefore, in case of a single FAM-Station we may assume that:

$$C_{n,m}(t) \approx C_{n,o}(t).$$

In other words, in such a case we have no need to model the operator capacity separately.
From case studies we know that during the operation time of a work order, usually it is possible for the operator to perform all operator tasks associated with the work order. For instance, a typical set of times required for operator activities for a work order is:

- $t_o(i) = 30.0$ (hrs)
- $t_m(i) = 2.0$ (hrs)
- $t_l(i) = 6.0$ (hrs)
- $t_f(i) = 6.0$ (hrs)

Thus, usually the following inequality will hold:

$$t_o(i) > t_m(i) + t_l(i) + t_f(i)$$

In fact, it is not uncommon to assume that the time required for the attended operations is sufficient for the operator to perform all the other required activities, including all activities for the unattended operations. In other words:

$$c_{o,a}(t) > c_m(t) + c_l(t) + c_f(t)$$

As a result, the third capacity constraint becomes redundant.

Sometimes it is the policy to perform unattended operations only during unmanned shifts, for instance in order to be able to perform during the manned shift(s) as much attended operations as possible, or because it is difficult to find other tasks for the operator to perform during (unattended) processing operations. In each of these cases the second capacity constraint can be replaced by:

$$c_{s,u}(t) + c_{o,u}(t) \leq C_{n,u}(t) \qquad (5.3')$$

5.3 Conclusions

Regarding the capacity check required, we conclude from the discussion that:
- the distinction between attended or unattended operations on the one hand, and manned or unmanned production on the other, is required to formulate the proper capacity constraints of FAM-Stations;
- usually a check only on the constraints for the machine capacity will be sufficient for the control of FAM-Station capacity and work load.

Clearly, in case constraint (5.2) on the manned production capacity is just met (i.e. $c_s(t) + c_{o,a}(t) \approx C_{n,m}(t)$), almost all manned capacity is required for attended operations. This is not an uncommon situation in the cases we have studied. For instance, in the MF-case most operations to be performed on the FAM-Stations had to be regarded as attended operations. Only after several changes had been made in the NC-programs, only some operations could be regarded as unattended operations. As a result, it will be required to perform most, if not all, unattended operations during the unmanned shift. This can be achieved by giving the highest priority to attended operations during the manned production mode. Even pre-emption of work orders with unattended operations should not be excluded as a possibility to increase the priority of attended operations.

This last conclusion stresses the fact that the volume flexibility of FAM-Stations is a limited flexibility. Usually the capacity of the FAM-Station during the manned production mode will be highly utilized (either by attended or by unattended operations). Increasing the total capacity in the short term is only possible for the unmanned production mode (and thus for unattended operations). Apart from loading a higher amount of work on the FAM-Station at the beginning of the unmanned shift, this may also be achieved by increasing the number of unmanned shifts while decreasing the length of an unmanned shift. For instance, instead of one unmanned shift of 8 hours, we could introduce two unmanned shifts of 4 hours each. This latter opportunity is especially worthwhile to consider in case also other machines are working in three shifts. In such a case, the operator can first load the FAM-Station and then attend these other machines.
In the long run it is possible to change the amount of attended and unattended work to be performed by interchanging the manned and unmanned capacities of the FAM-Station.

Chapter 6
SIMULTANEOUS PRODUCTION OF ORDERS IN MANNED PRODUCTION

In the Chapter 3 we have seen that the introduction of an Automated Part Changer and the use of a palletpool has an impact on the way work orders are taken into operation and completed. In this chapter we will study the impact of these changes on the order flow times.

As we recall from §3.3.1, parts are loaded on the FAM-Station using a product set-up (i.e. a particular set of positioning tools). An operation on a part may require one or more different part-specific product set-up types. In low volume manufacturing usually the maximum number of identical product set-ups (i.e. product set-ups of the same product set-up type) is limited, e.g. because of a limitation in the number of available fixtures. A pallet on a FAM-Station may contain one or more product set-ups. In §3.3.1 we called such a combination of product set-ups on one pallet a pallet set-up.
In one product set-up, one or more parts can be loaded. The set of parts always loaded together in one product set-up is called a cycle. The number of cycles per order is called the cycle-size of the order. Since one pallet may contain several product set-ups, one or more cycles may be loaded on the same pallet. Such a set of cycles loaded on one pallet set-up is called a run batch.
Due to a limitation in the maximum number of identical product set-ups, and due to a certain cycle-size per work order, the machine tool(s) of the FAM-Stations alternately is (are) processing cycles of two or more work orders. In this chapter we will study this new phenomenon more precisely in case of manned production and come to conclusions about the flow time effects. In the next chapter we will study the effects for unmanned production.

In the first paragraph we introduce the assumptions that will hold throughout this chapter. In the second paragraph of this chapter, we will study what we call the basic case of simultaneous production of work orders in manned production, i.e. the case where:
- all operations on all parts can be completed in exactly one (part-specific) type of product set-up;
- of each product set-up type only one product set-up is available.

In this second paragraph an analytical approach for determining the flow times in the basic case will be discussed. As we will see, some further assumptions are required for such an analytical approach. In the third paragraph we will introduce the instrument of computer simulation that has been used to validate the extra assumptions made in §6.2, and to extend the conclusions from this paragraph. The next paragraph (§6.4) discusses the simulation experiments on the basic case. Especially the influence of cycle-sizes on flow times will be discussed. Also based on computer

simulation, in §6.5 we will relax some of the assumptions made concerning the times required for operations and mounting/loading activities. In §6.6 we will extend the study to the more general case, i.e. the case where some parts may require more than one type of product set-up, and where the number of available identical product set-ups may be larger than one. Finally, in §6.7 we will summarize the observations and conclusions.

6.1 Assumptions

Throughout this chapter, we will limit ourselves to FAM-Stations with identical machine tools in the manned production mode. The machine tools are supposed to be insensitive to disturbances. We assume that the FAM-Station is part of a Production Unit. Work orders arrive at the FAM-Station in a random way. Due to the fact that we assume manned production, parts can be loaded on and unloaded from the FAM-Station at any time.
Since the duplication of cutting tools in low volume manufacturing is not very common, we assume that the set of cutting tools required for processing the parts of a particular work order will be loaded in the tool magazine of only one machine tool. Also, we will assume that either always the number of tool pockets available in the tool magazine of the FAM-Station is sufficient, or that a limitation in tool pockets can be expressed in a general limitation on the number of work orders that can be in operation simultaneously.
Usually it takes some time to prepare a pallet set-up. Also, some effort is required to achieve the required set-up accuracy, including the right cutting tool offset values and the exact location of the reference points of the pallet set-up. As a result, usually once the FAM-Station is set up for a particular work order, this work order will be completed before the set-up is changed such that parts of this work order can not be processed anymore. Consequently, we will assume that once a pallet set-up has been made, it will be dismounted only after the last run batch requiring this pallet set-up has been completed.
Finally, as in most FAM-Stations, the pallet transportation times are supposed to be negligible as compared to operation times.

6.2 Analytical approach to single product set-up case

In this paragraph we start our study with the basic case of simultaneous production of work orders, i.e. the single product set-up case.
In the basic case each product requires only one type of product set-up in order to be completed. Therefore, no re-loading of cycles is required. Also, we assume that the number of identical product set-ups is limited to one. Furthermore, we will assume that the preparation times (i.e. (dis-)mounting and (un-)loading of tools and parts) are negligible as compared to the operation times. Finally, we assume that each pallet set-up contains exactly

one product set–up. The remaining model is primarely aimed at the studying of the main phenomenon of our interest. This model is schematically given in Fig.6.1.

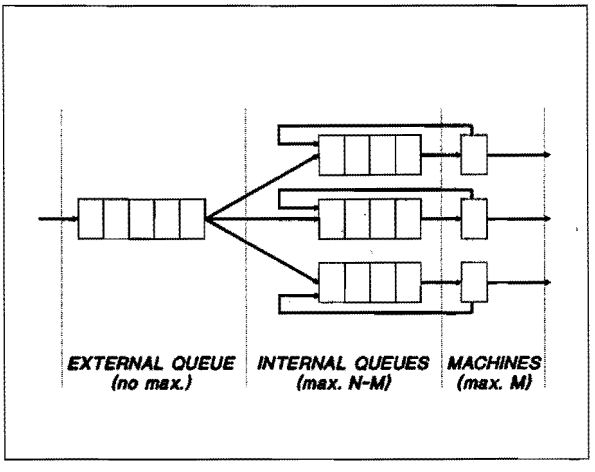

Figure 6.1:
Basic model of the simultaneous production of work orders.

As we can see, we can distinguish two kind of queues, viz. an external queue that is not limited on its length, and several internal queues with a limitation on the sum of the queue lengths. In the external queue, orders are waiting for the FAM–Station to be set up for processing the parts of the order. In other words, while the orders are waiting in the external queue, no pallet set–up is prepared yet for these orders. Once a pallet set–up is prepared, the order moves to the internal queue of the machine with the least number of orders on the system. Since the cutting tools are loaded only in the tool magazine of this machine, the order will not visit any of the other internal queues. Once arrived in the internal queue, the order will compete for machine capacity. Every time the order is taken out of the internal queue by the machine, only one cycle of the order is being completed. After the completion of this cycle, the order returns to the internal queue (i.e. the cycle is unloaded from the product set–up and replaced by the next cycle), unless the cycle was the last cycle of the order to be completed. In the latter case, the order will leave the system, the pallet set–up may be dismounted, and a new order from the external queue may join an internal queue. The last time the order has joined the internal queue will be called the *last arrival time.*
Sequencing decisions in all queues are based on the FCFS–priority rule (i.e. First Come, First Served). In other words, if a new pallet set–up can be prepared, it will be prepared for the work order in the external queue that has been waiting at the external queue for the longest time. Also, if the machine has completed a cycle of an order, the next order taken into operation will be the order with the earliest last arrival time in the

internal queue.
In Fig.6.2 an example is given of the mechanism of such a system in case of a single FAM–Station. In the example, work order *A* has arrived earliest at the FAM–Station. Therefore, the first cycle of order *A* is loaded first on the station. Although the number of pallets on the system is three, only one cycle of *A* can be loaded due to the limitation in the number of identical product set–ups. However, as soon as order *B* has arrived, the first cycle of this order is loaded too. From that moment on the machine will process alternately cycles of *A* and *B*. Finally, as soon as work order *C* has arrived at the system, also cycles of *C* will be loaded on the system and taken into operation.

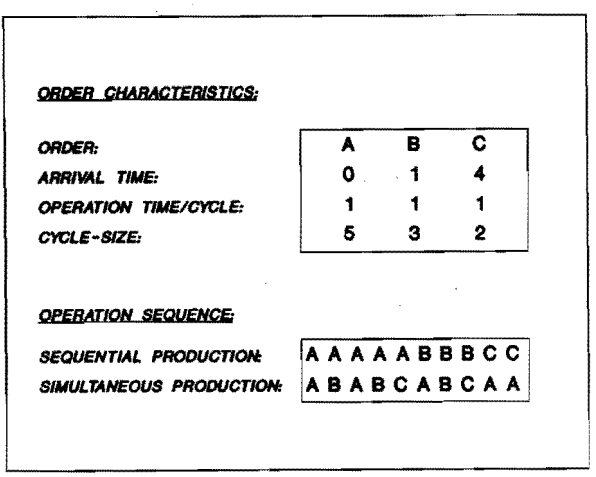

Figure 6.2:
Example of simultaneous production of work orders on a single FAM–Station with three pallets.

We are especially interested in the flow time behaviour of the system. We start our study with an analytical approximation concerning the expected order flow times. In §6.2.2 we will discuss the approximation and some of its assumptions. The limitations of the approximation will be shown using some extreme cases.

6.2.1 Analytical approximation of average flow time

Let $\underline{c}(i,j)$ be the time cycle j of order i spends on the manufacturing system (we will call $\underline{c}(i,j)$ the *cycle flow time* of cycle j of order i). Furthermore, let N be the number of pallets on the system, let M be the number of machines in the system, and let $\underline{n}$ be the number of orders that have arrived at the system given in Fig.6.1, but are not yet completed. We may

assume that $N \geq M \geq 1$. We assume that the operation time per cycle is the same for each cycle belonging to the same work order (i.e. $o(i,j)=o(i)$), and that the operation time per cycle of the population of work orders follows a negative exponential distribution. The cycle operation time is supposed to be independent of the cycle-size of the order. Finally, we assume a Poisson order arrival process with an average arrival rate of λ.

Assuming that $\underline{n}=n$, the expected cycle flow time (denoted by $E(\underline{c}_n(i))$) can be expressed as follows:

$$E(\underline{c}_n(i)) = \begin{cases} o(i) & (n \leq M) \\ o(i) + E(\underline{o}) \times (n-M)/M & (M \leq n \leq N) \\ o(i) + E(\underline{o}) \times (N-M)/M & (n \geq N) \end{cases} \quad (6.1a)$$

where:

$o(i)$: operation time of a cycle of order i;
$E(\underline{o})$: expected operation time of a cycle of an arbitrary order.

If we assume that the probability that a particular number of orders is present in the system (say n) is the same for all cycles, the expected value of $\underline{c}(i,j)$ can be obtained using the relation:

$$E(\underline{c}(i,j)) = \sum_{n=1}^{\infty} [\, E(\underline{c}_n(i)) \times p(\underline{n}=n \mid \underline{n} \geq 1) \,] \quad (6.1b)$$

where:

$p(\underline{n}=n \mid \underline{n} \geq 1)$: the probability that n orders are present in the entire system (i.e. on of in front of the FAM-Station), given that $\underline{n} \geq 1$ (n is an integer).

In other words, $E(\underline{c}(i,j))=E(\underline{c}(i))$ for all cycles j.

Combining eqn.(6.1a) and eqn.(6.1b) we get:

$$E(\underline{c}(i)) = o(i) + E(\underline{o}) \left\{ \sum_{n=M}^{N-1} \left[\left(\frac{n-M}{M}\right) p(\underline{n}=n \mid \underline{n} \geq 1) \right] + \left(\frac{N-M}{M}\right) \sum_{n=N}^{\infty} p(\underline{n}=n \mid \underline{n} \geq 1) \right\}$$

We know that $p(\underline{n}=n \mid \underline{n} \geq 1) = p(\underline{n}=n)/p(\underline{n} \geq 1) = p(\underline{n}=n)/(1-p(\underline{n}=0))$. Thus:

$$E(\underline{c}(i)) = o(i) + \left[\frac{E(\underline{o})}{1-p(\underline{n}=0)} \right] \times S \quad (6.2)$$

where:

$$S = \left\{ \sum_{n=M}^{N-1} \left[\left(\frac{n}{M}\right) p(\underline{n}=n) \right] + \sum_{n=M}^{\infty} \left[\left(\frac{N}{M}\right) p(\underline{n}=n) \right] - \sum_{n=M}^{\infty} p(\underline{n}=n) \right\}$$

In case M=1 (a single FAM–Station) we get:

$$E(\underline{c}(i)) = o(i) + E(\underline{o}) \left\{ \left[\frac{E(\underline{x})}{\rho} \right] - 1 \right\} \qquad (6.3)$$

with:

$$E(\underline{x}) = \sum_{n=1}^{N} np(\underline{n}=n) + \sum_{n=N+1}^{\infty} Np(\underline{n}=n) \quad \text{(average number of pallets occupied)}$$

$$\rho = 1 - p(\underline{n}=0) \quad \text{(the utilization rate)}$$

If we are able to $p(\underline{n}=n)$, we can calculate the total time order i will have cycles on the FAM–Station by:

$$E(\underline{t}_{int}(i)) = q(i) \times E(\underline{c}(i)) \qquad (6.4)$$

with:

$\underline{t}_{int}(i)$: time between loading and launching of first run batch and unloading of the last run batch containing a cycle of order i (also called the *internal flow time* of order i),

$q(i)$: cycle–size of order i.

The total expected flow time of order i (denoted by $E(\underline{t}(i))$) will be:

$$E(\underline{t}(i)) = E(\underline{t}_{int}(i)) + E(\underline{w}_{ext}(i))$$

with:

$\underline{w}_{ext}(i)$: waiting time of order i in front of the FAM–Station with no cycles loaded on the station (also called the *external waiting time*).

In fact, under the assumption of a FCFS–priority rule, the external waiting time is independent of i. Therefore, instead of '$E(\underline{w}_{ext}(i))$' we may write '$E(\underline{w}_{ext})$', or:

$$E(\underline{t}(i)) = E(\underline{t}_{int}(i)) + E(\underline{w}_{ext}) \qquad (6.5)$$

Clearly, the expected flow time of an arbitrary work order can be obtained using Little's result [Kleinrock, 1976], viz.:

$$E(\underline{t}) = E(\underline{n})/\lambda = (1/\lambda) \sum_{n=0}^{\infty} np(\underline{n}=n) \qquad (6.6)$$

Avi-Ithzak and Heyman give an approximation of 'p(n=n)' [Avi-Ithzak and Heyman, 1973]. First, they define γ_n as the average rate of completions of orders if there are n orders in the system as a whole, or:

$$\gamma_n = \begin{cases} n \;/\; (E(\underline{q}) \times E(\underline{c}_n)) & (n \leq N) \\ N \;/\; (E(\underline{q}) \times E(\underline{c}_n)) & (n \geq N) \end{cases}$$

where:

$E(\underline{q})$: the expected cycle-size of an arbitrary order;
$E(\underline{c}_n)$: the expected cycle flow time of an arbitrary cycle.

In case of a FAM-Station with negligible loading and unloading times, γ_n can be determined directly from $E(\underline{q})$, $E(\underline{o})$ and M, viz.:

$$\gamma_n = \begin{cases} n \;/\; (E(\underline{q}) \times E(\underline{o})) & (n \leq M) \\ M \;/\; (E(\underline{q}) \times E(\underline{o})) & (n \geq M) \end{cases}$$

In case of non-negligible loading and unloading times, we refer to [Avi-Ithzak and Heyman, 1973] for the calculation of $E(\underline{c}_n)$.
Knowing γ_n, they assume that the number of orders present in the system behaves as a 'birth-and-death' process with parameters λ and γ_n. A process is called a 'birth-and-death' process if [Kleinrock,1976]:
- the probability of getting into a particular state is only dependent on the present state, not on the state(s) in the past; the process has no memory: the time the process is expected to remain in a certain state is independent of the time the process has already been in that state;
- it is only possible to get to an adjoining state (i.e. the probability to get to other states is negligible).

In other words, they assume that both the expected inter-arrival time and the expected inter-departure time is independent of the past. Surely this will hold for the arrival process. However, this is not necessarily the case for the departure process.
Under the assumption of a 'birth-and-death' process, it is possible to obtain the following set of balance equations (assuming the existence of a steady state):

$$\lambda p(\underline{n}=0) = \gamma_1 p(\underline{n}=1),$$

$$(\lambda+\gamma_n)p(\underline{n}=n) = \lambda p(\underline{n}=n-1) + \gamma_{n+1} p(\underline{n}=n+1) \qquad (n = 1,2,...)$$

Such a process is shown in Fig.6.3.

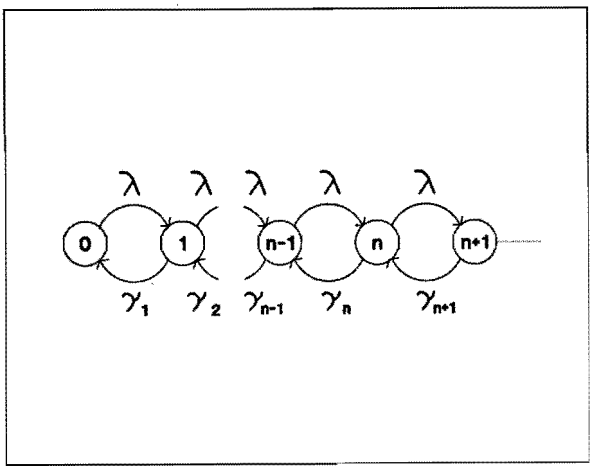

Figure 6.3:
The number of orders present in the system as a 'birth–and–death' process.

The solution to this set of equations is [Avi–Ithzak and Heyman, 1973]:

$$p(\underline{n}=n) = \begin{cases} p(\underline{n}=0) \times \lambda^n / (\gamma_1\gamma_2 \ldots \gamma_n) & (n = 1,2,..,N) \\ p(\underline{n}=N) \times (\lambda/\gamma_N)^{n-N} & (n = N,N+1,..) \end{cases}$$

Therefore, in our basic case:

$$p(\underline{n}=n) = \begin{cases} p(\underline{n}=0) \times \lambda^n E(\underline{q})^n E(\underline{o})^n / n! & (n = 0,1,..,M) \\ p(\underline{n}=0) \times \lambda^n E(\underline{q})^n E(\underline{o})^n / (M! M^{n-M}) & (n = M,M+1,..) \end{cases} \quad (6.7)$$

We know that $\sum_{n=0}^{\infty} p(\underline{n}=n) = 1$, thus:

$$p(\underline{n}=0) = \left\{ \sum_{n=0}^{M-1} \left[(\lambda E(\underline{q})E(\underline{o}))^n / n! \right] + \sum_{n=M}^{\infty} \left[(\lambda E(\underline{q})E(\underline{o}))^n / (M! M^{n-M}) \right] \right\}^{-1} =$$

$$= \left[\sum_{n=0}^{M-1} [A^n/n!] + MA^M/((M-A)M!) \right]^{-1},$$

with:

$$A = \lambda E(\underline{q})E(\underline{O})$$

In order to calculate $E(\underline{W}_{ext})$, we may use [Avi-Ithzak and Heyman, 1973]:

$$E(\underline{W}_{ext}) = \gamma_N p(\underline{n}=N) \; / \; (\gamma_N - \lambda)^2 \qquad (6.8)$$

6.2.2 Conclusions and discussion

From eqn.(6.4) we conclude that the total expected waiting time and thus the expected flow time of an order depends on the cycle-size of the order. In fact, the expected internal flow time of a work order according to eqn.(6.4) is proportional to the cycle-size of the order.
From eqn.(6.6) and eqn.(6.7) first of all the conclusion could be that the flow time averaged over all orders is dependent on the average cycle-size of an order, but independent of the distribution of the cycle-size per order. On top of that, we could conclude that the average flow time is also independent of the number of available pallets (N).
However, these last two conclusions are in contradiction with our intuition. We will discuss these conclusions for a single FAM-Station using three extreme cases, i.e. the case where the cycle operation time is assumed to be infinitesimal, the case where each order has the same cycle-size (or q(i)=q), and the case of orders having a highly varying number of cycles. However, we will first present the case N=1, i.e. the conventional M/G/1 case.

N=1
The case N=1 is known in literature as the '*Batch Processing Algorithm*'. Assuming a Poisson arrival process, a FCFS-queueing discipline, and one server, we may use the Pollaczek-Khinchin formula to calculate the average order flow time. In other words, the expected flow time of an order i with an order operation time of $O(i)$ can be expressed as:

$$E(\underline{t}(i)) = \frac{\lambda E(\underline{O}^2)}{2(1-\rho)} + O(i) \qquad (6.9)$$

where:

λ: average order arrival rate;
$\underline{O}$: order operation time of an arbitrary order;
ρ: utilization rate of server (= $\lambda E(\underline{O})$).

Infinitesimal cycle operation times

If we assume that the cycle operation times are infinitesimal quanta, we also can calculate the average order flow time exactly for the case where N is very large (see e.g. [Kleinrock, 1976]). For $N \to \infty$ (the so-called *'Round-Robin Algorithm'*), Kleinrock shows that under the assumption that all infinitesimal quanta are of the same size, the average flow time of an order i with operation time $O(i)$ can be expressed as:

$$E(\underline{t}(i)) = \frac{\rho O(i)}{1-\rho} + O(i) = \frac{O(i)}{1-\rho} \qquad (6.10)$$

If we compare eqn.(6.9) and eqn.(6.10), we conclude that for very small cycle operation times:

- in case of a constant order operation time ($E(\underline{O}^2)=E(\underline{O})^2$), the total average waiting time for N=1 will be half the total waiting time for a very large N;
- in case of a negative exponential order operation time ($E(\underline{O}^2)=2E(\underline{O})^2$), the average flow time will be equal for both cases;
- in case of an order operation time distribution with $E(\underline{O}^2)>2E(\underline{O})^2$, the average flow time will decrease for a very large N;
- for a very large N, the average flow time of an order tends to be a linear function of the order operation time. In other words, orders with a short operation time get a short waiting time, while orders with a long operation time also get a long waiting time.

Unlike what could be concluded from the analytical approximation given in the previous sub-section, the order flow time does seem to depend both on the cycle-size distribution and on N.

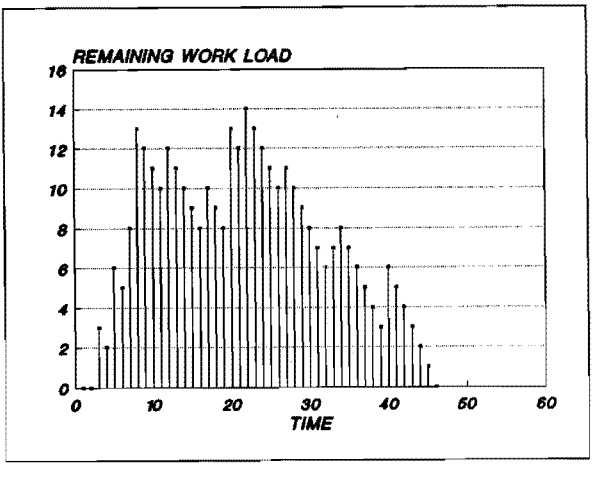

Figure 6.4:
Remaining work load for machine
in case of no unnecessary idle time on the machine.

Constant cycle-size

Assuming no idle time on the machine as long as work is available in the system, and an arrival process that is independent of the situation in the system (e.g. a Poisson-process), we know that the remaining work load for the machine is independent of the sequencing rule (the so-called '*Conservation Law*', see [Kleinrock, 1976]). For instance, in the example given in Fig.6.4, we see that work load will remain at the machine from time 3 till time 46. During these 43 time units the machine remains busy, independent of the sequence in which orders are completed. Such a period of time is called a *busy period*. Therefore, at any time, both in case of sequential production of orders and in case of simultaneous production of orders, the remaining work load at the machine will remain the same.

We will assume that $q(i)=q$. We denote the time the order leaves the system with $r(i,N)$, where N gives the maximum number of work orders that can be in operation at the same time. Let us assume that order i arrives at the system at time $a(i)$. The amount of work load left at the system at time t is $W(t)$. The priority-discipline in all queues is FCFS. The operation time required for work order i is $(q \times o(i))$, where $o(i)$ is the cycle operation time of a cycle of i.

In case of a sequential sequence ($N=1$), the last cycle of order i has to wait for the completion of all the previous cycles of order i, and for the completion of the remaining work load at the time of arrival. In other words:

$$r(i,1) = a(i) + W(a(i)) + (q \times o(i))$$

In case of the simultaneous production of orders ($N>1$) and an identical arrival process, the remaining work load at the machine at the time of arrival of an order will be equal to the sequential case. In other words, $W(a(i,1))=W(a(i,N))=W(a(i))$. The last cycle of the order again has to wait for the completion of all the previous cycles of the same order and for the completion of the remaining work load at the time of arrival. Or:

$$r(i,N) \geq a(i) + W(a(i)) + qo(i)$$

Due to the priority rule chosen, the cycle will always be completed before the last cycle is completed of an order that has arrived later. In other words:

$$\text{if } a(i) < a(j) \text{ then also } r(i,N) < r(j,N) \qquad \forall\ (i,j)$$

However, the last cycle of order i also may have to wait for the completion of some of the cycles of orders that will arrive between $a(i)$ and $r(i,N)$. For instance, in the example given in Fig.6.5, we see that in the simultaneous case the last cycle of work order A not only has to wait for the completion of the first three cycles of A (as in the sequential case), but also for the first two cycles of B.

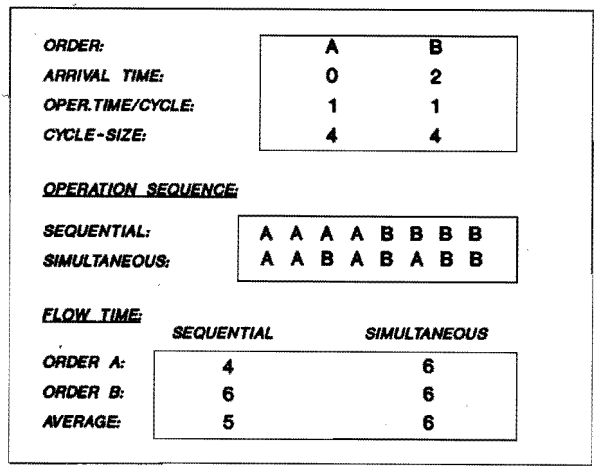

Figure 6.5:
Example of flow time consequence of simultaneous production of orders in case of constant cycle–size per order.

Let $\Delta W(i,N)$ be the work load of these cycles. Then:

$$r(i,N) = a(i) + W(a(i)) + \Delta W(i,N) + qo(i)$$

Therefore, we expect the flow time of an order to grow in case of the simultaneous production of orders. In fact, the higher the number of orders gets that can be in operation simultaneously, the larger $\Delta W(i,N)$ will be, and thus also the larger the flow time will be.

Highly variable cycle–size

Let us now assume that $q(i)$ varies a lot for different orders i. We know from eqn.(6.4) that orders with a small $q(i)$ will have a short flow time, whereas orders with a large $q(i)$ will have a long flow time. Therefore, in case of a highly variable q, the average flow time will depend on the number of orders with a small $q(i)$ compared to the number of orders with a large $q(i)$. In other words, if many orders have such a small cycle–size, the short flow times of the work orders with a small cycle–size may compensate the long flow times of orders with a large number of cycles (see Fig.6.6).

In the example of Fig.6.6, work order *B* arrives two time units later than *A*. Therefore, the FAM–Station will start with the operation on cycles of *A*. In the sequential case all cycles of *A* are completed before the first cycle of *B* is taken into operation. In the simultaneous case, the first cycle of *B* is taken into operation as soon as *B* has arrived at the station. As

we can see, order *A* is delayed, while *B* more or less sneaks through. As a result, the average flow time is reduced.

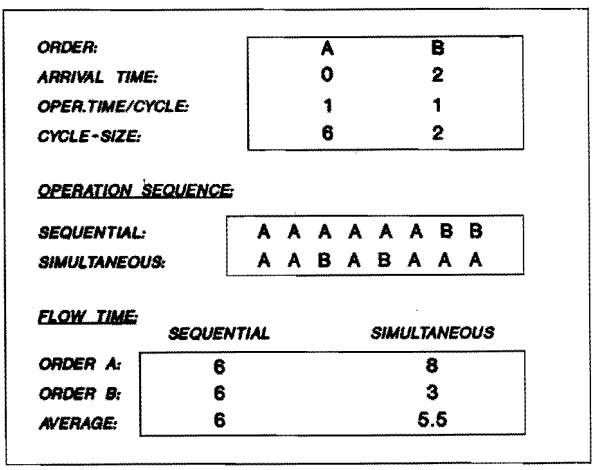

Figure 6.6:
Example of flow time consequence of simultaneous production of orders in case of variable cycle-size per order.

In fact, in case of a geometric distribution of $\underline{q}$ and a negative exponential distibution of $\underline{o}$, it is possible to calculate the average flow time of an order in two extreme cases, i.e. in case of only one pallet (N=1, resulting into a sequential production of orders), and in case of a very large number of pallets ($N \to \infty$). In both cases we will assume that each time a cycle is taken into operation, a random draw of the cycle operation time density is taken for the cycle operation time.
In Fig.6.7 the model is given for the case N=1. As we can see, as soon as an order is taken into operation, every time a cycle is completed there is a probability p that the order leaves the system, where $p = 1/E(\underline{q})$. In such a case, we can calculate the average flow time using the Pollaczek-Khinchin mean value formula (see §2.2). Let $\underline{O}$ be the operation time required for a whole order. We know that:

$$\text{var}(\underline{o}) = E(\underline{o})^2$$
$$E(\underline{q}^2) = 2E(\underline{q})^2 - E(\underline{q})$$

Since $\underline{q}$ and $\underline{o}$ are independent, we get:

$$E(\underline{O}) = E(\underline{q})E(\underline{o})$$
$$E(\underline{O}^2) = E(\underline{q})\text{var}(\underline{o}) + E(\underline{q}^2)E(\underline{o})^2 = 2E(\underline{q})^2E(\underline{o})^2$$

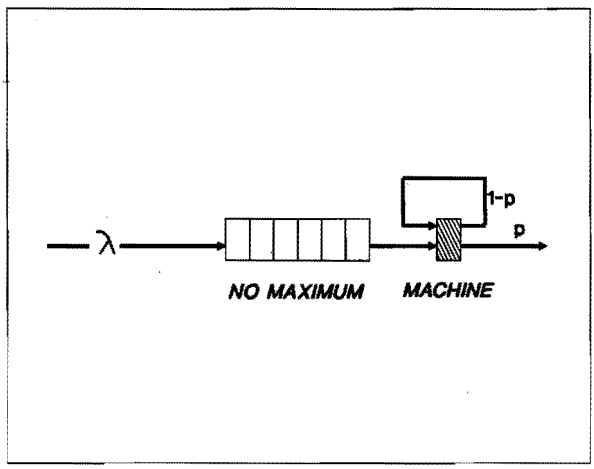

Figure 6.7:
Model of case with one pallet and geometrical distributed number of cycles.

Combining the expressions for $E(\underline{O})$ and $E(\underline{O}^2)$ with the Pollaczek–Khinchin formula, we get for the expected order flow time:

$$E(\underline{t}) = E(\underline{q})E(\underline{o}) + \lambda E(\underline{q})^2 E(\underline{o})^2 / (1-\lambda E(\underline{q})E(\underline{o})) =$$
$$= E(\underline{q})E(\underline{o}) / (1-\lambda E(\underline{q})E(\underline{o})) \qquad (6.11)$$

In case of a very large number of pallets ($N \to \infty$), we can use the model given in Fig.6.8. As we can see, again after the completion of a cycle, each order has the probability of p of leaving the system ($p=1/E(\underline{q})$). We can calculate $E(\underline{t})$ by realizing that the effective input of cycles in the system (with an average input rate of λ_{eff}, see Fig.6.8) again is a Poisson process. λ_{eff} can be calculated by using the principle of 'what comes in must come out' (assuming a steady state solution):

$$\lambda_{eff} = \lambda + (1-p)\lambda_{eff}, \text{ thus: } \lambda_{eff} = \lambda/p \qquad (6.12)$$

with $p = 1/E(\underline{q})$

The cycle flow time can be calculated using the results for a M/M/1 queue. The order flow time $E(\underline{t})$ can be determined by multiplying the cycle flow time with the expected cycle–size.

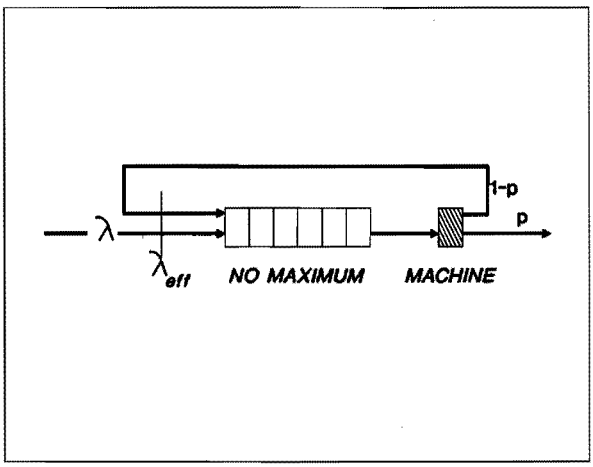

Figure 6.8:
Model of case with a very large number of pallets and geometrical distributed cycle–size.

Thus:

$$E(\underline{t}) = E(\underline{q})E(\underline{o}) \;/\; (1-\lambda_{eff}E(\underline{o})) = E(\underline{q})E(\underline{o}) \;/\; (1-\lambda E(\underline{q})E(\underline{o})) \qquad (6.13)$$

As we can see, $E(\underline{t})$ calculated by eqn.(6.11) is equal to $E(\underline{t})$ calculated by eqn.(6.13). In other words, the average flow time for the case N=1 is equal to the average flow time in case of a very large N.

Summary
In situations with a sequential production of work orders, the cyle–size of a work order only influences the order operation time, not the expected waiting time of the order. Therefore, the influence of an individual cycle–size on the flow time is limited. However, in case several work orders can be in operation at the same time, also a part of the expected waiting time will depend on the cycle–size of the order. As a result, the flow time will depend highly on the cycle–size.
If we assume that the departure process of orders is a pure 'death' process, the conclusion would be that the average order flow time is independent of both the distribution of the cycle–size of the orders and the number of pallets (N). However, it has been shown that this can not be true. In case of an equal cycle–size for all orders, the average flow time will grow with a growing N. In case of a highly variable cycle–size, the average flow time will be the same for all 'N' or may even (slightly) decrease with an increasing number of pallets. Therefore, the assumption on the departure process is not justified.

6.3 Introduction to simulation experiments

In order to validate the assumptions as formulated in the previous paragraph, and to extend our view to relevant different situations, we will use the instrument of computer simulation. In this paragraph we describe the simulation model and standard settings used in the experiments.
In all simulation experiments we have simulated a single FAM–Station (i.e. a FAM–Station with one machine). The simulation program is written in SIMULA, using SIMULATION, and runs on a IBM PS/2 Model 70 computer.

6.3.1 Simulation model

The model described in §6.2.1 is used as a starting point for the simulation model. However, as we can see in Fig.6.9, we have extended this model with a mounting/loading place.

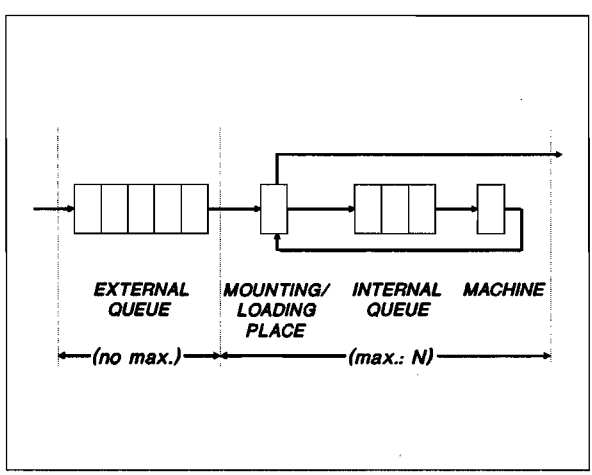

Figure 6.9:
The simulation model.

Work orders arrive in the system according to an independent arrival process. As soon as a work order has arrived in the system, the registration of the flow time of the order starts. The external waiting time of an order is considered to be ended as soon as the first product set–up of the order gets mounted on a pallet. The order is considered to be completed as soon as the last cycle of the order is unloaded.

As has been explained before, the set of cycles loaded on one pallet is called a run batch. Each of these run batches may contain one or more cycles of a particular order.

Work Order Characteristics

Work orders belong to a certain order class. The orders arrive in the system according to a class-dependent inter-arrival rate. A work order requires one or more different types of product set-ups to be completed. The maximum number of identical product set-ups (i.e. product set-ups of the same product set-up type), and the required number of product set-up types is the same for all orders belonging to the same order class. Also, both the distribution of the number of cycles per order and the distribution of the cycle operation time of a product set-up type are identical for all orders belonging to the same class. In the cases we have studied (including the MF-Case) there was hardly any dependency between the cycle-size and the cycle operation time of an order. Therefore, we will assume that indeed the cycle-size of an order is independent of the cycle operation time. Upon arrival of the order, the exact cycle-size, the cycle operation time for each product set-up type, the product set-up(s) mounting and dismounting times, and the cycle loading and unloading times are determined. Consequently, all times required are the same for all cycles of a work order (N.B.: Notice that in the discussion of §6.2.2 it was assumed that each cycle operation time is drawn again from a particular operation time distribution; clearly, in case of a FAM-Station in real life this is not a realistic assumption). An example of these order characteristics used in the experiments is given in Fig.6.10.

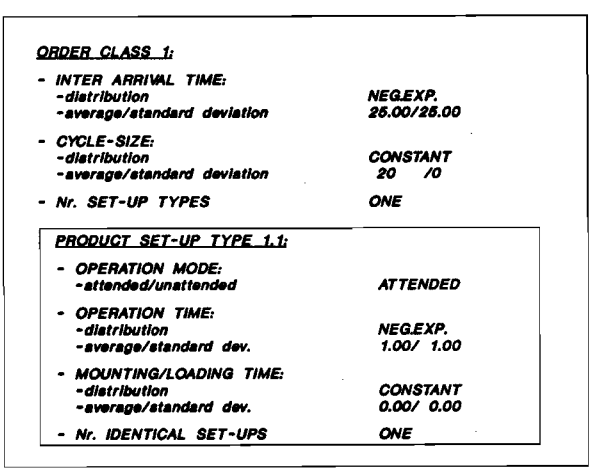

Figure 6.10:
Example of characteristics of orders belonging to one class.

Mounting and dismounting of pallet set-ups
As soon as possible (i.e. in case a pallet is empty and the mounting/loading place is available), a pallet set-up will be prepared with product set-ups of a work order with the highest (mounting) priority For instance in case of a FCFS-priority rule, a pallet set-up of the order that has arrived at the earliest time at the FAM-Station. If this work order has no product set-ups anymore to be mounted, then the work order next in priority will be taken into consideration, etc.. This logic is illustrated in Fig.6.11 for the FCFS-priority rule. Suppose that in the example there is a pallet available for a new pallet set-up. As we can see, there are three work orders in the system. Work order *A* has arrived earliest in the system. According to the FCFS-discipline, the pallet should be prepared for a product set-up of work order *A*. However, all product set-ups of work order 1 have already been mounted on a pallet. Therefore, the pallet will be prepared for the second product set-up of work order *B*. No product set-ups of work order *C* are mounted yet.

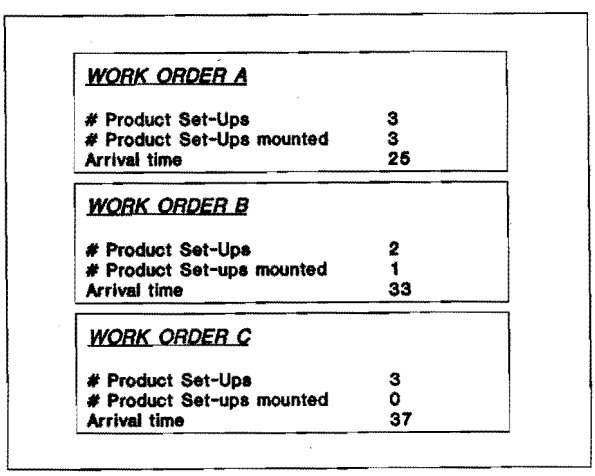

Figure 6.11:
Example of the logic of mounting product set-ups on pallets, based on the FCFS-discipline.

A pallet set-up remains mounted on a pallet as long as the number of cycles still requiring one or more of the product set-up types is not smaller than the number of identical pallet set-ups available for loading or unloading. As a result, not only the total time required by the operator for mounting and dismounting is limited, but also the idle time of the machine due to these activities. On top of that, often it takes some effort and one or more test-runs (and parts) to achieve the required position accuracy of a (new) pallet set-up.
Also, a pallet set-up that is not mounted yet, will not be mounted at all if this same constraint does not hold anymore. The reason is that the unloading time of a run batch usually is much shorter than the time

required for mounting a new pallet set-up. Therefore, it is better to unload and re-load a pallet than to mount and load a pallet.

Loading and unloading of cycles
A cycle can only be loaded on a pallet if the product set-up required is already mounted on the pallet. If a cycle is unloaded, it either joins the loading queue for the next product set-up type, or it is considered to be completed.

Activities at mounting/loading place
As we have seen, at the mounting/loading place the following activities have to be performed:
- mounting of pallet set-ups;
- loading of cycles;
- unloading of cycles;
- dismounting of pallet set-ups.

If possible, first cycles are unloaded from the pallet set-ups. As a result, both the pallets and the cycles are available for re-loading as soon as possible. Then, in order to prevent the machine from getting idle, cycles are loaded on the available pallets. Consequently, the machine stays idle as short as possible. If no unloading or loading activities can be performed, new pallet set-ups are mounted on empty pallets. Finally, if none of these previous activities can be performed, pallet set-ups are dismounted from pallets.
To summarize, the following priorities are used:
1. unloading of cycles;
2. loading of cycles;
3. mounting of pallet set-ups;
4. dismounting of pallet set-ups.

Program verification
In order to verify that the simulation program indeed performs according to the simulation model described above, several tests have been performed. First of all, for several test-runs with different experimental settings, the detailed output on all system state changes has been reviewed. Furthermore, for several experimental settings the simulation results have been compared with known analytical results. Also, the simulation program has been provided with several safety routines in order to locate 'impossible' system states. Finally, several subroutines have been tested separately. All of these tests have indicated that the simulation program indeed performs according to the simulation model.

6.3.2 Experimental settings

In the experiments we have assumed that the times required for activities on the mounting/loading place can be expressed as a linear function of the cycle operation time. More precisely, if $o(i,j)$ gives the operation time of a cycle in product set-up type j of order i, we assume that the time required for mounting a product set-up of that type equals $\alpha o(i,j)$. All other times on the mounting/loading place (i.e. the time required for loading a cycle, the time required for unloading a cycle, and the time required for dismounting a cycle) are expressed as $(\alpha o(i,j)/10)$. Clearly, this is a simplification. However, in the cases we have studied these assumptions

were reasonable. Usually, preparing a pallet set-up on the mounting/loading place requires more than one hour, while the loading and unloading of cycles (possibly with an exception for the first cycle to be loaded), and the dismounting of the product set-ups only takes several minutes (e.g. 5–6 min.). Furthermore, parts requiring long operation times often have complex shapes and require a high operation accuracy. These parts also require accurate and often complex product set-ups, and thus also long mounting and loading times. In other words, usually the preparation times are related to the operation times.

In all experiments, we have assumed that the priority-discipline in all queues is FCFS. For example, it is assumed that based on the FCFS-priority rule, each possible product set-up of a particular work order is mounted as soon as possible. As a result, due to the limitation in the number of pallets on the FAM-Station, the number of orders simultaneously in operation is limited too.

Both the order inter-arrival time and the order characteristics are determined by random draws from probability densities. The parameters used in these probability densities and the probability densities themselves are either based on data of the cases we have studied, or on hypothetical extreme values.

The runlength of each simulation run is chosen such that in case of a utilization rate of 80% about 2,000 orders are completed per order class (or 2,200 in case of a utilization rate of 90%). With this runlength the results can be expected to be independent of the starting situation. The time required to complete the first about 100 work orders is regarded as a starting-up period (the simulation starts with an empty system) and is not considered in the output. Depending on the experiment, we have repeated the simulation runs several times with different random draws.

Clearly, the (real) computer time required for a simulation run depends to a large extend on the number of events that will occur during the simulation. This number of events on its turn is largely dependent on the number of operation activities to be performed during the simulation. Furthermore, extra time is required for the 'overhead' of the program (e.g. system initialisation and reporting routines). It appeared that the following equation gives a good estimate of the time (in minutes) required per simulation run:

$$\tau = 2 + 3 \times (\theta\omega/10{,}000)$$

where:

θ: number of work orders completed during the simulation run;
ω: average number of operation activities per work order.

In case only one type of product set-up is required to complete a cycle, the number of operation activities per work order (ω) is equal to the cycle-size of the order. In case two or more product set-up types are required to complete a cycle, the cycle-size has to be multiplied by this number of product set-up types in order to obtain the number of operation acitivities per order.

6.4 Impact of cycle-sizes

In the experiments described in this paragraph, we will concentrate on the basic case of simultaneous production of work orders, i.e. the case where every part requires exactly one type of product set-up to be completed, only one product set-up is available for each product set-up type, and each run batch contains exactly one cycle.
Successively we will study in this paragraph:
- the influence of the order cycle-size on the order flow times;
- the influence of the distribution of the cycle-sizes of work orders on the flow time;
- the influence of the average cycle-size of the orders on the flow times.

6.4.1 Order cycle-size

In the first experiment we will investigate the influence of q(*i*) (the cycle-size of a work order) on the expected flow time of the order. We are especially interested in the influence of q(*i*) on the flow times as a function of N (the number of pallets) and ρ (the utilization rate).

Expectations
As we have seen in §6.2, we expect the flow time of an order to be dependent on:
- the cycle-size of an order;
- the number of pallets in the system (i.e. N);
- the utilization rate.

In fact, from eqn.(6.4) in §6.2.1, we conclude that under the assumption that the average number of cycles loaded on the system is equal for all cycles of all orders, the internal flow time of an order is proportional to the cycle-size of the order.
Increasing N will increase the number of pallets that are occupied, and thus also the internal flow time. However, increasing N will decrease the external waiting time of an order. Once the external waiting time is reduced to zero for a certain N_{max}, increasing N above N_{max} will have no effects anymore on any part of the order flow times.
The higher the utilization rate, the more orders on average will be present in the system, and therefore the more pallets are occupied. Consequently, we may expect that both the average waiting time of a cycle on the FAM-Station and the external waiting time will increase with an increasing utilization rate.

Input
In the first experiment we have simulated two classes of orders, where all orders in one class have the same cycle-size (resp. 10 and 30). Since the arrival rate is the same for the two classes, the average cycle-size is 20. We assume that the operation time per cycle is negative exponentially distributed, with an average of 1.0. Consequently, the average total operation time per order is 20.0. All times required for the activities on the load-/unload place are negligible (α=0).
We varied the number of pallets (N) and the pre-set utilization rate (resp. ρ_{pre}=80% and ρ_{pre}=90%; due to randomness of the order-stream the exact

utilization rate ρ can only be determined after the simulation run). Because of the limitation on the number of identical product set-ups, the maximum number of orders that simultaneously can be in operation, equals the number of pallets on the FAM-Stations. The simulation of the system containing only one pallet (N=1) is equivalent with the situation where all cycles of an order are completed before cycles of a new order is loaded on the system (i.e. sequential production).

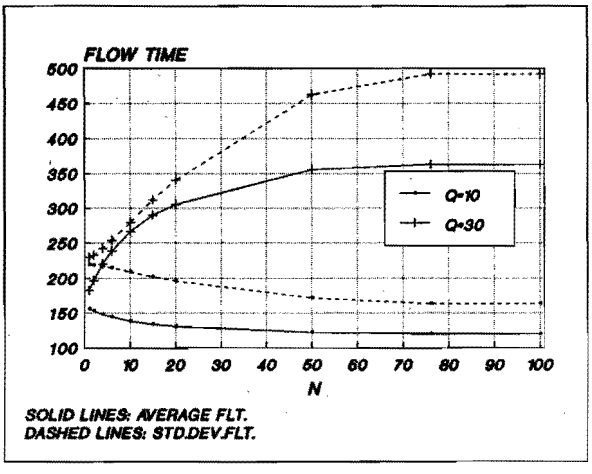

Figure 6.12:
Average flow time and standard deviation in flow time in first experiment as function of N (ρ_{pre}= 80%).

Results

The results are given per class of orders, where a class of orders contains those orders that have the same cycle-size. Fig.6.12 presents in a diagram the average flow time and the standard deviation in flow time per class of orders for the case with a pre-set utilization rate of 80%. The figure clearly shows that the average flow time indeed depends both on the number of cycles per order and on N. If N is chosen large enough, there will be no external waiting time at all: all orders can join an internal queue immediately. As a result, increasing N above N_{max} (N_{max}=76 in the case where ρ_{pre}=80%) has no effect anymore. As can be expected, long average order flow times go with large standard deviations in flow time. Since the average order flow time is longer for order with a large cycle-size, also the variance in order flow time is large for these orders, whereas the opposite goes for orders with a small cycle-size. In case of a limited N, the standard deviation in flow time does not change as fast as the average flow time.

In Fig.6.13 the results for the case with a 90% utilization rate are shown. Comparing this figure with Fig.6.12, we see that for a higher utilization rate, the differences in flow time between the order classes for a large N

get larger. In other words, not only the external waiting time will increase, but also the internal waiting times!

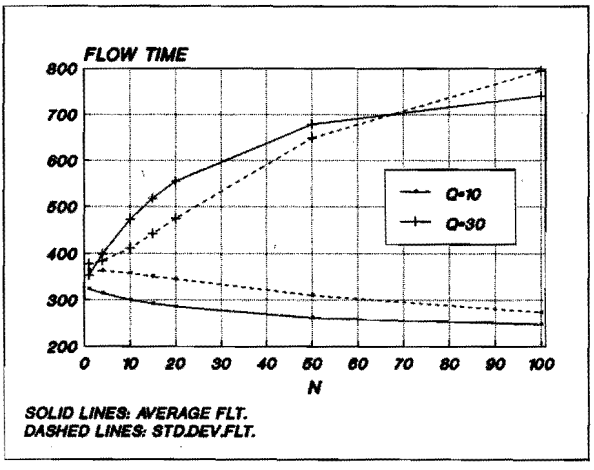

Figure 6.13:
Average flow time and standard deviation in flow time in first experiment as function of N (ρ_{pre}= 90%).

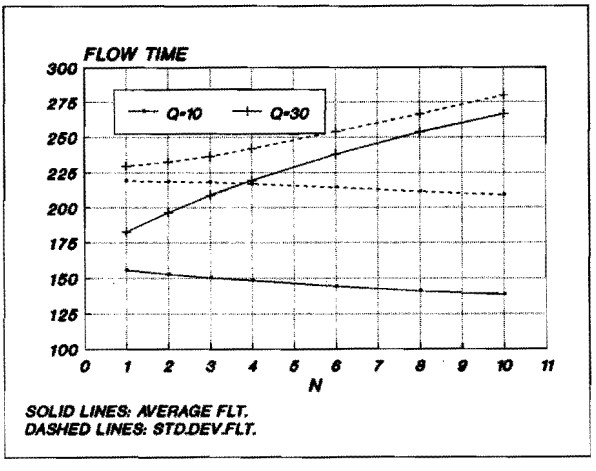

Figure 6.14:
Average flow time and standard deviation in flow time in first experiment for N=1 until N=10 (ρ_{pre}= 80%).

In real life the number of pallets available on a single FAM-Station usually does not exceed 10. For this range of N, the results are shown more clearly in Fig.6.14 and Fig.6.15 (resp. ρ_{pre}=80% and ρ_{pre}=90%).

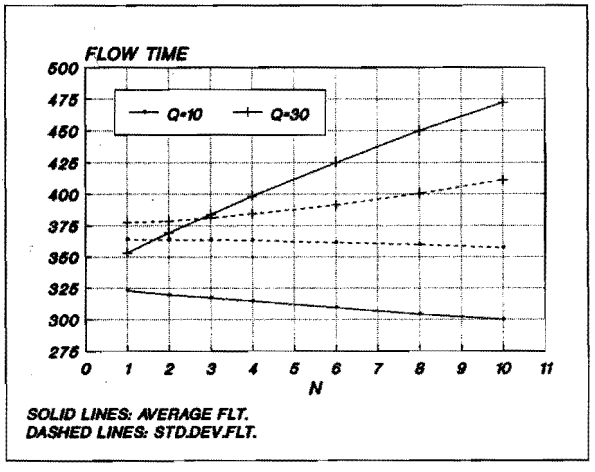

Figure 6.15:
Average flow time and standard deviation in flow time in first experiment for N=1 until N=10 (ρ_{pre}= 90%).

Notice that also for this more realistic range of N the simultaneous production of work orders has a strong impact on the flow times.

Statistical analysis

Although most expectations expressed in this subsection clearly are validated by the experiment, one expectation requires a further (statistical) analysis, i.e. the expectation that the internal flow time of an order is proportional to the cycle-size of the order. This expectation is based on the assumption that the average internal waiting time of a cycle on the FAM-Station is equal for all cycles of all orders.
Due to the independent arrival process, this assumption will hold at least for the first cycles of each work order. However, as we have seen, in case of simultaneous production of work orders, orders with a large cycle-size will have a long flow time. These orders are more likely to be completed at the end of each busy period of a machine (i.e. near t=46 in Fig.6.4) than the orders with a small cycle-size. Consequently, the average number of cyles loaded on the FAM-Station at the time the last cycles of these work orders are loaded on the system, will be less than the average for all cycles. In other words, the average internal waiting time of a cycle of a work order with a large cycle-cize will be (slightly) shorter than the average internal waiting time of a cycle of an order with a small cycle-size. This is illustrated in Table 6.1. The table is based on the results of the simulation experiment as described above (for N=10 and ρ=79.9%). In the table the internal waiting times of the j-th cycle of each of the two order

classes are given. As we can see, the last cycles of the orders of class 2 indeed seem to have a shorter internal waiting time than the other cycles.

Table 6.1:
Average internal waiting times (Int.Wt.) of cycles in first experiment for N=10 and ρ=79.9%.

	Class 1	Class 2		
Cycle-size:	10		30	
Cycle:	1–10	1–10	11–20	21–30
	5.98	6.08	6.22	6.04
	6.43	6.49	6.17	6.04
	6.41	6.45	6.17	6.03
	6.40	6.44	6.13	6.00
Int.Wt.:	6.39	6.40	6.14	5.95
	6.34	6.34	6.10	5.95
	6.33	6.32	6.07	5.90
	6.32	6.33	6.03	5.89
	6.25	6.30	6.03	5.88
	6.23	6.27	6.03	5.85

In order to validate this observation, we have repeated the simulation experiments described above nineteen times for the cases N=2, N=4 and N=10, each with a different random input. For each 'N' we have tested the hypothesis (H_0) that the difference between the average internal waiting time of a cycle of an order with cycle-size 10 and the average internal waiting time of a cycle of an order with cycle-size 30 (denoted by $\underline{d}$), is not larger then zero, using the Student's t-density. The test is based on:

$$t(d) = \frac{\bar{d}}{s(\underline{d})/\sqrt{n}} \simeq \underline{t}_{n-1} \qquad (6.14)$$

where:

$\bar{d}$: average difference in internal waiting time;
$s(\underline{d})$: standard deviation of difference in internal waiting time;
n: number of observations (=20);
$\underline{t}_m$: Student's t-density for m observations.

H_0 is not accepted if the t(d), calculated according to the given formula, is larger than $\underline{t}_{n-1}$. The chosen level of significance is 5%. For this value, $\underline{t}_{19} \approx 1.73$ (one-sided).
In Table 6.2 the results are given resp. for ρ_{pre}=80% and for ρ_{pre}=90%. As we can see, in all cases H_0 can not be accepted (i.e. in all cases t_d, given in the fifth column, is larger than $\underline{t}_{19}$, given in the sixth column). In fact, even for lower levels of significance the hypothesis can not be accepted. For instance, in case α=0.01, $\underline{t}_{19} \approx 2.54$.

Table 6.2:
Results Student's t–test on internal waiting time.

ρ_{pre}	N	$\bar{d}$	s_d	$(\bar{d}/s(d))\sqrt{20}$	$t_{19}(\alpha=0.05)$
80%	2	0.05	0.029	6.87	1.73
	4	0.13	0.051	11.34	1.73
	10	0.30	0.16	8.42	1.73
90%	2	0.03	0.025	5.02	1.73
	4	0.08	0.059	6.36	1.73
	10	0.21	0.14	6.40	1.73

Due to the less frequent occurence of idle–periods of the machine, the difference in average internal waiting time per cycle reduces for a higher utilization rate.

Conclusions
We can summarize the results from the experiment(s) as follows:
- In case of simultaneous production of work orders, the internal waiting time of an *order* depends heavily on the order cycle–size. In consequence the orders with a large cycle–size will get long flow times.
- The expected internal waiting time of a *cycle* is not equal for orders with different cycle–sizes, but decreases slightly in case of larger cycle–sizes. However, the higher the utilization rate, the smaller the differences in average internal waiting time per cycle get.
- The variance in flow time is positively correlated with the average flow time of an order.
- The higher the utilization rate, the bigger the differences in flow time get between orders with different cycle–sizes.

6.4.2 Cycle–size distribution

We know from the first experiment that in the basic case of simultaneous production of work orders the flow time of an order heavily depends on the cycle–size of each individual order. In the second experiment we will study the influence of N on the flow time averaged over all orders ($E(\underline{t})$) and on the standard deviation in flow time ($\sigma(\underline{t})$).

Expectations
The expectations for this experiment follow straightforward from the discussion in §6.2.2. In case of a constant cycle–size, the average flow time should grow with an increasing N. In fact, the largest relative increase in average flow time can be expected for a constant $\underline{q}$. Only in case of a highly variable cycle–size, the average flow time may decrease with an

increasing N. In the special case of a geometrical distributed cycle-size and cycle operation times having a negative exponential density, we have shown that the average flow times in case N=1 and in case of a very large N, are equal. In other words, for a large N, the average flow times are likely to get closer for all cases, may be even equal. For infinitesimal cycle operation times, we have shown in §6.2.2 that indeed this will happen.
In case of a FAM-Station with only one pallet, we can calculate the average flow time for all cases exactly, using the Pollaczek-Khinchin mean value formula. As an example, we will derive the result for the geometrical case. Let $\underline{O}$ be the operation time required for a whole order. Since $\underline{q}$ and $\underline{o}$ are independent, we get:

$$E(\underline{O}) = E(\underline{q})E(\underline{o}) \quad \text{and} \quad E(\underline{O}^2) = E(\underline{q}^2)E(\underline{o}^2)$$

Using the Pollaczek-Khinchin formule and the expressions for $E(\underline{O})$ and $E(\underline{O}^2)$, we get for the expected order flow time:

$$E(\underline{t})_{geo} = \{E(\underline{q})E(\underline{o}) + \lambda E(\underline{q})^2E(\underline{o})^2(1-E(\underline{q})^{-1})\}/(1-\lambda E(\underline{q})E(\underline{o}))$$

Similarly, we can obtain for the constant case:

$$E(\underline{t})_{con} = (E(\underline{q})E(\underline{o}))/(1-\lambda E(\underline{q})E(\underline{o}))$$

Input
Since we expect the influence of N on the flow times to depend on the distribution of the cycle-size, we have repeated the first experiment using different distributions for the number of cycles per order, viz. a constant cycle-size and a geometrical distributed cycle-size. Again, the cycle operation time is drawn form a negative exponential distribution on the moment the work order arrives in the system. All other inputs are identical to the inputs for the first experiment. The expected cycle-size in all experiments was 20.

Results
The results of the experiments are shown in Fig.6.16 and Fig.6.17, depicting the average flow time and the standard deviation in flow times for a pre-set utilization rate of resp. 80% and 90%. The figures include the results of the previous experiment using two order classes ('2cl').
As can be seen from the figures, the simultaneous production of orders indeed has the consequences for the average flow time as we have expected. For a large N the average flow time in case of a (more or less) constant cycle-size seems to get even larger than in case of a geometrical distributed cycle-size.
Again, for the realistic range of N=1 until N=10, the results are shown more clearly in Fig.6.18 and Fig.6.19.

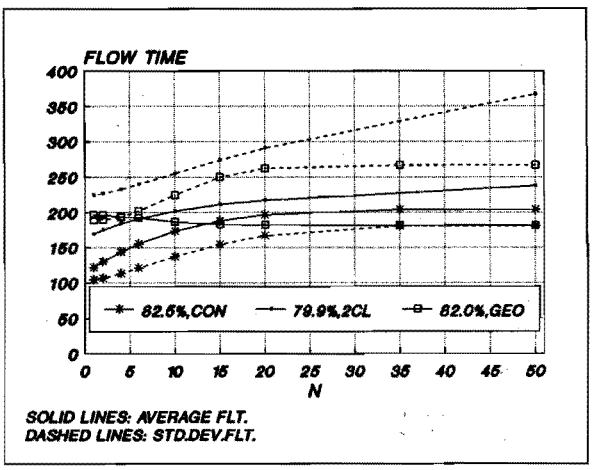

Figure 6.16:
Average flow time and standard deviation in flow time in second experiment as function of N (ρ_{pre}= 80%).

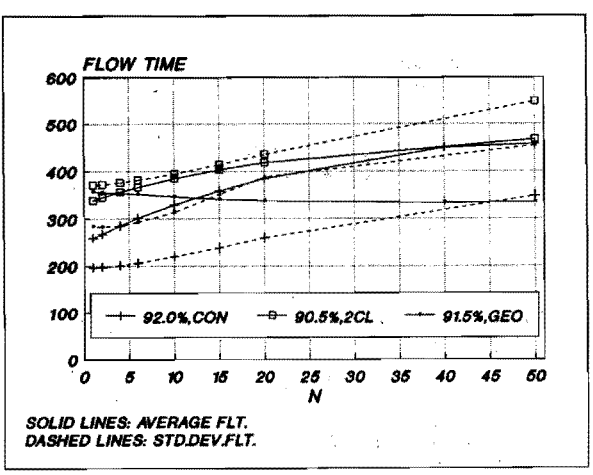

Figure 6.17:
Average flow time and standard deviation in flow time in second experiment as function of N (ρ_{pre}= 90%).

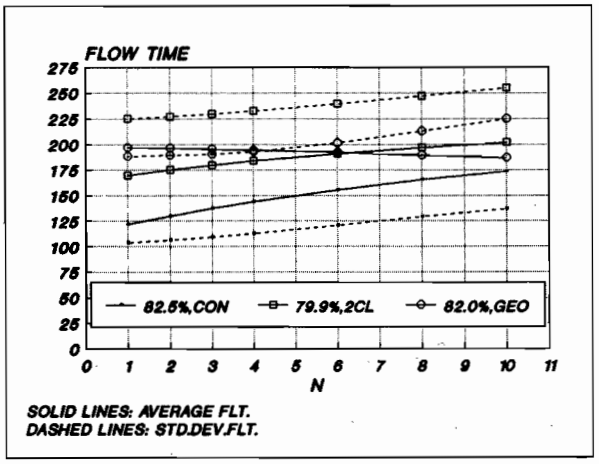

Figure 6.18:
Average flow time and standard deviation in flow time in second experiment for N=1 until N=10 (ρ_{pre}= 80%).

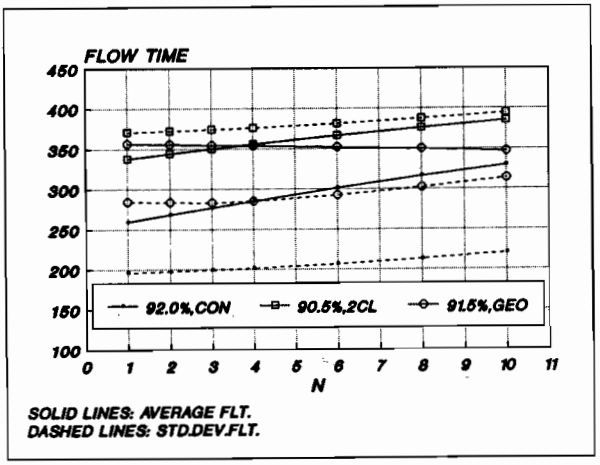

Figure 6.19:
Average flow time and standard deviation in flow time in second experiment for N=1 until N=10 (ρ_{pre}= 90%).

In all cases, the simultaneous production of orders has consequences for the standard deviation (or variance) in flow time. In case of a constant cycle-size this can easily be explained. If N=1 then the variance in flow time will be the sum of the variance of the remaining work load at the time of arrival, and the variance of the operation time of the order. In case N>1, also the variance in work load of orders arriving at the FAM-Station after the arrival time of the order, will influence the variance of the flow time. The larger N gets, the larger this variance in work load is likely to be. The higher the utilization rate is and the larger the number of pallets are, the stronger these effects will be.
Notice that for a small N the average flow time changes almost proportionally to N, at least for a high utilization rate.

Statistical analysis
The first issue that requires a further study, is the assumption that for a large N the average flow time in the geometrical case will be more or less equal to the average flow time in the (more) constant case. In order to validate this assumption, we have repeated the simulation experiments for N=10 and N=50 nineteen times, using different random input. We have tested the hypothesis (H_0) that, for a pre-set utilization rate of 80%, the difference between the average flow time of an order-stream with a constant cycle-size, an order-stream with a 'two classes' cycle-size, and an order-stream with a geometrical distributed cycle-size, is zero. In order to determine these differences (denoted by $\underline{d}$), the results of the 20 runs are ranked according to resulting utilization rate. Using the differences in average flow times of these ranked results, H_0 is tested applying the Student's t-density (see §6.4.1). H_0 is not accepted if $|t(d)|$ is larger than $\underline{t}_{n-1}$ ($t(d)$ calculated according to eqn.(6.14) in §6.4.1). For a significance level of 5% (α=0.05), $\underline{t}_{19} \approx 2.10$ (two-sided). Note that if the hypothesis is not rejected for this level of significance, then surely it also will not be rejected for lower levels of significance.
In Table 6.3 the results of this test are given. As we can see, in case N=50, H_0 is not rejected in all cases. For N=10, H_0 is not rejected for the 'two classes' case vs. the geometrical case. We conclude that for a large N even if there is a difference in average flow times, this difference will be negligible.

Table 6.3:
Results Student's t-test on differences in average flow time for different cycle-size distributions (α=0.05).

	N	$\bar{d}$	s(d)	$(\bar{d}/s(d))\sqrt{20}$	$\underline{t}_{19}$
Constant vs.	10	-18	28	-2.93	2.10
Geometrical	50	3	32	0.36	2.10
Two classes vs.	10	- 5	29	-0.84	2.10
Geometrical	50	13	32	1.73	2.10
Constant vs.	10	-13	22	-2.60	2.10
Two classes	50	-10	31	-1.42	2.10

The second observation requiring a further study, is the fact that the relative increase in average flow time seems to be largest for the case with a constant cycle-size.
In Table 6.4 the average increase, the standard deviation in relative increase, and the mimimum and maximum relative increase of the 20 simulation runs described above are given. As we can see, the obtained results are rather stable, i.e. both the standard deviation and the range is small.

Table 6.4:
Increase in average flow time for different values of N as percentage of average flow time for N=1 resp. for constant case, 'two classes' case, and geometrical case (ρ_{pre}=80%).

Constant	N=2	N=4	N=10	N=50
$\bar{r}$	8.1	21.0	44.2	61.6
s(r)	1.16	2.4	2.9	4.7
min(r)	5.9	16.0	36.5	49.8
max(r)	10.9	26.2	48.0	68.4
Two classes	**N=2**	**N=4**	**N=10**	**N=50**
$\bar{r}$	4.4	11.4	24.1	35.7
s(r)	0.64	1.4	2.0	2.4
min(r)	3.2	8.6	19.3	31.2
max(r)	5.6	14.1	26.9	40.4
Geometric	**N=2**	**N=4**	**N=10**	**N=50**
$\bar{r}$	−0.6	−1.7	−4.3	− 5.9
s(r)	0.56	1.5	2.7	3.3
min(r)	−2.0	−3.8	−8.8	−10.7
max(r)	0.4	1.8	−0.3	− 0.6

N.B.:

$\bar{r}$: average relative increase (in %);
s(r): standard deviation relative increase (in %);
min(r): minimum relative increase (in %);
max(r): maximum relative increase (in %).

The table clearly shows that indeed the relative increase is larger for more constant cycle-sizes. In fact, if we combine the conclusions on the small differences in flow times in case of a large N between the cases with different cycle-size distributions (see Table 6.3) with the fact that the flow times for N=1 are shorter for the cases with less variable cycle-sizes than for the cases with highly variable cycle-sizes, it is clear that in case of more constant cycle-sizes the relative increase in flow times is larger than in case of variable cycle-sizes.

Conclusions
To summarize:
- In case of a more or less constant number of cycles per order, the average flow time will grow with a growing N. Only in case of a highly variable cycle-size, the average order flow time will decrease with an increasing N. For a small N ($N \leq 10$) the average flow time changes almost proportionally to N.
- For a large N the differences in average flow times between cases with different cycle-size distributions are small.
- The largest relative change in average flow time due to an increase in N is obtained in the case of a less variable cycle-size distribution.
- In all cases the variance in flow time increases with an increasing N.

6.4.3 Average cycle-size

In the previous two experiments we have studied for the basic case the impact of the cycle-size of an individual order on its expected flow time, and the impact of the distribution of the cycle-sizes of all orders on the flow times of the orders. In the third experiment we will study the influence of the average cycle-size (or lot-size) of the orders on the expected flow time over all orders ($E(\underline{t})$). We will assume that the variation coefficient of the cycle-size density remains the same.

Expectations
We know from queueing theory that for a sequential production of orders and negligible set up times, decreasing the lot-size of the orders will also decrease the expected flow time. In fact, in such a case the average flow time will be proportional to the lot-size if we assume no change in the variation coefficient of the order operation time (see e.g. the Pollaczek-Khinchin formula, §2.2). Therefore, if N=1 the flow time will change proportionally to the change in lot size.
The relative impact on the order flow time of increasing N as shown in the previous subsections is likely to depend on the average cycle-size. For instance, in case the cycle-size of all orders is one, the flow time will not change by increasing N. Increasing the cycle-size from 1 to 2 will introduce the flow time effects of the simultaneous production of work orders for the first time. Increasing the cycle-size from 50 to 51 will have hardly any effect at all. In other words, a slight increase in cycle-size in case of a small average cycle-size will have a larger impact on the flow time than a similar change in cycle-size for a large average cycle-size. Every larger increase in average cycle-size is likely to increase these flow time effects, but less rapidly.

Input
In this experiment we have repeated the simulation runs described above, i.e. for a constant $\underline{q}$, a 'two classes' $\underline{q}$, and a highly variable $\underline{q}$, using different expected cycle-sizes, viz. $E(\underline{q})=5$, $E(\underline{q})=10$ and $E(\underline{q})=30$. In case of the 'two classes' case, the cycle-sizes of the first resp. the second order class were 2 resp. 8, 5 resp. 15, and 15 resp. 45. In all cases the expected operation time per cycle was 1.0, and the utilization rate was pre set at 80%. Note that only in case of a 'two classes' cycle-size and $E(\underline{q})=5$, the variation coefficient of the cycle-size density slightly increases. Unfortunately, with these values this exception could not be avoided.

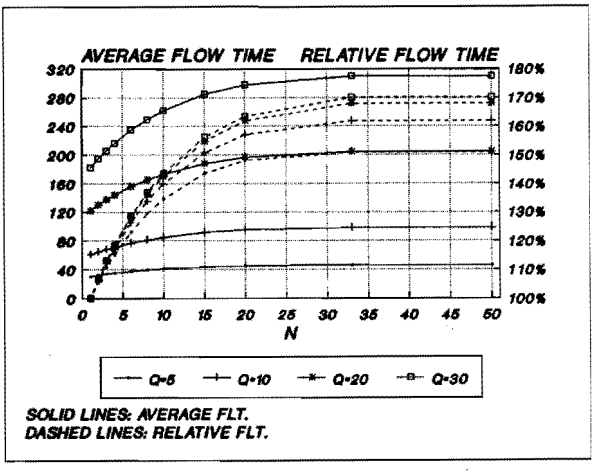

Figure 6.20:
Average flow time for constant cycle–size as function of N (ρ_{pre}=80%).

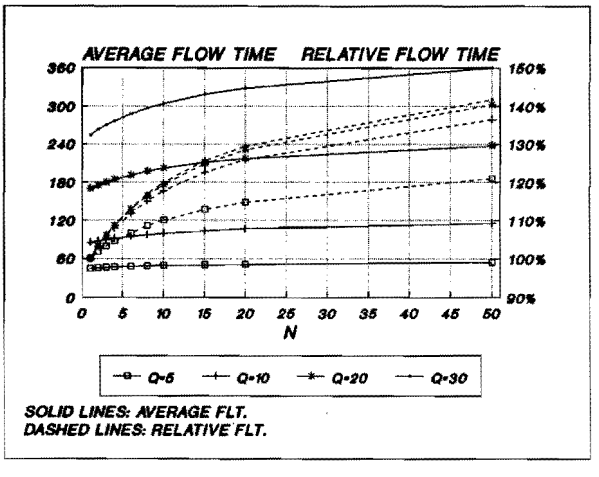

Figure 6.21:
Average flow time for 'two classes' cycle–size as function of N (ρ_{pre}=80%).

Results
The results from the experiments are shown in three figures, depicting the results for the average flow time for resp. the case with a constant cycle-size, the case of a 'two classes' cycle-size, and the case where the cycle-size has a geometrical density (resp. Fig.6.20, Fig.6.21, and Fig.6.22). The dashed lines in the figures give the increase (in percentages) in average flow time compared to the average flow time if N=1.

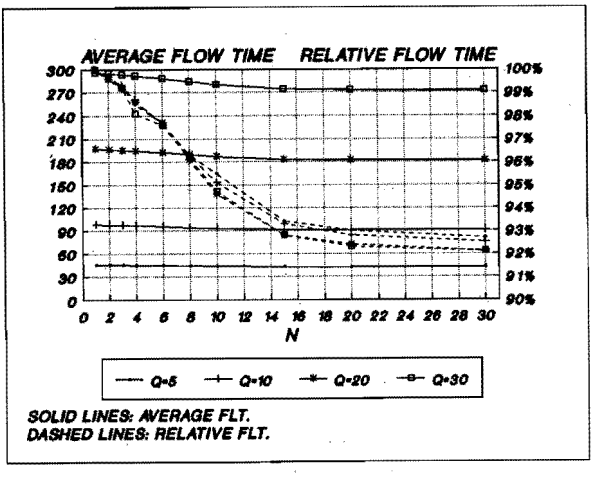

Figure 6.22:
Average flow time for geometrical cycle-size as function of N (ρ_{pre}=80%).

As can be seen from the figures, the effects of the simultaneous production of orders indeed depend on the average cycle-size of the orders, especially in case of a more or less constant number of cycles per order.

Statistical analysis
We noticed that the relative impact of an increase in N on the average flow time is likely to depend on the average cycle-size. In the figures given above, we can see that for a certain N the distances between the dashed lines grow for a smaller average cycle-size. In other words, for a certain N, a change in the average cycle-size starting with a small average cycle-size will cause a larger change in the relative increase in average flow time than an identical change starting with a larger average cycle-size.
In order to validate this observation, we have repeated the experiment for two extreme cases (viz. the constant case and the geometrical case). The detailed results of the simulation runs are given in Table 6.5. The table presents for both cases and for each cycle-size:
- the average relative increase in flow time due to an increase in N;
- the standard deviation in relative increase in flow time;
- the minimum and maximum relative increase in flow time.

Table 6.5:
Increase in average flow time for different values of N in constant and geometrical case as percentage of average flow time when N=1, resp. for E(q)=5, E(q)=10, E(q)=20, and E(q)=30 (ρ_{pre}=80%).

Constant:		N= 2	N= 4	N=10	N=50	Nr.runs
q= 5	$\bar{r}$	6.8	17.4	35.	47.	20
	s(r)	0.99	2.0	2.2	3.3	
	min(r)	4.9	13.3	29.3	37.8	
	max(r)	9.2	21.5	39.1	50.9	
q=10	$\bar{r}$	7.6	20.	41.	56.	20
	s(r)	1.11	2.3	2.7	4.2	
	min(r)	5.5	15.0	34.0	45.6	
	max(r)	10.3	24.6	45.5	62.2	
q=20	$\bar{r}$	8.1	21.	44.	62.	20
	s(r)	1.16	2.4	2.9	4.7	
	min(r)	5.9	16.0	36.5	49.8	
	max(r)	10.9	26.2	48.0	68.4	
q=30	$\bar{r}$	8.2	21.	45.	64	10
	s(r)	1.3	2.6	2.8	5.4	
	min(r)	6.5	17.5	41.2	51.2	
	max(r)	11.1	26.7	50.0	70.6	
Geometrical:		**N= 2**	**N= 4**	**N=10**	**N=50**	**Nr.runs**
E(q)= 5	$\bar{r}$	−0.5	−1.8	−4.1	− 6.	10
	s(r)	0.21	0.45	1.9	3.1	
	min(r)	−0.9	−2.7	−7.7	−10.7	
	max(r)	−0.2	−1.1	−2.0	− 1.5	
E(q)=10	$\bar{r}$	−0.7	−2.0	−4.7	− 7.	20
	s(r)	0.46	0.97	2.2	3.1	
	min(r)	−2.0	−3.6	−8.6	−11.6	
	max(r)	−0.0	0.2	−1.7	− 1.1	
E(q)=20	$\bar{r}$	−0.6	1.7	4.3	− 6.	20
	s(r)	0.56	1.5	2.7	3.3	
	min(r)	−2.0	−3.8	−8.8	−10.7	
	max(r)	0.4	1.8	−0.3	− 0.6	
E(q)=30	$\bar{r}$	−0.4	1.6	3.9	− 6.	10
	s(r)	0.30	1.1	2.0	3.5	
	min(r)	−1.0	−3.7	−7.5	−13.4	
	max(r)	−0.1	−0.1	−1.5	− 2.0	

N.B.:

$\bar{r}$: average relative increase (in %);
s(r): standard deviation relative increase (in %);
min(r): mimimum relative increase (in %);
max(r): maximum relative increase (in %).

As we can see, the relative increase in average flow time in the constant case is the largest for E(q)=30. However, the change in relative increase in flow time is the largest for a small average cycle-size. Notice that the standard deviation in relative increase is not very large. As was expected, in the geometrical case for all values of the average cycle-size the flow time decreases for a larger N. This decrease is already noticeable for a small average cycle-size.
The table is illustrated in Fig.6.23, where the average relative increase in flow time is given for the cases E(q)=5, E(q)=10, E(q)=20, and E(q)=30, each based on several simulation runs with different random input.

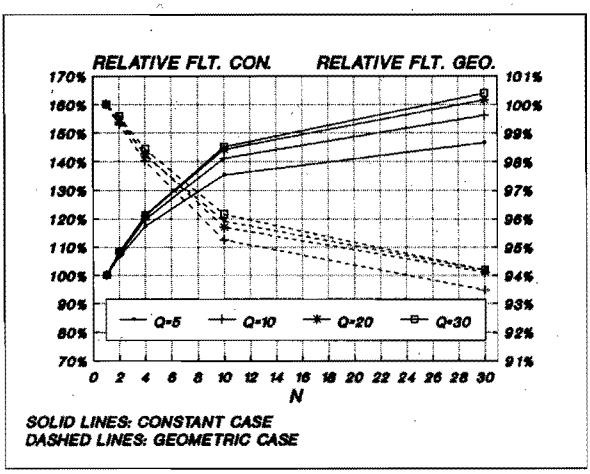

Figure 6.23:
Relative increase in average flow time
for E(q)=5, E(q)=10, E(q)=20, and E(q)=30 (ρ_{pre}=80%).

Conclusions
We conclude that the flow time effects of the simultaneous production of work orders already are noticable in case of a small average cycle-size. Therefore, efforts to limit the flow time effects of the simultaneous production of orders by decreasing the lot-size of the orders (and thus also decreasing the cycle-size) will only have remarkable results in case the cycle-sizes already are small.

6.5 Impact of time settings

In the analysis of and experiments on the basic case, assumptions have been made regarding:
- the distribution of the operation time per cycle;
- the average operation time per cycle;
- the (dis-)mounting and (un-)loading times;

In this paragraph we will study the impact of these assumptions on the results we have obtained.

6.5.1 Cycle operation time density

In the analysis of §6.2 and the simulation experiments of §6.4, we have assumed that the operation time per cycle has a negative exponential density. In this subsection we will study the impact of this assumption. In real life, the assumption of a cycle operation time having a negative exponential density may be somewhat extreme. For instance, usually at least the maximum operation time will be shorter than what may be concluded from a pure negative exponential distribution.

Expectations
We know from the Pollaczek-Khinchin formula (see §2.2), that at least for N=1 the average flow time is positively correlated to the variation coefficient (i.e. the standard deviation divided by the expected value) of the density of the operation time of an order. In our case, the average order operation time can be expressed as:

$$E(\underline{O}) = E(\underline{q})E(\underline{o})$$

where:
$\underline{O}$: order operation time;
$\underline{q}$: order cycle-size;
$\underline{o}$: cycle operation time.

The variance in order operation time can be expressed as:

$$var(\underline{O}) = E(\underline{q}^2)E(\underline{o}^2) - (E(\underline{q})E(\underline{o}))^2$$

As a result, the quadratic variation coefficient of the order operation time can be expressed as:

$$C(\underline{O})^2 = \frac{E(\underline{q}^2)E(\underline{o}^2) - E(\underline{q})^2E(\underline{o})^2}{E(\underline{q})^2E(\underline{o})^2} = (C(\underline{q})^2 + 1)(C(\underline{o})^2 + 1) - 1$$

Clearly, in case of a less extreme density for the operation time per cycle (i.e. a smaller C(q)), the variation coefficient of the order operation time will be smaller than for a more variable distributed cycle operation time. Therefore, for N=1 the average flow time will be shorter.

The flow time effects we have seen in the previous paragraph are caused by the cycle-sizes, not by the cycle operation times. For instance, in case of a constant cycle-size per order, we can, irrespective of the operation time density, apply the same reasoning as we have done in §6.2.2. Again, we may assume that the remaining work load for the machine will be independent of the sequencing rule used. Therefore, in case of a constant cycle-size and simultaneous production, the last cycle of an order *i* will have to wait for the completion not only of the work already present at the moment of arrival of order *i*, but also for the completion of some of the cycles of orders that will arrive after the moment of arrival of *i*. Thus, we expect the flow time to grow with an increasing number of orders simultaneously in operation. In fact, under the assumption that the cycle operation times can be regarded as infinitesimal quanta, it is shown in §6.2.2 that the flow time indeed increases from N=1 to $N \to \infty$.
In case of a highly variable cycle-size, again we expect the short flow times of orders with a small cycle-size to compensate for the long flow times of orders with a large cycle-size. However, in this case we may not apply the same analysis for a cycle-size with a geometrical distribution as we could in §6.2.2, since for a very large N the arrival process of cycles cannot be regarded as a Poisson process. Nevertheless, we expect a similar effect as in the case of negative exponential cycle operation times.

Input
In order to investigate the impact of the assumption regarding the operation time distribution, we will study the case where the operation time per cycle is equal for all cycles. In all experiments the operation time per cycle is set at 1.0, while the expected cycle-size was set at resp. 5 and 20. The remaining input of the experiment is chosen equal to the experiment described in §6.4.2 for a pre-set utilization rate of 80%, i.e. we will repeat the experiments for a constant cycle-size, the 'two classes' case, and a geometrical cycle-size.

Results
In Fig.6.24 and Fig.6.25 the results are given for the average flow times resp. for E(q)=5 and E(q)=20, while Fig.6.26 and Fig.6.27 present the results for the relative increase in flow time (compared to the flow time in case N=1). The dashed lines in the figures give the results for the comparable simulation runs with negative exponential cycle operation times (see Fig.6.20 and Fig.6.22).
If we compare the dashed lines with the lines for constant cycle operation times, we can see that indeed the flow time is affected by the density of operation time per cycle. However, also in case of constant cycle operation times, the flow time effects shown in the previous sub-sections appear. Notice that in case of constant cycle operation times a small increase in N creates a larger relative increase in the flow time than in case of exponential cycle operation times. On the other hand, the maximum relative increase or decrease is the largest for the cases with exponential cycle operation times.

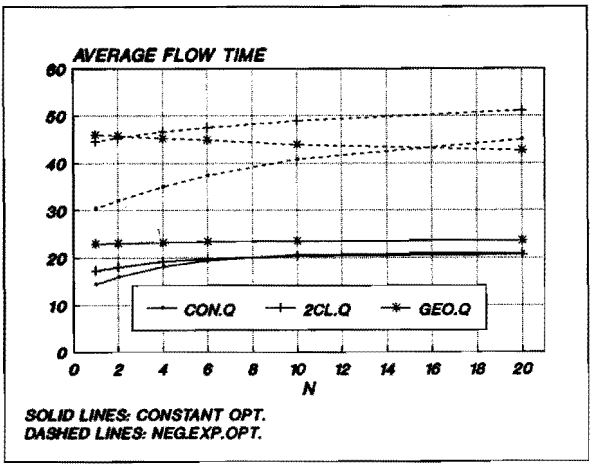

Figure 6.24:
Average flow time for constant and exponential cycle operation time as function of N in case E(q)=5 (ρ_{pre}=80%).

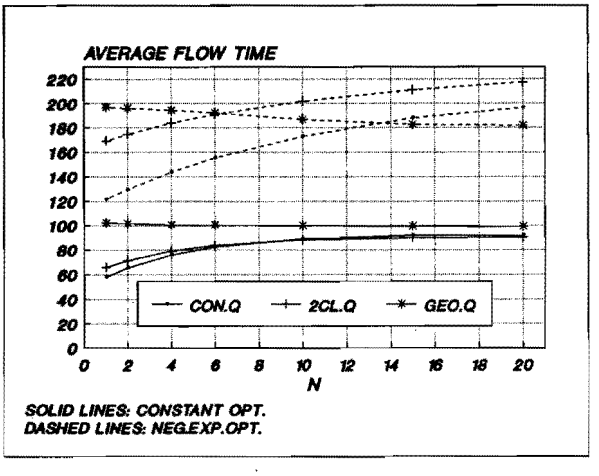

Figure 6.25:
Average flow time for constant and exponential cycle operation time as function of N in case E(q)=20 (ρ_{pre}=80%).

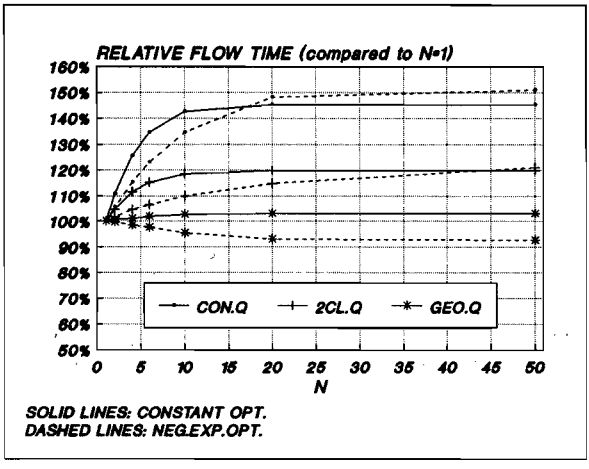

Figure 6.26:
Relative increase in flow time (compared to N=1) for constant and exponential cycle operation time as function of N in case $E(\underline{a})=5$ ($\rho_{pre}=80\%$).

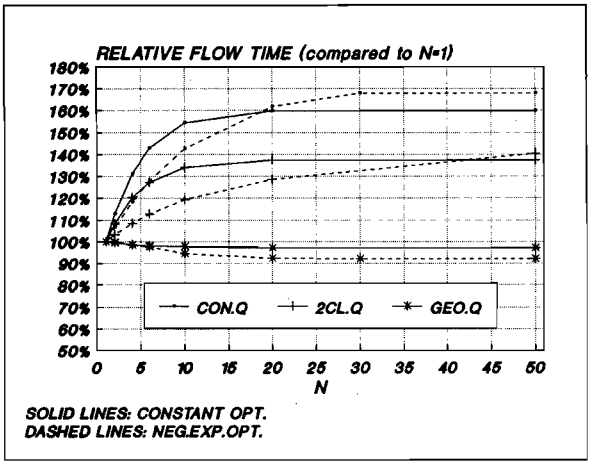

Figure 6.27:
Relative increase in flow time (compared to N=1) for constant and exponential cycle operation time as function of N in case $E(\underline{a})=20$ ($\rho_{pre}=80\%$).

Conclusion
To summarize: although the value of the average flow time and the variance in flow time will be affected by the density of the operation time per cycle, the appearance of the flow time effects of the simultaneous production of work orders is not dependent on this density. In fact, the less variable the cycle operation time is, the more sensitive the flow time will be to a small increase in N if N is small.

6.5.2 Average cycle operation time

Since the FCFS–rule is used in the external queue, we know that the average external waiting time will be equal for all work orders, independent of the cycle operation time. In the analysis and in the previous simulation experiments we have shown that the average internal waiting time of a cycle of a work order depends on the cycle–size of the order (see §6.4.1). In this subsection we will show that this average internal waiting time also (slightly) depends on the cycle operation time. As we recall, in the previous experiments we have assumed for all work orders an equal average cycle operation time.

Expectations
Up till now we have assumed that each cycle of any order has a negative exponential density with an average of 1.0. As a result, we concluded that in case of a single FAM–Station the average number of pallets occupied by cycles of other orders would be independent of the cycle considered (i.e. $E(\underline{x}(i)) = E(\underline{x}(j)) = E(\underline{x})$ for all cycles i and j; see eqn.(6.3), §6.2.1).
This will not be the case anymore for work orders with different cycle operation times. An example to illustrate this is given in Fig.6.28. In the example we have two situations. In the first case the first cycle of a work order i can be loaded on a pallet at time t_1. This first cycle has to wait for the completion of the cycles already loaded on the system before it is taken into operation. Let us assume that the number of pallets occupied by cycles of other orders at the time the first cycle of i is loaded, is $x_1(i)$ (NB: in case of N pallets, $x_1(i)$ has a maximum of N–1). Let us further assume that from these $x_1(i)$ orders, $r_1(i)$ orders are completed after the first cycle of i is completed. In other words, $r_1(i)$ pallets become free. Due to the FCFS–rule, if possible these $r_1(i)$ pallets will be occupied by the first cycles of work orders already waiting in the external queue at time t_1. We will denote this number of orders as $w_1(i)$. Finally, we will assume that during the cycle flow time of the first cycle of i, $a_1(i)$ new work orders have arrived in the system. As a result, the number of pallets occupied by cycles of other work orders at the time the second cycle of i is loaded ($t_2(i)$) will be:

$$x_2(i) = x_1(i) - r_1(i) + \min(w_1(i),r_1(i)) + \min(a_1(i),z_2(i)) \qquad (6.15)$$

where:
$z_2(i) = N - 1 - x_1(i) + r_1(i) - \min(w_1(i),r_1(i))$,

(i.e. number of pallets not occupied when the second cycle of i is loaded, assuming that no orders have arrived in the system during the cycle flow time of the first cycle of i)

If the number of orders in the system is much larger than the number of pallets on the FAM-Station, we know that $x_1(i) = N-1$, and we may assume that $w_1(i) \geq r_1(i)$. Therefore, $z_2(i)$ will be equal to 0, and thus also $x_2(i)$ will be N-1.

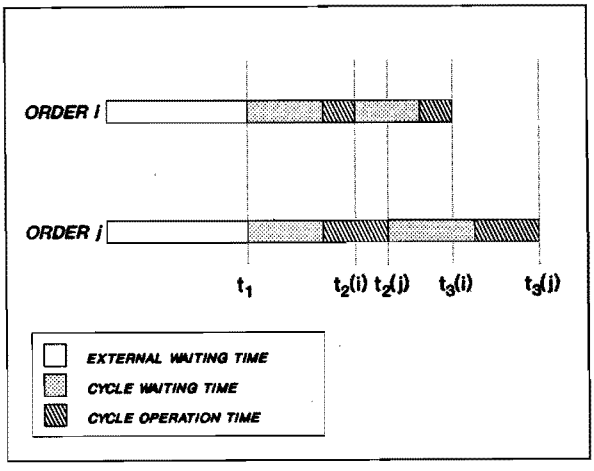

Figure 6.28:
Example of cycle flow time of first cycle
in case of work orders with different cycle operation times.

In the second situation given in Fig.6.28, at time t_1 instead of the first cycle of a work order i, the first cycle of work order j will be loaded on the system. The only difference between i and j is the cycle operation time, viz. $o(j)>o(i)$. All other characteristics of these work orders are identical (e.g. $q(j)=q(i)$, i.e. order i and j have equal cycle-sizes). We assume that also all other characteristics of the two cases are identical. Similar to the first case, we know for the time the second cycle of order j is loaded (i.e. $t_2(j)$) that:

$$x_2(j) = x_1(j) - r_1(j) + \min(w_1(j),r_1(j)) + \min(a_1(j),z_2(j))$$

Under the assumptions made, we know that $x_1(j)=x_1(i)$ and $w_1(j)=w_1(i)$. We also know that $r_1(j)=r_1(i)$, since this quantity is only dependent on the progress of the other work orders, not on order i or j. As a result, also $z_2(j)=z_2(i)$. However, since $o(j)>o(i)$, we may expect that $a_1(j)>a_1(i)$, for the arrival process is independent of the present situation. In other words:

$$x_2(j) = x_1(i) - r_1(i) + \min(w_1(i),r_1(i)) + \min(a_1(j),z_2(i)) \qquad (6.16)$$

Therefore, we conclude that:

- if $z_2(i) \leq a_1(i)$, then $x_2(j) = x_2(i)$;
- if $z_2(i) > a_1(i)$, then $x_2(j) > x_2(i)$;

The same logic can be applied to the next cycles of i and j. In these cases the conclusion will be that:

- if $x_y(j) = x_y(i)$, then $x_{y+1}(j) \geq x_{y+1}(i)$;
- if $x_y(j) > x_y(i)$, then surely $x_{y+1}(j) > x_{y+1}(i)$

Consequently, we may assume that $E(\underline{x}(j)) > E(\underline{x}(i))$.
In other words, the number of orders simultaneously in operation in case of orders with a long cycle operation time will be larger than in case of orders with short cycle operation times. Therefore, the average cycle waiting time of orders with long cycle operation times will be longer than average, whereas the cycle waiting time of orders with short cycle operation times will be shorter than average. This difference will be noticable in the order flow time especially in case of:
- orders with a large cycle size, since for these orders the internal flow time will be much larger than the external waiting time;
- a large N, since in such a case the probability that $z_{y+1}(i) > a_{y+1}(i)$ is higher than in case of a small N;
- a low utilization, since in that case the probability that $z_{y+1}(i) > a_{y+1}(i)$ is higher than in case of a high utilization rate, due to the fact that the number of pallets occupied will be smaller.

However, in all cases similar flow time effects will appear (i.e. an increasing variance and a cycle-size dependent waiting time), since the orders are still taken into operation simultaneously.

Table 6.7:
Average internal cycle waiting time
in case of distinct cycle operation times ($q(i)=q=20$; $\rho_{pre}=80\%$).

N	Class 1 ($o(i)=0.1$)	Class 2 ($o(i)=1.9$)
1	0.00	0.00
2	0.81	0.87
4	2.08	2.35
10	4.28	4.88
20	5.39	6.15
50	5.58	6.32

Input
In order to illustrate the above phenomenon, we have repeated the 'two classes' experiment. The cycle-size of the two classes were set at 20. In the experiment the cycle operation time was set at extreme values, viz. for the first class at 0.1, and for the second class at 1.9. As in the previous experiments, the number of orders completed per order class was about 2,000.

Results
Table 6.7 gives the results on the average cycle internal waiting time of the experiment. The table clearly underlines the conclusion that orders with a longer cycle operation time also will have a longer cycle waiting time.

6.5.3 Mounting and loading times

Before the operation on a cycle of a work order can start, several activities have to be performed on the mounting/loading place (e.g. a pallet set-up has to be mounted and cycles have to be loaded and unloaded). We will call the time involved in these activities the mounting and loading time. In the analysis and experiments of §6.2 and §6.4 we have assumed that the mounting and loading times are negligible. In this subsection we will study the impact of this assumption on the results obtained.

Expectations
Especially in case of a system containing only one pallet, mounting and loading times will have a considerable impact on the flow times of an

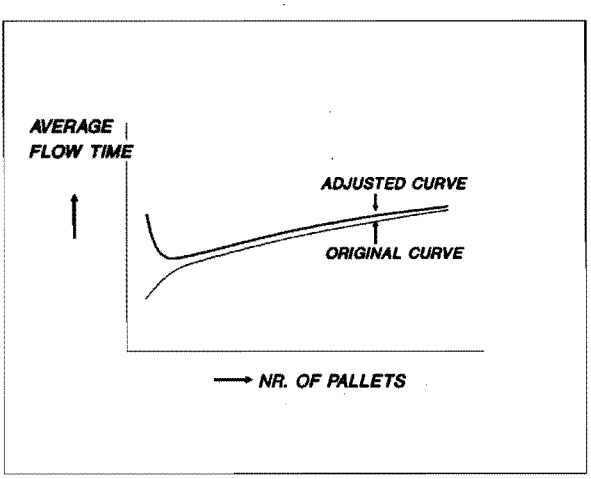

Figure 6.29:
Expected adjustment of flow time curve in case of non-negligible mounting and loading times (see also [Dirne, 1990]).

order. In fact, if N=1, during the mounting and loading activities the machine will be idle. In other words, in such a case, the service time of the machine tool no longer can be regarded as purely processing time, but should also include the required mounting and loading times. As we know from the Pollaczek–Khinchin formula, the average flow time will grow proportionally with the average service time. However, due to the growing service time, also the utilization rate of the machine tool will grow. So on top of the increase due to a longer average service time, the average flow time will grow exponentially due to a higher utilization rate. In other words, in case of non–negligible mounting and loading times, the flow time curve should be adjusted as presented in Fig.6.29.
As we can see, we expect that there will be an optimal N (called N_{opt}) for which the average flow time is minimal. In case of variable cycle operation times, the mounting and loading times of one order may be larger than the cycle operation time of another order. Consequently, the probability that a machine gets idle due to mounting and loading activities even for N>1 is larger in that case. As a result, N_{opt} will be larger for variable cycle operation times than for more constant cycle operation times.

Input
We recall that the mounting and loading times are expressed as a factor α or $(\alpha/10)$ times the operation time per cycle (see §6.3.2). In all previous experiments we have chosen α=0. In order to validate the assumption given in Fig.6.29, we have repeated the simulation experiments as described in §6.4.2 and in §6.5.1 for E(q)=20 using non–negligible mounting and loading times, viz. with α=2.0, α=1.0 and α=0.5.

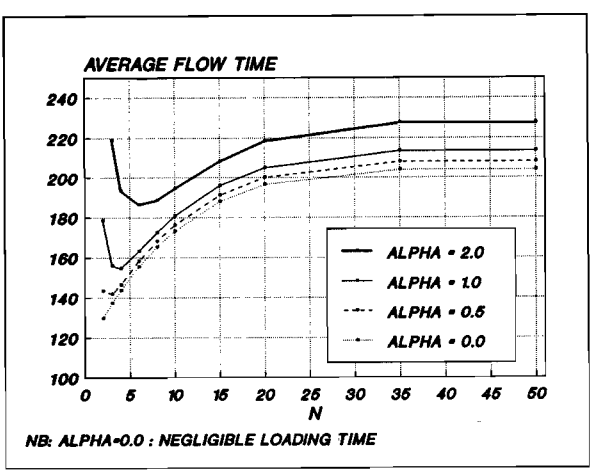

Figure 6.30:
Average flow time in case of non–negligible mounting/loading times for constant cycle–size and negative exponential cycle operation times (ρ_{pre}= 80%).

Notice that for N=1 the machine will be occupied not only due to the average order operation time (i.c. 20.0), but also due to mounting and loading activities at the mounting/loading place. In the experiments this means that the machine service time per work order will be the order operation time plus the sum of all mounting and loading activity times (i.e. the mounting time ($1.0 \times \alpha$), the mounting and loading time for all cycles ($20 \times 2 \times 1.0 \times \alpha/10$), and the dismounting time ($\alpha/10$)). Only if $\alpha<0.83$ the utilization rate of the machine be lower than 100%.

Results

Fig.6.30, Fig.6.31 and Fig.6.32 present the results of the experiments in case of negative exponential operation times (resp. for constant cycle-size, 'two-classes' cycle-size, and geometrical cycle-size). As we can see from the average flow times curves drawn in the figure, the impact of mounting and loading times indeed decreases with an increasing maximum number of orders simultaneously on the FAM-Station. For not too variable cycle-sizes the flow time increases more rapidly left of the optimum than right of the optimum.

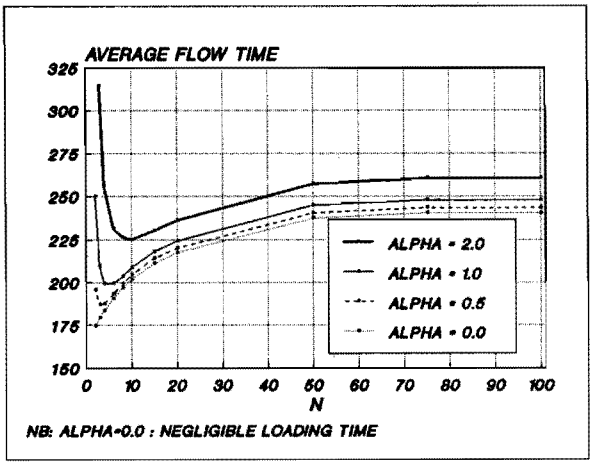

Figure 6.31:
Average flow time in case of non-negligible mounting/loading times for 'two classes' cycle-size and negative exponential cycle operation times (ρ_{pre}= 80%).

In Table 6.8 the optimum number of pallets is given (i.e. the number of pallets N_{opt} for which the average flow time is the shortest), both in case of negative exponential cycle operation times and in case of constant cycle operation times. Of course, N_{opt} is the smallest in case of constant cycle operation times. Only for a large α the optimum number of pallets exceeds 2, because in that case the single mounting/loading place frequently will be occupied.

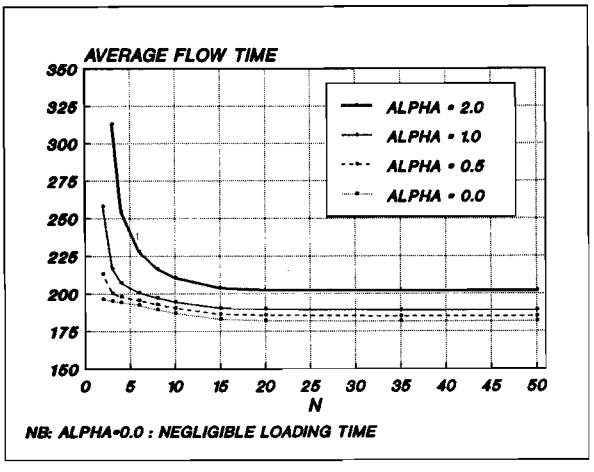

Figure 6.32:
Average flow time curves in case of non–negligible mounting/loading times for geometrical cycle–size and negative exponential cycle operation times (ρ_{pre}=80%).

Table 6.8:
Optimum number of pallets in simulation runs with non–negligible mounting and loading times.

NE – cycle operation time:	α=0.0	α=0.5	α=1.0	α=2.0
Constant q	1	3	4	6
Two classes q	1	3	5	10
Geometrical q	∞	∞	∞	∞
C – cycle operation time:	**α=0.0**	**α=0.5**	**α=1.0**	**α=2.0**
Constant q	1	2	2	4
Two classes q	1	2	3	4
Geometrical q	∞	∞	∞	∞

In real life, usually it will be possible to prevent the machine from getting idle when $N \geq 3$, especially if some of the preparation activities are carried out not on the mounting/loading place, but e.g. in a special preparation area.

Conclusion
We conclude that from the point of view of minimizing the average flow time, there is an optimum number of pallets. This optimum is larger than

one, and in real life usually will be about three pallets. With three pallets it should be possible to prevent the machine from getting idle due to mounting and loading activities, while at the same time the number of orders in operation is limited.

6.6 Product and pallet set-ups

In our study we have assumed up till now that each run batch contains only one cycle, that for each type of product set-up only one product set-up is available, and that each part requires only one type of product set-up (no re-loading). In this paragraph we will relax these assumptions and study their impact on the order flow times. More specifically, we will study consecutively the assumptions regarding:
- the number of parts per product set-up;
- the number of identical product set-ups;
- the number of types of product set-ups required.

6.6.1 Number of parts per product set-up

If parts are not too large, it usually is possible to change the cycle-size of an order without changing the lot-size by increasing the number of parts loaded in one product set-up. Consequently, the cycle-size of the order will be reduced, while the average cycle operation time will be increased. As a result, the total order operation time will not be changed.
In §6.4.3 we already studied the impact of a change in cycle-size on the flow time effects. We concluded that the impact of the simultaneous production of orders increases with an increase in cycle-size. However, in that subsection we assumed that the average cycle operation time remained the same. In this subsection we will assume that the total order operation time remains the same.

Expectations
We know from queueing theory that the average waiting time of a work order can be expressed as a factor times the average order operation time. If we change only the average order operation time and not the operation time density nor the utilization rate, the waiting time of the order will change proportionally to the change in average order operation time (see e.g. the Pollaczek-Khinchin formula in §2.2). In our case, we can use this fact as follows. If we change the cycle operation time for each work order, but maintain the original number of cycles and utilization rate, the order flow time will change proportionally to that change in cycle operation time. In other words, increasing the average cycle operation time for the cases where $E(q)=10$ with a factor 2, will increase the resulting flow time also with a factor 2. This is true for all N. Therefore, under these assumptions, the relative increase in order flow time due to an increase in N is exactly the same for all average cycle operation times.
By increasing the number of parts loaded in one product set-up, we reduce the cycle-size with a certain factor, and increase the cycle operation time

with the same factor. We know from §6.4.3 what the effects are of changing the cycle-size of an order while maintaining the same cycle operation time. If we increase the number of parts per product set-up with a factor 2 in the case where E(q)=20, the new situation will resemble the case described in §6.4.3 where E(q)=10. The relative increase in average flow time due to an increase in N will be identical in both cases. However, since we do not change the order operation time, the average flow time for N=1 remains the same irrespective of E(q). Thus, as opposed to the case described in §6.4.3, changing the cycle-size will not change the flow time for N=1.
To summarize, if we reduce the cycle-size of an order without changing the lot-size, we expect that:
- the order flow time for N=1 will not change;
- the relative change in the order flow time due to an increase in N will be identical to the relative flow time change due to an increase in N in case of a reduced lot-size (see §6.4.3).

Input
In this experiment we will change the characteristics of the work orders to be completed such that the expected operation time for the entire work order remains the same (i.e. 20.0). In other words, a larger expected cycle-size per order will be compensated with a shorter expected operation

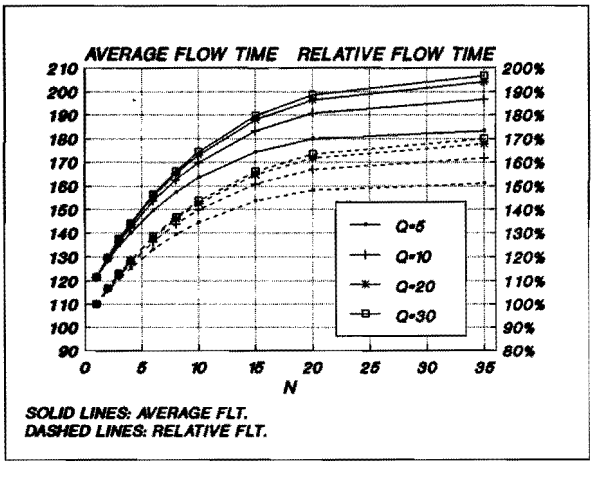

Figure 6.33:
Average flow time for different cycle-sizes but equal order operation times in case of constant cycle-size as function of N (ρ_{pre}=80%).

time per cycle. We will study two of the cases described above, i.e. the case of a constant cycle-size and the case of the 'two classes' cycle-size.

Results
The results from the experiments are shown in two figures, depicting the

results for the average flow time and the change in average flow time for resp. the case with a constant cycle-size and the case where the cycle-size is either 10 or 30 (resp. Fig.6.33 and Fig.6.34). If we compare these figures with Fig.6.20 resp. Fig.6.21, we can see that the (relative) effects of the simultaneous production of orders indeed depend on the average cycle-size of the orders, not on the average cycle operation times (see the dashed lines).

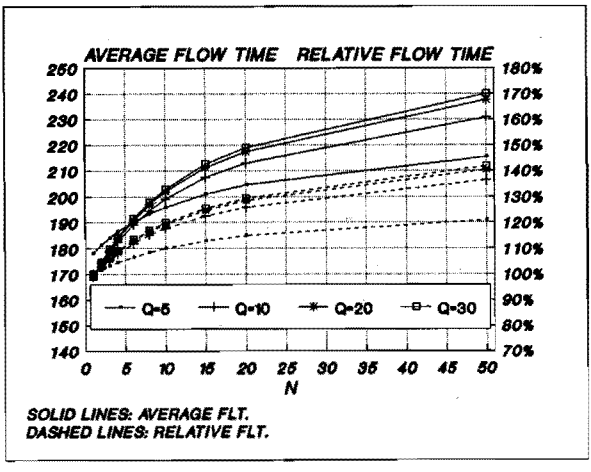

Figure 6.34:
Average flow time for different cycle-sizes but equal order operation times in case of 'two classes' cycle-size as function of N (ρ_{pre}=80%).

Conclusion
We conclude that the relative impact of the simultaneous production of work orders on the flow times increases with an increasing E(q). In other words, decreasing the cycle-size without changing the lot-size of a work order will decrease the flow time effects of the simultaneous production of work orders. However, as we concluded in §6.3.4, the flow time effects of the simultaneous production of work orders already are noticable in case of a small average cycle-size. Therefore, even for a small cycle-size these flow time effects cannot be neglected.

6.6.2 Number of identical product set-ups

The next assumption we will study, concerns the number of identical product set-ups. We will denote the maximum number of identical product set-ups for order i with f(i). In all previous experiments, we have assumed that for the type of product set-up required for an order i only one

product set-up can be mounted on a pallet concurrently ($f(i)=1$), usually due to a limitation in the number of identical fixtures. Of course, we will assume that these extra product set-ups are mounted on separate pallets, since mounting the product set-ups on one pallet resembles the situation studied in the previous subsection.

Expectations
The flow time effects shown in the previous simulation experiments are caused by the simultaneous production of work orders. Assuming that the number of product set-ups per pallet is equal to one, increasing the number of identical product set-up per type of product set-up ($f(i)>1$) means increasing the number of pallets that is set up for a particular work order. Therefore, given a certain N, the number of work orders simultaneously in operation will decrease in case of an increase in $f(i)$. As a result, the flow time effects of the simultaneous production of work orders are likely to diminish (i.e. the average flow time will change less with a growing N, and the standard deviation in flow time will grow more slowly with a growing N). In fact, if exactly $f(i)$ pallets are occupied, these flow time effects will disappear completely.
In case of a large N, the number of work orders simultaneously in operation will not be limited. In such a case there is no difference between occupying two pallets simultaneously with a cycle of one particular work order (i.e. if $f(i)=2$), and occupying one pallet with twice as much parts of one work order (thus decreasing the cycle-size without changing the lot-size; see §6.6.1). In both cases the two cycles will be completed one after the other. Therefore, increasing $f(i)$ in that case will have the same effect as decreasing the cycle-size without changing the lot-size. We know from the previous subsection that this latter case will reduce the effects of the simultaneous production of work orders.

Input
We have repeated the experiment described in §6.4.3 (i.e. the constant, the 'two classes', and the geometrical case) resp. with $f(i)=2$ and $f(i)=4$, for all orders. We have assumed an average cycle operation time of 1.0.

Results
In Fig.6.35, Fig.6.36 and Fig.6.37 the results are given from the experiments assuming resp. for the constant case, the 'two classes' case, and the geometrical case, assuming a maximum of one, two or four identical product set-ups.
As we can see, especially for a realistic range of values for N (viz. from 1 until 15), the average flow time is reduced. In case of a large N, we see that the change in average flow time indeed is reduced.

Statistical analysis
If we compare the effects of increasing $f(i)$ with the effects of decreasing the cycle-size $q(i)$ of the order as described in §6.4.2, we see a strong resemblance. In fact, in case N is very large, these two cases are likely to obtain the same effects, because in that case it is of no importance if two cycles of the same order are loaded on one pallet at the same time, or on two pallets. The first option resembles the situation where $q(i)$ is reduced with a factor 2, the second option resembles the situation where $f(i)$ is increased with a factor 2. However, for a small N, the option of increasing the maximum number of identical product set-ups will have more effect than reducing the cycle-size. The reason is that if more than one product set-up per order is loaded on the station at the same time, the number of

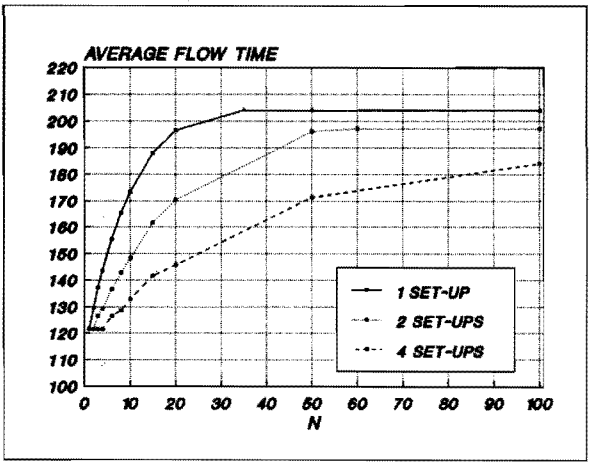

Figure 6.35:
Average flow times for constant cycle–size
in case of resp. f(i)=1, f(i)=2, and f(i)=4 (ρ_{pre}= 80%).

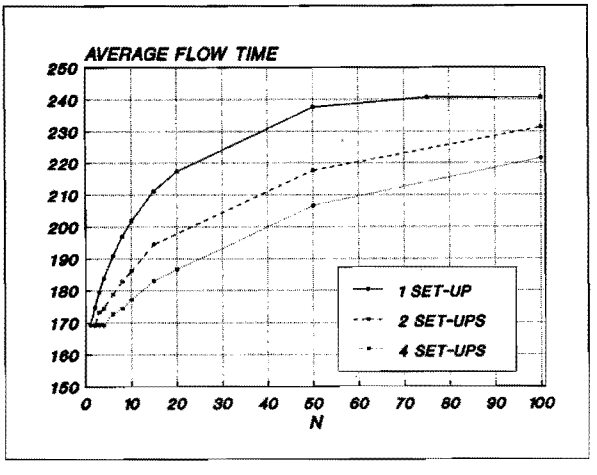

Figure 6.36:
Average flow times for "two classes" cycle–size
in case of resp. f(i)=1, f(i)=2, and f(i)=4 (ρ_{pre}= 80%).

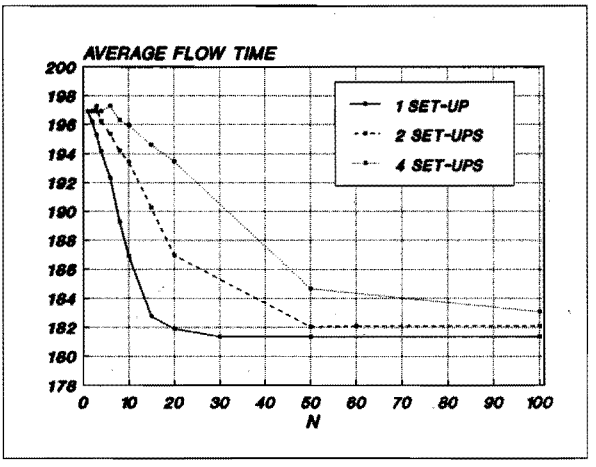

Figure 6.37:
Average flow times for geometrical cycle-size
in case of resp. f(i)=1, f(i)=2, and f(i)=4 (ρ_{pre}= 80%).

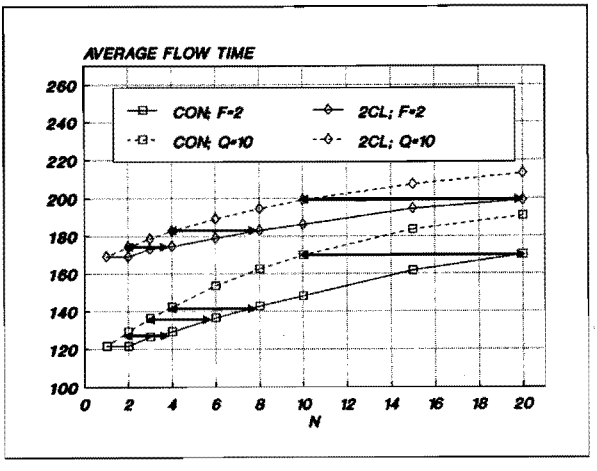

Figure 6.38:
Average flow times in case of f(i)=1 and q(i)=10 ($\forall$ i),
compared to the case of f(i)=2 and q(i)=20 ($\forall$ i) (ρ_{pre}= 80%).

orders in operation simultaneously will decrease. In other words, in case of a small N, the situation of $f(i)=2$ for each order i resembles the situation with half the cycle-size (and the same order operation time) and $N/2$ pallets.
In order to illustrate the expectations, we can use the results from the experiments described above on the constant case and the 'two classes' case, viz. for $f(i)=2$ and $E(q)=20$ (see resp. Fig.6.35 and Fig.6.36) and for $f(i)=1$ and $E(q)=10$ (resp. Fig.6.20 and Fig.6.21). In Fig.6.38 we have compared the results from these experiments. The results shown in the figure underline the expectations stated above.
We will generalize this observation by testing it for the constant case. The hypothesis tested is: the difference 'd' between:

a) the average flow time for $f(i)=2$ in case $N=4$ and $N=8$,

and:

b) the average flow time in case $f(i)=1$, the number of parts per product set-up is increased with a factor 2, and N is reduced by 50%,

is zero.
This hypothesis (H_0) is tested applying the Student's t-density (see §6.4.1). H_0 is not accepted if $|t(d)|$ is larger than $\underline{t}_{n-1}$ ($t(d)$ calculated according to eqn.(6.14); see §6.4.1). We recall that for a level of significance of 5% ($\alpha=0.05$), $\underline{t}_{19} \approx 2.10$ (two-sided).
In Table 6.9 the results of this test are given.

Table 6.9:
Results Student's t-test on differences (d) in average flow time in the multiple product set-up case between the case where $f(i)=2$, $q(i)=q$, $N=N$, and the case where $f(i)=1$, $q(i)=q/2$, $N=N/2$.

N	$\bar{d}$	s(d)	$t(\underline{d})$	$\underline{t}_{19}(0.05)$	Range
4	0.16	0.039	19.01	2.10	0.17
8	0.27	0.070	17.17	2.10	0.29

As we can see in the table, for both values of N, H_0 is rejected. However, the table also shows that the differences between the flow times:
- are very small (on the average less than 0.2%);
- only have a small range and a low standard deviation.

For real life, these kind of differences are negligible.

Conclusions
In case of a small N, increasing the number of identical product set-ups of an order will decrease the number of orders that are simultaneously in operation. Therefore, the flow time effects of the simultaneous production of orders are reduced.
Increasing the maximum number of identical product set-ups in case of N pallets with only one product set-up per pallet from 1 to f has a similar effect as decreasing the cycle-size without changing the lot-size in case of N/f. For a very large N there will be hardly any difference between these two situations.

6.6.3 Multiple product set-up type case

In the basic case, we have assumed that all parts can be completed in only one product set-up. However, as we know from §4.2.1 (see Fig.4.3), frequently this will not be the case. In the cases we have studied it was not uncommon for about half of the work orders to require two product set-up types. Only few work orders required more than two set-ups.
Therefore, we should study the possible effects in case more type of product set-ups are required to complete a part. In this so-called multiple product set-up type case, each cycle has to be re-loaded at least once in order to be completed.
We will start our study with the case where all product set-up types required for a work order are mounted on one pallet (i.e. the multiple pallet set-up case). After that we will discuss the situation where for each type of product set-up a separate pallet is prepared (i.e. the single pallet set-up case).

a) The multiple product set-up type, multiple pallet set-up case

In order to gain insight in the possible effects of the multiple pallet set-up case, we will assume that the cycle-size will be equal for each type of product set-up required to complete a work order. Also, we will assume that all product set-ups for one work order are mounted on one pallet. In other words, one pallet contains all types of product set-ups required for completing a part. As a result, after the first operation in the first product set-up type is completed, each cycle will be unloaded from this product set-up and re-loaded in a product set-up on the same pallet, but of a different product set-up type.

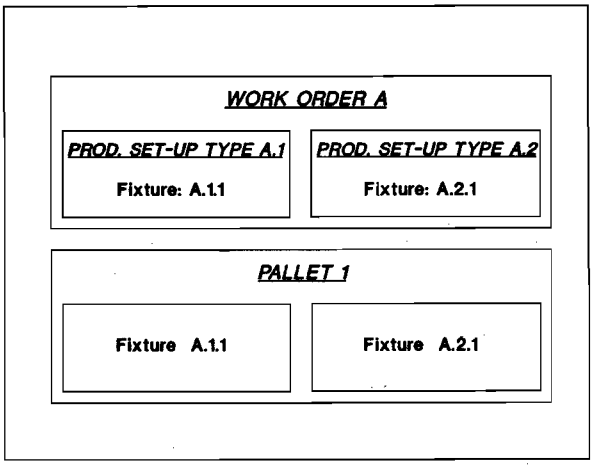

Figure 6.39:
Example of the multiple product set-up type, multiple pallet set-up case.

An example of this case is given in Fig.6.39. As we can see, in the example order *A* requires two types of product set-ups, i.e. *A*.1 and *A*.2. For each type of product set-up only one fixture is available. Both fixtures can be mounted at the same time on one pallet.

Expectations
Let $o(i,j)$ be the operation time required to complete a cycle of work order i in the j-th type of product set-up, and let $p(i)$ be the number of types of product set-ups required to complete a part of order i. We assume that the number of fixtures available is limited to one per product set-up type ($f(i,j)=1$). We will compare this situation with the case where all cycles of an order can be completed in one type of product set-up. We assume that the operation time required for an entire work order will be the same in both cases, or:

$$o(i) = \sum_{j=1}^{p(i)} o(i,j).$$

Since we assume that in case of $p(i)$ types of product set-ups all product set-ups required for an order are mounted on one pallet, the operation time required for a run batch containing $p(i)$ cycles will be $o(i)$.
In any case, the first cycle has to be (re-)loaded exactly $(p(i)-1)$ times before it is loaded in the last required product set-up. After the first cycle is loaded in the last type of product set-up, we will have to re-load a run batch exactly $(q(i)-1)$ times before the last cycle can be completed in the last product set-up ($q(i)$ is the cycle-size of order i). Therefore, the larger $p(i)$ gets, the larger the number of times cycles of one work order will have to wait on the FAM-Station for machine capacity. As a matter of fact, increasing the number of product set-up types from 1 to $p(i)$ resembles the hypothetical situation where the cycle-size of an order is increased because some cycles are split up into several smaller cycles, thus increasing the 'cycle-size' with a factor $(q(i)+p(i)-1)/q(i)$, and decreasing the average 'cycle' operation time with a factor $q(i)/(q(i)+p(i)-1)$. We know from §6.6.1 that increasing the cycle-size also increases the flow time effects of the simultaneous production of work orders. In consequence, we expect the flow time of an order to grow with an increasing $p(i)$. Only in case $N=1$, an increase in $p(i)$ will have no effects on the flow time (assuming that mounting and loading times are negligible). However, due to the minor changes in the 'cycle-size', the overall effect will be small.

Input
In order to validate these expectations, we have repeated the simulation experiments of the cases with a constant cycle-size and of the 'two classes' case as described in §6.3.3., assuming two types of product set-ups required for each work order. The average cycle operation time in each product set-up type is set at 0.5. The rest of the input is kept unchanged.

Results
Table 6.10 gives the results from the experiments, including the results for $p(i)=1$ (see Fig.6.16, §6.3.3). As we can see, the average flow time for a certain $N>1$ indeed seems to increase very slightly if $p(i)$ increases from 1 to 2. However, in real life, such an increase will be negligible.

Table 6.10:
Average flow times, average external waiting times, and standard deviation in flow times in the multiple pallet set–up case as function of N in case of constant cycle–size and 'two classes' cycle–size, resp. for p(i)=2 and p(i)=1 (ρ_{pre}=80%).

Constant	p(i)=2			p(i)=1		
N	$\bar{t}(i)$	$\bar{t}_{ext}(i)$	s(t(i))	$\bar{t}(i)$	$\bar{t}_{ext}(i)$	s(t(i))
1	121.49	100.95	103.92	121.49	100.95	103.92
2	129.54	91.05	106.33	129.52	91.04	106.32
4	143.64	74.29	112.86	143.60	74.25	112.86
10	173.33	37.78	136.86	173.15	37.70	136.78
20	196.84	8.27	167.15	196.52	8.23	166.91
50	204.58	0.00	181.13	204.04	0.00	180.47
Two classes	p(i)=2			p(i)=1		
N	$\bar{t}(i)$	$\bar{t}_{ext}(i)$	s(t(i))	$\bar{t}(i)$	$\bar{t}_{ext}(i)$	s(t(i))
1	169.16	149.21	224.70	169.16	149.21	224.70
2	174.83	137.74	226.72	174.61	137.54	226.62
4	183.98	118.32	232.20	183.66	118.10	232.48
10	202.89	79.56	254.13	201.83	79.14	254.68
20	219.01	47.29	289.57	217.33	46.81	290.43
50	240.04	8.08	366.11	237.58	7.81	366.94
75	243.39	0.00	384.36	240.59	0.00	384.48

Table 6.11:
Differences in order flow time, external waiting time, resp. cycle flow time, between the cases p(i)=2 and p(i)=1 (N=10; ρ_{pre}=80%).

	$\bar{t}(i)$	$\bar{t}_{ext}(i)$	$\bar{c}(i)$
$\bar{d}$	0.23	0.06	− 0.27
s(d)	0.058	0.034	0.030
min(d)	0.1629	0.0074	− 0.3174
max(d)	0.3404	0.1355	− 0.2200
$(\bar{d}/s(d))\sqrt{10}$	12.24	5.76	28.78

Statistical analysis
In order to validate the observation that the flow time indeed increases when p(i) is increased from 1 to 2, we have repeated the simulation experiment for the constant cycle–size and N=10 nine times. The hypothesis

tested is that the difference in average flow time between the case p(i)=p=2 and p(i)=p=1 is not larger than zero (H_0). The results of the test are given in the first column of Table 6.11, again applying the Student's t-density. For this test the critical value for α=0.05 is 1.83 (one-sided). As we can see, the hypothesis is rejected, even for a very small α. The table also gives some details on the results for the differences in external waiting time and in internal cycle flow time. These results underline the expectations stated above. In fact, if we perform a test on the external waiting time and the cycle flow time similar to the test on the average flow time, we find that also for these values the differences are significant. Notice however, that all differences are very small. In real life these differences are negligible.

Conclusion
In case all product set-ups are mounted on one pallet, the order flow time hardly will be influenced by the number of product set-up types required to complete a part (again, assuming negligible mounting and loading times). At least in real life the differences in flow time are negligible. Clearly, if the mounting and loading times cannot be neglected, the differences in flow time will get larger compared to the case studied in this subsection.

b) The multiple product set-up type, single pallet set-up case

In the previous subsection we have assumed that all product set-ups required for one work order are mounted on one pallet. In the single pallet set-up case we will assume that each pallet contains only one product set-up. In other words, if p(i) product set-up types are required to complete a part, also p(i) pallets are required.
From a flow time point of view, it would not be wise to mount the product set-up of the next type only after the last cycle has been completed and unloaded from a product set-up of the previous type. Such a 'mounting logic' would resemble the situation where the cycle-size is doubled. Therefore, similar to the case where the number of identical product set-ups is increased, we will assume that all product set-ups of an order are mounted on a pallet as soon as possible after the first product set-up of this order is mounted.

Expectations
If N$\leq$p(i), there will be only one work order in operation at the same time. Therefore, in such a situation the flow time effects of the simultaneous production of work orders will disappear completely. If N>p(i), the logic of mounting product set-ups on pallets will decrease the number of orders that are in operation simultaneously, and therefore reduce the possible flow time effects of the simultaneous production of orders. In case N is very large, there will be no limitation on the number of orders that can be in operation simultaneously. Consequently, there will be no difference in average flow time between this case and the multiple pallet set-up case. In other words, for a small N this case resembles the situation where p(i)=1, but f(i)=2. For a large N, the single pallet set-up case resembles the multiple pallet set-up case.

Input
We have repeated the experiment described under *a)*, assuming that the two types of product set-ups required to complete a part are mounted on separate pallets. Again, the average order cycle-size is kept at 20. The

cycle operation time in each product set-up type is assumed to be half of the original cycle operation time. As a result, also the average order operation time is left unchanged (i.e. 20.0).

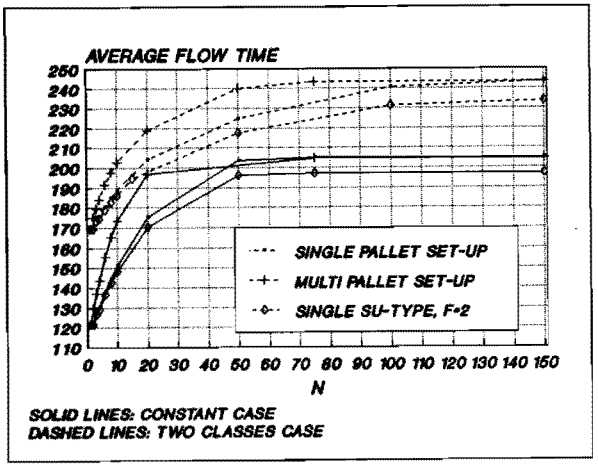

Figure 6.39:
Average flow time in single pallet set-up case as function of N in case of constant cycle-size and 'two classes' cycle-size, resp. for p(i)=1 and p(i)=2 (ρ_{pre}=80%).

Results
The results are shown in Fig.6.39. The figure includes the results of §6.6.1 for f(i)=2, and of the multiple pallet set-up case. Notice that the flow time curve for p(i)=2 indeed runs from the flow time curve for f(i)=2 to the curve for the multiple pallet set-up case.

Conclusion
In case each pallet set-up contains exactly one product set-up, increasing p(i) will decrease the flow time effects of the simultaneous production of work orders for most values of N. If N is chosen very large, there will be no difference between the single pallet set-up case and the multiple set-up case.

6.7 Conclusions

The conclusions from the analysis and experiments in this chapter can be summarized as follows. First of all, we have seen that the total waiting time of an order in case of a limitation in the number of identical

product set-ups, depends on the number of cycles of that order. This influence is stronger in case of higher utilization rates. In other words, due to the simultaneous production of orders, the waiting time of an order is cycle-size dependent (see Fig.6.40). If we compare Fig.6.40 with Fig.4.9 (§4.1.2), the difference with the conventional situation becomes clear.

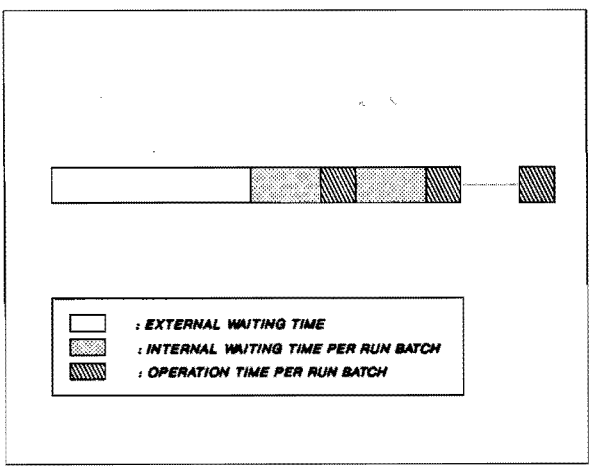

Figure 6.40:
Expected flow time at FAM-Stations
in case of a limitation on the number of identical product set-ups.

Secondly, the influence of the order cycle-size on the flow time depends on the distribution of the cycle-size. Only in case of a highly variable cycle-size, the average flow time will not increase and even decrease slightly with an increasing number of orders that may be in operation simultaneously. In case of less variable distributed cycle-sizes, both the average flow time and the variance in flow time will increase with an increasing maximum number of orders simultaneously in operation.
Thirdly, the flow time effects of the simultaneous production of orders depend on the average cycle-size. Decreasing the cycle-size by increasing the number of parts in one product set-up, will diminish these flow time effects. The flow time effects also depend on the number of pallets that contain product set-ups for a particular order. Increasing this number, e.g. by increasing the maximum number of identical product set-ups, or by increasing the number of product set-up types, results into a lower (or no) increase in the average flow time. In fact, in case of a small number of pallets, increasing the maximum number of identical product set-ups will have the largest effect on the average flow time.
Finally, if mounting and loading times cannot be neglected, the average flow times increase rapidly in case of a small number of orders simultaneously in operation on the FAM-Station. In real life, the optimum number of pallets for manned production from the point of view of flow time reduction, will be about three.

Chapter 7
SIMULTANEOUS PRODUCTION OF ORDERS IN UNMANNED PRODUCTION

In the previous chapter we have seen that the simultaneous production of work orders during the manned production mode has an important impact on the flow time of work orders. In this chapter we will study this phenomenon for the unmanned production mode.

In the first paragraph we introduce the assumptions that will hold throughout this chapter. In the next two paragraphs of this chapter, we will study what we call the basic case of simultaneous production of work orders in unmanned production, i.e. the case where all operations on all parts can be completed in exactly one type of product set-up. In §7.2 an analytical approach for determining the flow times in the basic case will be discussed. In the third paragraph we will introduce briefly the simulation model and experimental settings used in order to generalize the conclusions from §7.2. In §7.4 we will use the simulation model to validate the assumptions and generalize the conclusions of the basic case. Also based on computer simulation, in §7.5 we will relax some of the assumptions made in §7.2 and §7.4, and extend the study to the more general case, i.e. the case where for each type of product set-up one or more product set-ups may be available, and where some parts may require more than one type of product set-up. Finally, in §7.6 we will summarize the observations and conclusions.

7.1 Assumptions

Similar to the previous chapter, we will limit ourselves to FAM-Stations with identical machine tools. The machine tools are supposed to be insensitive to disturbances. We assume that the FAM-Station is part of a Production Unit. Work orders arrive at the FAM-Station in a random way, and are supposed to be completed entirely during unmanned production.
Again, we assume that the set of cutting tools required for processing the parts of a particular work order will be loaded in the tool magazine of only one machine tool. Like in the manned production case, we will assume that either always the number of tool pockets available in the tool magazine of the FAM-Station is sufficient, or that a limitation in tool pockets can be expressed in a general limitation on the number of work orders that can be in operation simultaneously (i.e. a limitation on the number of pallets to be used).

Furthermore, we assume that work can be loaded on the FAM-Station at the start of an unmanned shift as long as the work load already loaded does not exceed the usable machine capacity of the FAM-Station. In other words, as long as the work load of the cycles already loaded on the system is lower than the work load that can be finished during one unmanned shift, it still is possible to load another cycle on the system. As soon as the work load of the cycles loaded on the system equals or exceeds the work load that can completed during one shift, no more cycles will be loaded on the system, even though there may be cycles available for loading. Due to this constraint, not always all pallets will be occupied even though the number of orders in the system is sufficient to do so.
Again, once a pallet set-up has been made, it will be dismounted only after the last run batch requiring this pallet set-up has been completed.
All mounting and loading activities are supposed to take place between two shifts. We assume that the (operator) capacity is sufficient to do so.
Finally, as in most FAM-Stations, the pallet transportation times are supposed to be negligible compared to operation times.

7.2 Analytical approach to single product set-up case

In this paragraph we start our study with the basic case of simultaneous production of work orders.
In the basic case each product requires only one type of product set-up in order to be completed. Therefore, no re-loading of cycles is required. Also, we assume that the maximum number of identical product set-ups is limited to one, and that each pallet set-up contains exactly one product set-up. Sequencing decisions in the external queue are based on the FCFS-priority rule (i.e. First Come, First Served). In other words, if a new pallet set-up can be prepared, it will be prepared for the work order in the external queue that has been waiting at the external queue for the longest time.
In Fig.7.1 an example is given of the mechanism of such a system in case of a single FAM-Station. In the example, work order *A* has arrived earliest at the FAM-Station. Therefore, the first cycle of order *A* is loaded first at the start of the first unmanned shift on the station. Although the number of pallets on the system is three, only one cycle of *A* can be loaded due to the limitation in the number of identical product set-ups. However, once as order *B* has arrived, the first cycle of this order is loaded too at the start of the next shift. From that moment on the machine will process alternately cycles of *A* and *B*. Finally, as soon as work order *C* has arrived at the system, also cycles of *C* will be loaded on the system and taken into operation. In other words, the loading sequence is identical to the manned case (see Fig.6.2, §6.2), only the timing will be different.
We are especially interested in the flow time behaviour of the system. We start our study with an analytical approximation concerning the expected order flow times. In §7.2.2 we will discuss the approximation and some of its assumptions. The limitations of the approximation will be shown using some extreme cases.

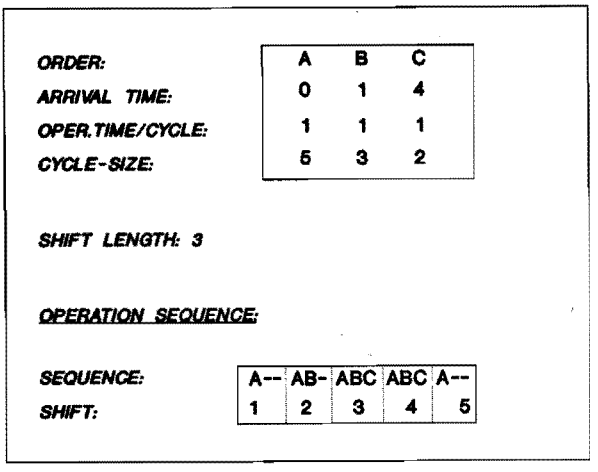

Figure 7.1:
Example of simultaneous production of work orders on a single FAM–Station in unmanned production.

7.2.1 Analytical approximation of average flow time

When a cycle is loaded on the system at the start of an unmanned shift, we know that the cycle can only be unloaded after the end of the shift. Therefore, for all cycles loaded on the system, the expected cycle flow time will be T, where T is the length in time of an unmanned shift. The internal flow time of an order i in the basic case will then be:

$$E(t_{int}(i)) = q(i) \times T \qquad (7.1)$$

where:
$q(i)$: cycle–size of order i.

For a steady state situation, we have to assume that:
a): the average amount of work load arriving at the system during T does not exceed the machine capacity in unmanned production mode during this period, or:

$$\lambda E(q)E(o)T \leq (MT) \qquad (7.2)$$

where:
- λ: average arrival rate of work orders for unmanned production at the FAM-Station;
- $\underline{q}$: cycle-size;
- $\underline{o}$: cycle operation time;
- M: number of machines in FAM-Station;
- T: length of unmanned shift.

and:

b): the average number of cycles arriving at the system during an unmanned shift does not exceed the maximum number of cycles that can be completed during the unmanned shift, or:

$$\lambda E(\underline{q})T \leq N \qquad (7.3)$$

where:
- N: maximum number of orders simultaneously in operation (i.e. the number of pallets in the system).

Assuming that constraints *a*) and *b*) hold, we conclude, applying Little's result, that the average number of pallets occupied ($E(\underline{x})$) will be:

$$E(\underline{x}) = \lambda T E(\underline{q})$$

If we assume that the average cycle operation time is equal for all orders, the expected external waiting time of an order will be independent of the order characteristics. Then, similar to the case of manned production, the total estimated flow time of order i will be:

$$E(\underline{t}(i)) = E(\underline{t}_{int}(i)) + E(\underline{w}_{ext}) \qquad (7.4)$$

where:
- $E(\underline{w}_{ext})$: expected external waiting time of an order (in the unmanned shift).

This queueing problem can be regarded as a M/G/N-problem, with an average operation time of $E(\underline{q})T$, and a variance in operation time of $T^2 var(\underline{q})$ (note that the variation coefficient of the operation time is the same as the variation coefficient of $\underline{q}$). Unfortunately, these queueing problems are hard to solve (see e.g. [Kleinrock, 1976]). Therefore, we have to apply an approximation. Again, applying the approximation of Avi-Ithzak and Heyman [Avi-Ithzak and Heyman, 1973], we define the average rate of completions of work orders in case n orders are present in the system as:

$$\gamma_n = \begin{cases} n \,/\, (E(\underline{q}) \times T) & (n \leq N) \\ N \,/\, (E(\underline{q}) \times T) & (n \geq N) \end{cases}$$

Then, assuming that the number of orders present in the system behaves as a 'birth-and-death' process with parameters λ and γ_n, following the same procedure as in §6.2.1, we obtain the following solution to the set of equations for the steady state situation:

$$p(\underline{n}=n) = \begin{cases} p(\underline{n}=0) \times \lambda^n / (\gamma_1\gamma_1 \cdots \gamma_n) & (n = 1,2,\ldots,N) \\ p(\underline{n}=N) \times (\lambda/\gamma_N)^{n-N} & (n = N,N+1,\ldots) \end{cases}$$

Therefore, in our basic case:

$$p(\underline{n}=n) = \begin{cases} p(\underline{n}=0) \times \lambda^n E(\underline{q})^n T^n / n! & (n = 0,1,\ldots,N) \\ p(\underline{n}=0) \times \lambda^n E(\underline{q})^n T^n / (N! N^{n-N}) & (n = N,N+1,\ldots) \end{cases} \quad (7.5)$$

We know that $\sum_{n=0}^{\infty} p(\underline{n}=n) = 1$, thus:

$$p(\underline{n}=0) = \left\{ \sum_{n=0}^{N-1} [(\lambda E(\underline{q})T)^n/n!] + \sum_{n=N}^{\infty} [(\lambda E(\underline{q})T)^n / (N! N^{n-N})] \right\}^{-1}$$

$$= \left\{ \sum_{n=0}^{N-1} [A^n/n!] + NA^N/((N-A)N!) \right\}^{-1} \quad (7.6),$$

with:
$A = \lambda E(\underline{q})T = E(\underline{x})$

In order to calculate $E(\underline{w}_{ext})$ we may use [Avi-Ithzak and Heyman, 1973]:

$$E(\underline{w}_{ext}) = \gamma_N p(\underline{n}=N) / (\gamma_N - \lambda)^2 \quad (7.7)$$

7.2.2 Conclusions and discussion

From eqn.(7.1) we may conclude that the internal flow time of a work order depends on the cycle-size of the order, not on the operation time of the order. From eqn.(7.6) and eqn.(7.7) the conclusion could be that the flow time averaged over all orders is dependent on N and on the average cycle-size of an order. This dependency is illustrated in Fig.7.2 for some values of $E(\underline{q})$ and λ, following the approximation given above.

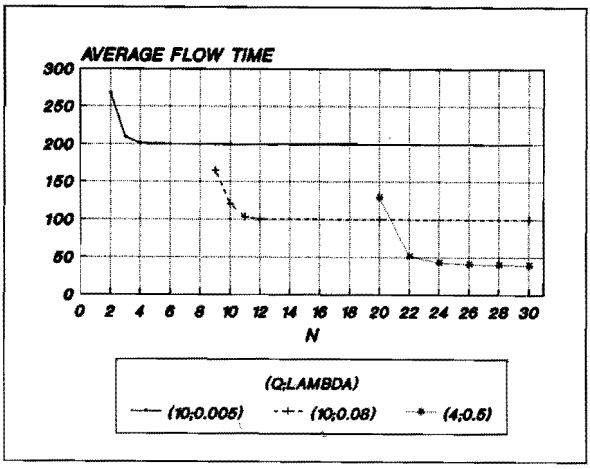

Figure 7.2:
Average flow time as function of N for several values of E(q) and λ (T=10) calculated according to analytical approximation.

The conclusion could also be that the flow time is independent of the distribution of the cycle-size per order.
However, again this last conclusion is in contradiction with our intuition. Especially for a small N, the flow time will depend on the cyle-size density function. In fact, in case N=1, we can calculate the exact average flow time.

N=1
In case N=1 (which of course is a very hypothetical situation), we may apply the Pollaczek-Khincin formula (see §2.2). Realizing that $\rho = 1-p(\underline{n}=0) = \lambda E(\underline{q})T$, we get:

$$E(\underline{w}_{ext}) = E(\underline{q})T \times \frac{\lambda E(\underline{q})T(1+C^2(\underline{q}))}{2(1-\lambda E(\underline{q})T)}$$

Realizing that $\gamma_n = [E(\underline{q})T]^{-1}$, and applying eqn.(7.4) of the approximation, we obtain :

$$E(\underline{w}_{ext}) = \frac{1}{E(\underline{q})T} \times \frac{\lambda E(\underline{q})T \times (1-\lambda E(\underline{q})T)}{\{\ (1-\lambda E(\underline{q})T)\ /\ E(\underline{q})T\ \}^2} =$$

$$= E(\underline{q})T \times \frac{\lambda E(\underline{q})T}{1-\lambda E(\underline{q})T}$$

In other words, in the approximation it is assumed that $C^2(\underline{q}) = 1$, i.e. very variable. In case of a constant $\underline{q}$, the approximation over-estimates the external waiting time with a factor 2.
Notice however, that usually the number of pallets on a single FAM-Station is about 10. Therefore, the situation where N=1 is not very realistic.

Large N
Let N denote the number of pallets on the FAM-Station. The expected internal flow time of an order i is $q(i)T$ (see eqn.(7.1)). In other words, if we regard the N pallets as parallel servers, the operation time per server will be $q(i)T$, independent of N. Increasing N in the unmanned shift will mean that more work load can be loaded on the FAM-Station at the beginning of the shift. Consequently, this will result in a better utilization of the machine capacity per shift. Therefore, the external waiting time will decrease very rapidly with an increasing N. In fact, if N is large enough and the machine capacity is sufficient, the average external waiting time will disappear almost completely (with a minimum of T/2). As a result, $(q(i)+0.5)T$ will be the minimal flow time of order i. Only if the machine capacity is not sufficient (which will not often be the case in real life since the number of unattended operations usually is limited), the average external waiting time will be larger than T/2 for a large N.
In case of suffient machine capacity, similar results can be obtained by applying the approximation given above (see e.g. Fig.7.2). However, in case the machine capacity is not sufficient, the approximation will underestimate the external waiting time.

Utilization rate
The combination of a high λ (i.e. average order arrival rate) and a low N, often will make it impossible to complete all work orders (viz. see constraint *b*), eqn.(7.3)). As a result, due to the low number of pallets, it will be impossible to load enough work load on the FAM-Station to keep the machine tools busy. However, in real life the unmanned shift usually is poorly utilized. In the cases we have knowledge of, a utilization rate of 50% or 60% was considered to be a good result.
In case of a large N, the higher the utilization rate, the more pallets will be occupied during an unmanned shift. Consequently, the external waiting time is likely to increase with an increasing utilization rate.
Once the external waiting time is reduced to zero for a certain N_{max}, increasing N above N_{max} will have no effects anymore.

Summary
For a small N, the approximation using the approach of Avi-Ithzak and Heyman will overestimate the external waiting time in case $\underline{q}$ is more or less constant. For a large N, the approximation will underestimate the external waiting time if the machine capacity is not sufficient to complete during one shift all parts that can be loaded on the FAM-Station simultaneously. In order to understand the real relations, we will use computer simulation.

7.3 Introduction to simulation experiments

In order to extend the conclusions and to validate the assumptions of the first paragraph, we have used computer simulation. The simulation model described in Chapter 6 is also used in the experiments concerning unmanned production. However, instead of continuous availability of the mounting/loading capacity, we assume that the mounting/loading place is only available during a short (change-over) period between two subsequent unmanned shifts. The time required to perform all (dis)mounting and (un)loading activities is considered to be negligible. As a result, as long as the capacity constraints of the FAM-Station are not violated, the mounting/loading place will perform all possible mounting and loading tasks during this change-over period. This logic is schematically drawn in Fig.7.3. The simulation starts with a change-over period during which the status of the mounting/loading place is 'open'. During the unmanned shift, the status of this place is set at 'close'. Therefore, the only activity on the FAM-Station can be the processing of parts. After T time units, the status of the mounting/loading place is changed to 'open'. As long as the status is 'open', parts can be unloaded, new parts can be loaded, product set-ups may be dismounted, and new product set-ups may be mounted.

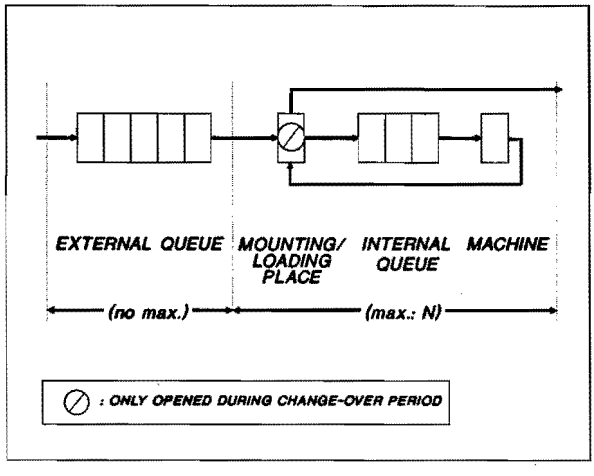

Figure 7.3:
Simulation model for a single FAM-Station in unmanned production.

Work orders belong to a certain order class. All orders in a class arrive in the system according to a class-dependent inter-arrival time. The expected arrival rate is the same for all order classes.

Both the real order inter-arrival time and the order characteristics are determined by random draws from probability density functions. The parameters used in these probability density functions are derived from data of the cases we have studied. Since in these cases the number of unattended operations was very low, most data used were data of work orders with attended operations. The number of cycles per order and the operation time of each cycle follow the same distribution for all orders in a class. Upon arrival of an order, the cycle-size and the cycle operation time is determined (i.e. the cycle operation time is equal for every cycle of a work order). Again, we assume no dependency between cycle-size and cycle operation time.

As before, we have assumed that the priority-discipline in all queues is FCFS. Both the decision rules for mounting and dismounting pallet set-ups, and the decision rules for loading and unloading cycles are the same as the respective rules described in §6.3.

The length of every experiment is chosen such, that the results can be expected to be independent of the starting situation. The time required to complete the first about 150 work orders is regarded as a starting-up period (the simulation starts with an empty system) and is neglected in the output. The length of the starting-up period can be chosen small, since we only consider a single-stage manufacturing system.
In each simulation run where the pre-set utilization rate is 60%, the number of work orders completed is about 2000. In case of a pre-set utilization rate of 80%, the number of orders completed per run is about 2700. If required for the experiment, a simulation run is repeated several times with different random draws.

As in the manned case, the (real) computer time required for a simulation run depends on the number of events that will occur during the simulation. This number of events on its turn is largely dependent on the number of operation activities to be performed during the simulation. It appeared that hardly any extra time was required for the 'overhead' of the program (e.g. system initialisation and reporting routines). The following equation gives a reasonable estimate of the time (in minutes) required per simulation run:

$$\tau = 4 \times (\theta\omega/10{,}000)$$

where:
θ: number of work orders completed during the simulation run;
ω: average number of operation activities per work order.

In case only one type of product set-up is required to complete a cycle, the number of operation activities per work order (ω) is equal to the cycle-size of the order. In case two or more product set-up types are required to complete a cycle, the cycle-size has to be multiplied by this number of product set-up types in order to obtain the number of operation acitivities per order.

7.4 Impact of cycle-sizes

In this paragraph we will describe the simulation experiments on the basic case of simultaneous production of work orders, i.e. the case where every part requires exactly one type of product set-up to be completed, only one product set-up is available for each product set-up type, and each run batch contains exactly one cycle.
Successively we will study in this paragraph:
- the influence of the order cycle-size on the order flow times;
- the influence of the distribution of the cycle-sizes of work orders on the flow time;
- the influence of the average cycle-size of the orders on the flow times.

7.4.1 Order cycle-size

In the first experiment we will investigate the influence of $q(i)$ (the order cycle-size) on the expected flow time of an order.

Expectations
As we conclude from the analysis and discussion in §7.2, we expect the flow time of an order to be dependent on the cycle-size of an order. In fact, from eqn.(7.1) in §7.2.1, we conclude that the internal flow time of an order will be proportional to the cycle-size of the order (viz. $q(i)T$). In other words, independent of the number of pallets, $q(i)T$ will be the internal flow time.
Increasing N (the number of pallets) is likely to increase also the number of pallets occupied. As a result, increasing N will decrease the external waiting time of an order. However, in case of a large N, the amount of work loaded on the FAM-Station at the beginning of a shift will not be limited anymore by N, but only by the machine capacity. There will be an N_{max} for which the average external waiting time either is reduced to nearly zero (or more precisely: $T/2$), or remains at a certain level due to the constraint on the machine capacity. Increasing N above N_{max} will have no effects anymore.
The higher the utilization rate, the more orders will be present in the system, and therefore the more pallets will be occupied. Consequently, the external waiting time will increase with an increasing utilization rate. However, the internal flow time of a work order will not be influenced by the utilization rate, since T (i.e. the length of one unmanned shift) is independent of the utilization rate.
Also the variance in internal flow time for an arbitrary work order is independent of N, viz. $T^2var(q)$. The variance of the entire order flow time depends on both the variance in internal flow time (i.e. $T^2var(q)$) and the variance in external waiting time. The longer the external waiting time will be, the higher the variance in waiting time can be expected to be. Increasing N will decrease the external waiting time. Therefore, we conclude that the variance in order flow time decreases with increasing N.

Input
In the experiment the cycle-size per order will either be 10 (order class 1) or 30 (order class 2), each with an equal probability. As a result, the average cycle-size will be 20. We assume that the operation time per cycle has a exponential density function with an average of 1.0. Therefore, the expected total operation time per order will be 20.0. The length of one unmanned shift is set at 10.0. Consequently, the minimum average external waiting time will be 5.0. Also, we know that the minimum average order flow time is minimum average external waiting time plus the internal order flow time. In other words, in this experiment the minimum average flow time will be (5.0 + 10×10.0) for order class 1, resp. (5.0 + 30×10.0) for order class 2.
The utilization rate is pre-set at resp. 60% and 80% (thus λ=0.03 resp. λ=0.04). As we recall, in real life the first utilization rate is more realistic. In order to complete all cycles, we know that for these settings N_{min} should be larger than 6 resp. 8 (see eqn.(7.3), §7.2.1). In other words, N_{min} equals 7 resp. 9. In the experiments, we will vary the number of pallets, viz. in case of ρ_{pre}=60% N will be set at resp. 7, 8, 9, 10 and 20, while for ρ_{pre}=80% N will be set at resp. 9, 10, 12, 15 and 50. Due to the limitation on the number of identical product set-ups, the maximum number of orders that can be in operation simultaneously, equals the number of pallets on the FAM-Stations.

Results
Table 7.1 presents the results of the simulation experiment with ρ_{pre}=60%, whereas the results for ρ_{pre}=80% are given in Table 7.2.

Table 7.1:
Average external waiting time, average flow time, and standard deviation in flow time, for orders with cycle-size 10 resp. 30 in first simulation experiment (ρ_{pre} = 60%).

N	q(i)	$\bar{t}_{ext}(i)$	$\bar{t}(i)$	s(t(i))
7	10	138.97	242.15	179.19
	30	138.75	443.44	179.80
8	10	48.42	151.82	82.10
	30	47.32	351.11	77.14
9	10	33.88	138.34	70.23
	30	32.71	337.17	65.52
10	10	27.95	132.93	64.76
	30	26.53	331.48	60.53
20	10	24.29	129.86	61.65
	30	22.85	328.55	58.09

N.B.: N_{max}=15; ρ = 58.8%

Table 7.2:
Average external waiting time, average flow time, and standard deviation in flow time, for orders with cycle–size 10 resp. 30 in first simulation experiment (ρ_{pre} = 80%).

N	q(i)	$\bar{t}_{ext}(i)$	$\bar{t}(i)$	s(t(i))
9	10	559.06	666.54	384.99
	30	552.74	860.11	381.12
10	10	240.77	349.84	270.74
	30	239.43	548.68	268.99
12	10	134.40	244.57	198.00
	30	133.12	443.77	194.38
15	10	118.40	229.58	187.62
	30	115.91	427.06	184.30
50	10	117.69	229.03	187.12
	30	114.86	426.11	183.48

N.B.: N_{max}=17; ρ = 79.1%

As was expected, the higher N gets, the shorter the external waiting time becomes. In fact, as already was shown in the approximation (see e.g. Fig.7.2), a small increase in N has a large impact on this external waiting time. The maximum number of pallets occupied is limited by the machine capacity once the utilization rate of the pallets becomes negligible (e.g. less than 50%). Therefore, even if N is chosen very large, there still will be some external waiting time. For instance, increasing N above 15 in the simulation run where ρ_{pre}=60% has no effect anymore.
As we can see in the tables, the differences between the flow times of the order classes for all N can be explained by (a) the differences in average external waiting time due to randomness, and (b) the differences in internal flow time due to different cycle–sizes.

Conclusions
We can summarize the results from the experiment as follows:
- the internal flow time of an order in case of unmanned production strongly depends on the order cycle–size; in consequence the orders with a large cycle–size will get long flow times;
- starting with N=N_{min}, increasing N at first has a strong positive effect on the external waiting time due to a drop in pallet utilization rate, and thus also on the flow time; however, once the pallet utilization rate is negligible, increasing N hardly has any effect on the flow times anymore;
- the variance in flow time decreases for all orders with an increasing N due to the reduction in external waiting time;
- increasing the utilization rate has no effect on the differences in flow time between orders with different cycle–sizes.

7.4.2 Cycle-size distribution

We know from the first experiment that in the basic case of the simultaneous production of work orders in unmanned production the flow time of an order heavily depends on the cycle-size of each individual order. In the second experiment we will study the influence of N on the flow time averaged over all orders ($E(\underline{t})$) and on the standard deviation in flow time ($\sigma(\underline{t})$).

Expectations
In §7.2.2 we noticed that increasing N will only decrease the expected external waiting time, and will not influence the internal flow times. Therefore, if $E(\underline{q})$ is the same for all cycle-size distribution considered, the average internal flow time will be the same too for all distributions.
Independent of the cycle-size density, the average external waiting time will drop in case N gets larger. Consequently, as opposed to the case of manned production, also the average flow time will decrease with an increasing N for all distributions (i.e. both in case of a constant cycle-size and in case of a highly variable cycle-size).
In case of a highly variable $\underline{q}$, the variance in internal flow time of a work order also will be high, viz. $T^2var(\underline{q})$ (where T is the length of an unmanned shift). In other words, the time a pallet is occupied by a particular work order is very variable. Consequently, the inter-departure time of work orders (i.e. the time between two subsequent completions of work orders) will be more variable than in case of a constant $\underline{q}$. We know from queueing theory that in such a case the (external) waiting time will be longer than in case of more regular inter-departure times. In other words, in case of a highly variable $\underline{q}$, the external waiting time will be longer than in case of a more or less constant $\underline{q}$.
For a large N the external waiting time will be small, especially for a low utilization rate. In fact, the minimum average flow time is equal for all cases. In other words, the differences between the average flow times for all cycle-size distributions can be expected to decrease rapidly with an increasing N.
As we noticed in the previous subsection, the variance in internal flow time is independent of N (viz. $T^2var(\underline{q})$). The variance of the entire order flow time is the sum of the variance in internal flow time and the variance in external waiting time (plus twice the co-variance). The longer the external waiting time will be, the higher the variance in waiting time can be expected to be. Increasing N will decrease the external waiting time. Therefore, we conclude that for all densities of $\underline{q}$, the variance in order flow time decreases with increasing N.

Input
In order to validate the assumption that the effect of N on the flow times is similar for all cycle-size distributions, we have repeated the first experiment using two extreme distributions for the number of cycles per order, viz. a constant cycle-size and a geometrical distributed cycle-size. All other input was chosen identical to the input of the first experiment. The expected cycle-size in all experiments was 20.

Results
The results of the experiments are shown in Fig.7.4 and Fig.7.5, depicting the average flow time and the standard deviation in flow times for a

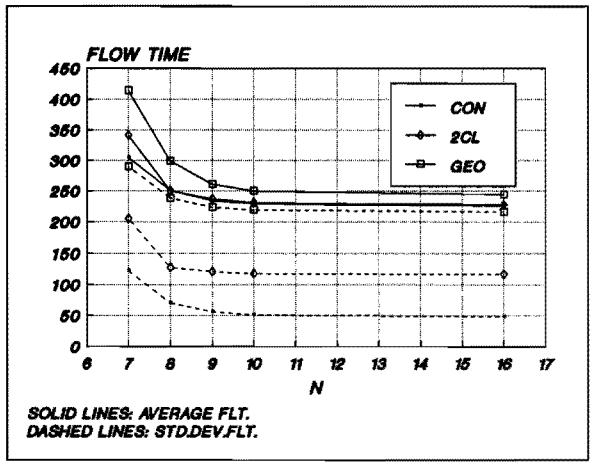

Figure 7.4:
Average flow time and standard deviation in flow time as function of N in case of constant, 'two classes' and geometrical cycle–size (ρ_{pre}= 60%).

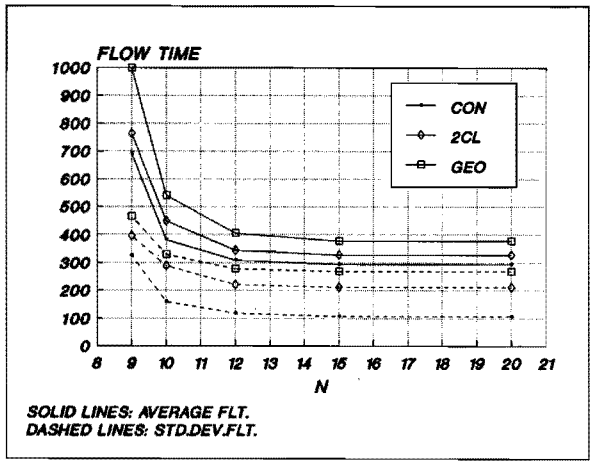

Figure 7.5:
Average flow time and standard deviation in flow time as function of N in case of constant, 'two classes' and geometrical cycle–size (ρ_{pre}= 80%).

pre-set utilization rate of resp. 60% and 80%. Apart from the results for the constant cycle-size and a geometrical cycle-size, the figures also give the overall results of the first experiment (referred to as the 'two classes' experiment, or '2cl').
Independent of the cycle-size density, the average flow time decreases rapidly with a small increase of N due to the decrease in external waiting time (dotted lines in figures). The average internal flow time is about 200 in all cases. Also, the simultaneous production of orders has consequences for the standard deviation in flow time.

Conclusions
To summarize:
- independent of the cycle-size density, the average flow time will decrease rapidly with every increase in N as long as N is only slightly larger than the average number of cycles arriving at the FAM-Station during one shift; once the pallet utilization rate is negligible, the order flow time hardly is influenced by an increase in N;
- for low utilization rates, the minimum average flow time is about the same for all cycle-size distributions;
- the variance in order flow time decreases with an increasing N.

7.4.3 Average cycle-size

In the previous two experiments we have studied for the basic case the impact of the cycle-size of an individual order on its expected flow time, and the impact of the distribution of the cycle-sizes of all orders on the flow times of the orders. The third experiment studies the influence of the average cycle-size of the orders on the expected flow time over all orders ($E(\underline{t})$) and the standard deviation in flow time ($\sigma(\underline{t})$).

Expectations
Obviously, decreasing the cycle-size of an order will decrease the internal flow time of an order proportionally. If there is no limitation on the amount of work loaded on the FAM-Station at the start of an unmanned shift (i.e. the cycle operation times are negligible compared to the length of the unmanned shift), the external waiting time can be reduced almost to zero for a large N. In such a case, a reduction in the cycle-size also reduces the entire flow time proportionally.
If the operation times cannot be neglected, and/or N is not very large, certainly the external waiting times will decrease for smaller cycle-sizes. In fact, we know from special cases (e.g. for M/M/C-queues) that in case of C parallel servers decreasing the operation times while maintaining the same utilization rate will reduce the expected waiting time proportionally (see e.g. [Shelton, 1960]). We expect a similar effect in our case. Decreasing the cycle-size will decrease the internal order flow time ($=q(i)T$). As long as the number of pallets occupied is not limited by the machine capacity, we can model our system as a M/G/N queueing system with the internal order flow time as the operation time, and the pallets as N parallel servers. Consequently, the external waiting time will decrease proportionally to a reduction in $q(i)$.
As a result, the flow time will change almost proportionally with the cycle-size, at least for a small N. For larger values of N, the machine capacity may limit the number of pallets used. Therefore, in these cases

the external waiting time will change less than proportional.

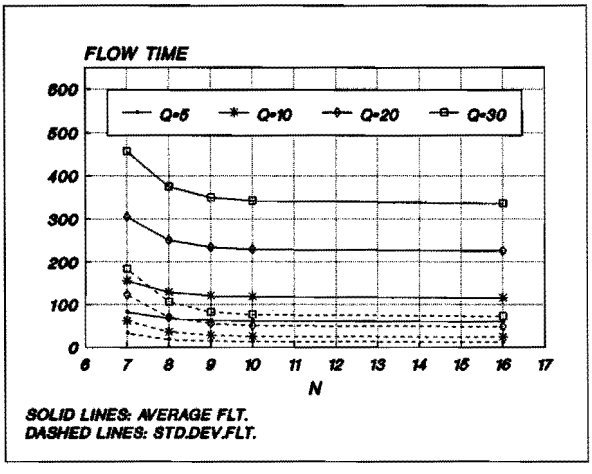

Figure 7.6:
Average flow time and standard deviation in flow time for several cases with different constant cycle–sizes as function of N (ρ_{pre}=60%).

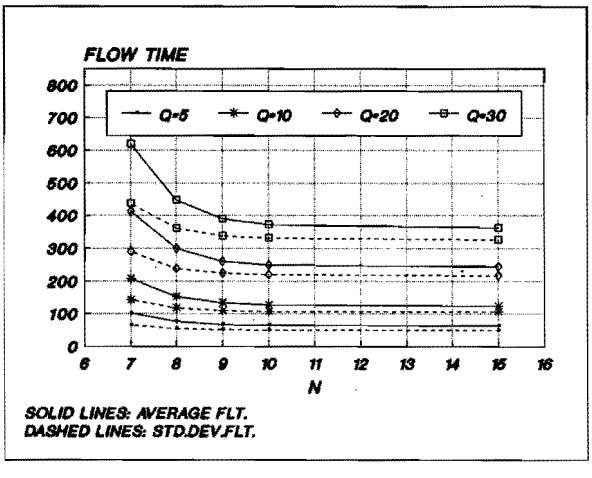

Figure 7.7:
Average flow time and standard deviation in flow time for several cases with geometrical distributed cycle–sizes with different average values as function of N (ρ_{pre}=60%).

Input
In this experiment we have repeated the simulation runs of the two extreme cases described above (i.e. a constant q, and a geometrical distributed q), using different expected cycle-sizes, viz. $E(q)=5$, $E(q)=10$ and $E(q)=30$. In all cases, the average operation time per cycle remained 1.0, while the utilization rate was pre set at 60%.

Results
The results from the experiments are shown in two figures, depicting the results for the average flow time and the standard deviation in flow time for resp. the case with a constant cycle-size and the case where the cycle-size has a geometrical density (resp. Fig.7.6 and Fig.7.7). As can be seen from the figures, the effects of the simultaneous production of orders indeed depend on the average cycle-size of the orders. For N=7 the change in flow time indeed is proportional to the change in cycle-size. In all cases, the variance in flow time drops with an increasing N.

Table 7.3:
External waiting time and order flow time in case N=7 resp. N=20, for $E(q)=5$ (case I) and $E(q)=10$ (case II) compared to the case where $E(q)=20$, resp. for constant and geometric case (ρ_{pre}=60%; 10 runs of 2000 entries).

Constant cycle-size

	External waiting time				Order flow time			
Case	I	I	II	II	I	I	II	II
N	7	20	7	20	7	20	7	20
$\bar{r}$	3.29	2.08	1.88	1.53	3.77	3.733	1.964	1.954
$s(r)$	0.12	0.17	0.035	0.049	0.025	0.018	0.0052	0.0052
min(r)	3.10	1.83	1.84	1.43	3.71	3.69	1.96	1.95
max(r)	3.54	2.35	1.93	1.59	3.79	3.75	1.97	1.96

Geometrical cycle-size

	External waiting time				Order flow time			
Case	I	I	II	II	I	I	II	II
N	7	20	7	20	7	20	7	20
$\bar{r}$	3.69	2.8	1.988	1.77	3.85	3.78	1.994	1.968
$s(r)$	0.17	0.36	0.022	0.084	0.075	0.048	0.010	0.009
min(r)	3.46	2.31	1.96	1.66	3.80	3.70	1.98	1.96
max(r)	4.08	3.32	2.01	1.93	4.05	3.85	2.01	1.99

NB: $r = \bar{t}(20)/\bar{t}(q)$
where $\bar{t}(q)$: external waiting time resp. order flow time in case $E(q)=q$ ($E(q)=5$ for case I; $E(q)=10$ for case II).

Statistical analysis
In order to validate the observations, we have repeated the experiments of the constant case and the geometrical case with $E(q)=5$, $E(q)=10$, and $E(q)=20$ nine times resp. for $N=7$, and $N=20$. Table 7.3 gives the results for the relative changes in external waiting time, and in total order flow time. Of course, the internal flow time changes proportionally to the cycle-size. As we expected, the relative change in external waiting time reduces for larger values of N. However, due to a reduced impact of the external waiting time on the order flow time, even for a large N the total order flow time changes almost proportionally to the change in cycle-size.

Conclusion
We conclude that reducing the cycle-size in case of unmanned production also reduces the average flow time almost proportionally.

7.5 Relaxing the assumptions of the basic case

In the study described in the previous subsections we have made several assumptions. For instance, we have assumed that for each type of product set-up only one product set-up is available, and that each part requires only one type of product set-up (no re-loading). In this paragraph we will relax these assumptions and study their impact on the order flow times. More specifically, we will study consecutively the assumptions on:
- the number of parts per product set-up;
- the number of identical product set-ups;
- the number of types of product set-ups required.

7.5.1 Number of parts per product set-up

Usually it is possible to change the cycle-size of an order without changing the lot-size by increasing the number of parts loaded in one product set-up. Consequently, the cycle-size of the order will be reduced, while the average cycle operation time increases. As a result, the total order operation time will not be changed.
In §7.3.4 we already studied the impact of a change in cycle-size on the flow time effects. We concluded that the order flow time increases almost proportionally to an increase in cycle-size. However, in that subsection we assumed that the average cycle operation time remained the same. In this subsection we will assume that the total order operation time remains the same. In other words, we assume that the lot-sizes of work orders remain unchanged, even though the cycle-sizes of the orders are changed by increasing or decreasing the number of parts per product set-up.

Expectations
As in the case described in §7.4.3, the internal flow time of an order will change proportionally to the change in cycle-size. Due to the change in cycle operation time, also the number of pallets that will be occupied, changes. In fact, we know from eqn.(7.3) (§7.2.1) that decreasing the

cyle-size without changing the average arrival rate will reduce the minimum value of N proportionally to the change in cycle-size. Also, we know from previous experiments that a small increase in N already reduces the average flow time considerably. Of course, in case of an increase in the number of parts loaded on one pallet, the external waiting time will grow too. However, due to the proportional reduction in internal flow time, the entire order flow time can expected to be reduced by an increase in the number of parts per pallet.

Input
In this experiment we will change the characteristics of the work orders to be completed such that the expected operation time for the entire work order remains the same (i.e. 20.0). In other words, a larger expected cycle-size per order will be compensated with a shorter expected operation time per cycle. We will study the two extreme cases described above, i.e. the case of a constant cycle-size and the case of the geometrical cycle-size.

Results
The results from the experiments are shown in two figures, depicting the results for the average flow time and the external waiting time for resp. the case with a constant cycle-size and the case with a geometrical cycle-size (resp. Fig.7.8 and Fig.7.9). As can be seen from the figures, increasing the number of parts per pallet has a strong impact both on the average flow time and on the number of pallets required.

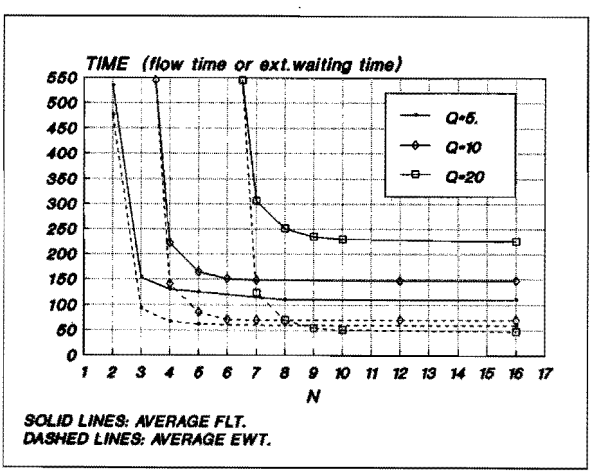

Figure 7.8:
Average flow time and external waiting time in case of constant cycle-size for q=5, q=10 and q=20, and equal order operation time, as function of N (ρ_{pre}=60%).

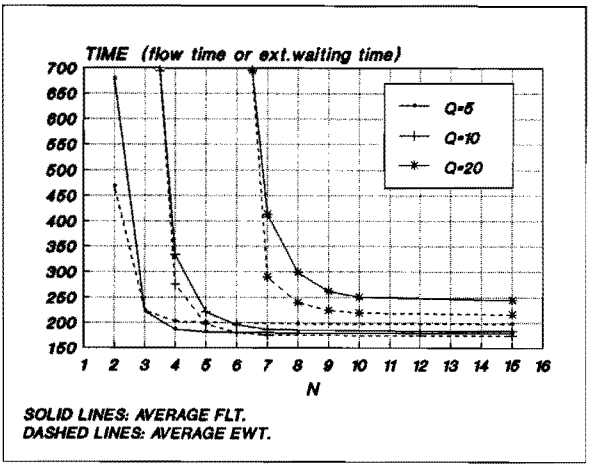

Figure 7.9:
Average flow time and external waiting time in case of geometrical cycle-size for E(q)=5, E(q)=10 and E(q)=20, and equal order operation time, as function of N (ρ_{pre}=60%).

Conclusion
We conclude that for low utilization rates, due to the relative impact of the internal flow time on the entire order flow time, increasing the number of parts on one pallet (thus decreasing the cycle-size without changing the lot-size of the order) will reduce the average flow time. Also, the number of pallets required to complete all work orders can be reduced in case of an increase in the number of parts per pallet.

7.5.2 Number of identical product set-ups

The next assumption we will study, concerns the number of identical product set-ups. We will denote the maximum number of identical product set-ups for order i with f(i). In all previous experiments described in this chapter, we have assumed that for the type of product set-up required for an order i only one product set-up can be mounted on a pallet concurrently (f(i)=1), usually due to a limitation in the number of identical fixtures.

Expectations
Assuming that the number of product set-ups per pallet set-up remains limited to one, increasing the maximum number of identical product set-up per type of product set-up would mean increasing the maximum number of pallets that can be set up simultaneously for a particular work order.

Therefore, given a certain N, the number of shifts required to complete the work order once pallets are prepared for the order will decrease. As a result, the internal flow time of a work order will decrease. In fact, if f(*i*) cycles of order *i* can be loaded on the FAM-Station at the same time, the number of shifts required to complete the work order will be the lowest integer equal or larger than f(*i*)/q(*i*). For example, if the cycle-size of the order is 10 and the number of identical fixtures for this order is 2, we require 5 unmanned shifts to complete the order. If the cycle-size of the order is 11 in stead of 10, one more shift is required to complete the last cycle of the order. Therefore, the internal flow time will be reduced (almost) proportionally to f(*i*).
If more pallets are occupied by cycles of one work order, other work orders may have to wait longer before their first cycle can be loaded. In other words, the external waiting time will be longer for a larger f(*i*). However, since it is possible to use the available unmanned production capacity better in case of a larger f(*i*), and since the largest part of the order flow time will be the internal flow time, the average order flow time can expected to be reduced by an increase in f(*i*).

Input
We have repeated the experiment described in §7.4.2 twice, resp. with f(*i*)=2 and f(*i*)=4 for all orders.

Results
In Fig.7.10 the results are given for the runs with a constant cycle-size and resp. one, two and four identical product set-ups. Fig.7.11 presents the results for the runs assuming a geometrical cycle-size.

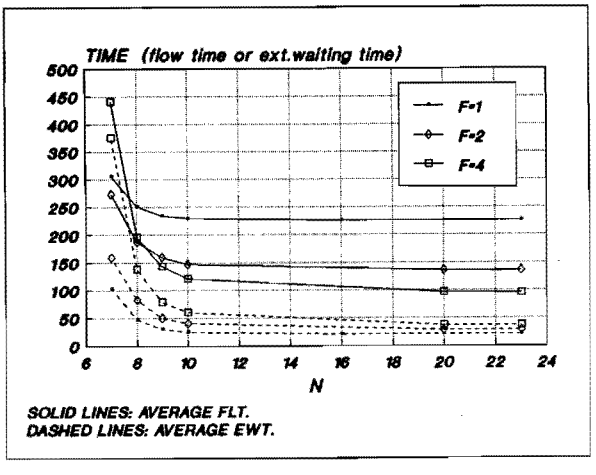

Figure 7.10:
Average flow times and external waiting times in case of constant cycle-size, resp. for f(*i*)=1, f(*i*)=2, and f(*i*)=4 (ρ_{pre}= 60%).

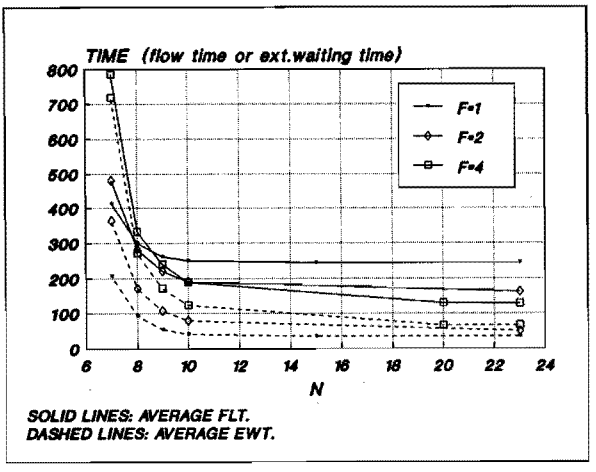

Figure 7.11:
Average flow times and external waiting times in case of geometrical cycle-size, resp. for f(i)=1, f(i)=2, and f(i)=4 (ρ_{pre}= 60%).

As we can see, a small increase in f(i) already reduces the average flow time considerably. The increase in external waiting time is more than compensated by the (proportional) decrease in internal flow time.

Conclusion
The internal flow time changes (almost) inversely proportional to the change in the number of identical product set-ups. In case of low utilization rates, increasing the number of identical product set-ups will decrease the order flow time due to the relative large effect the internal flow time has on the entire order flow time, even though the external waiting time will increase.

7.5.3 Multiple product set-up type case

As we know, in the cases we have studied it was not uncommon for about half of the work orders to require two product set-up types. Only few work orders required more than two types of set-ups.
Therefore, we will study next the case where more types of product set-ups are required to complete a part (i.e. the multiple product set-up type case). As we recall from the previous chapter, in this case each cycle has to be re-loaded at least once in order to be completed.
We will start our study with the case where all product set-up types required for a work order are mounted on one pallet (i.e. the multiple pallet set-up case). After that we will discuss the case where for each type

of product set-up a separate pallet is prepared (i.e. the single pallet set-up case).

a) The multiple product set-up type, multiple pallet set-up case

In order to gain insight in the possible effects of this multiple product set-up type case, we will assume that the cycle-size will be equal for each type of product set-up required to complete a work order. Also, as we did in the multiple pallet set-up case in manned production, we will assume that all product set-ups for one work order are mounted on one pallet.

Expectations
As we recall, the first cycle has to be re-loaded exactly $(p(i)-1)$ times before it is loaded in the product set-up required last. After the first cycle is loaded in the last type of product set-up, we will have to re-load a run batch exactly $(q(i)-1)$ times before the last cycle can be completed in the last product set-up ($q(i)$ is the cycle-size of order i). Therefore, increasing $p(i)$ will increase the number of unmanned shifts required to complete the work order. In other words, the internal flow time of an order grows with an increase in $p(i)$. The situation resembles the case where the cycle-size of the order in increased with $(p(i)-1)$.
Due to the increase in internal flow time, also the external waiting time will grow (cf. what is known from queueing theory for M/M/N queues). This increase in external waiting time will be more than proportional to the change in internal flow time, since not only the average 'operation time' per pallet will increase (viz. with a factor $(q(i)+p(i)-1)/q(i)$), but also the pallet utilization rate (viz. with the same factor). Therefore, we expect the flow time of an order to grow already for a small increase in $p(i)$.

Input
In order to validate these expectations, we have repeated the simulation experiments of the cases with a constant cycle-size and of the geometrical case as described in §7.3.3, assuming two types of product set-ups required for each work order ($p(i)=p=2$). The average cycle operation time in each product set-up type is set at 0.5. Since the 'cycle-size' of each work order is changed with a factor $(q(i)+p(i)-1)/q(i)$ (in our case 1.05), also the minimum number of pallets required to complete all work orders is changed with this factor. In the previous experiments, N_{min} had to be larger than 6.0 in case $\rho_{pre}=60\%$ (see §7.4.1). Consequently, if $p(i)=2$, N_{min} has to be larger than 6.3 (viz. 1.05×6.0). Therefore, all other input can be left unchanged. Notice however, that in case the factor $(q(i)+p(i)-1)/q(i)$ is equal to or larger than 7/6 (in other words, if $q(i)\leq6$), this increase in $p(i)$ will require an increase in the number of pallets.

Results
Fig.7.12 gives the results from the experiments, including the results for $p(i)=1$ (see Fig.7.6, §7.3.3). As we can see, as we have expected, the average flow time increases for all $N>1$ if $p(i)$ increases from 1 to 2.

Conclusion
In case all product set-ups are mounted on one pallet, the number of product set-up types required to complete a part should be kept as low as possible.

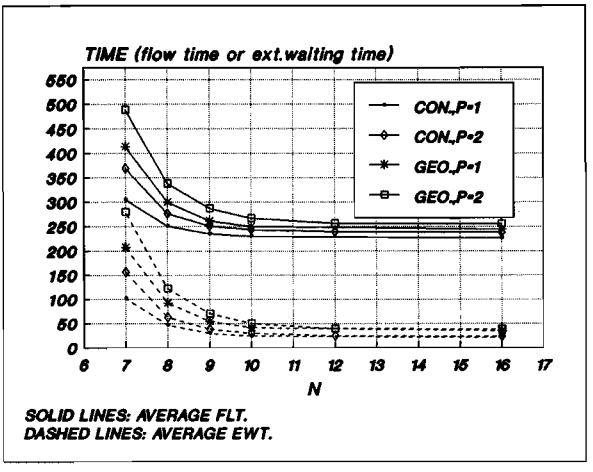

Figure 7.12:
Average flow time and external waiting time in multiple pallet set–up case as function of N in case of constant cycle–size and geometrical cycle–size, resp. for p(i)=1 and p(i)=2 (ρ_{pre}=60%).

b) The multiple product set–up type, single pallet set–up case

In the previous subsection we have assumed that all product set–ups required for one work order are mounted on one pallet. In the single pallet set–up case we will assume that for each type of product set–up a separate pallet is prepared (i.e. each pallet contains only one product set–up). In other words, if p(i) types of product set–ups are required to complete a part, also p(i) pallets are required. Similar to the manned production case, we will assume that all product set–ups of an order are mounted on a pallet as soon as possible after the first product set–up of this order is mounted.

Expectations
For each order p(i) pallets have to be prepared. Therefore, the number of pallets required to complete all cycles will be larger than in all previous cases. In fact, eqn.(7.3) (§7.2.1) should be re–formulated as follows:

$$\lambda E(\underline{q})E(\underline{p})T \leq N \qquad (7.8)$$

where:
λ: average arrival rate of orders for unmanned production;
$\underline{q}$: cycle–size;
$\underline{p}$: number of product set–up types required;
T: length of unmanned shift;
N: the number of pallets in the system.

For instance, if p(*i*)=2 for all work orders, the number of pallets with completed cycles at the end of the unmanned shift, will be N/2. The other pallets are occupied by cycles still requiring the operation in the second product set-up type. Consequently, the number of pallets required to complete all cycles in case E(p) is increased, will increase proportionally. Only in case it is possible to mount several product set-ups on one pallet (i.e. the multiple pallet set-up case), there is no need to increase N.
We assume that both the total cycle operation time and the order operation time remain unchanged. Similar to the multiple pallet set-up case, the internal flow time will increase for a larger p(*i*). More precisely: in case of p(*i*) product set-up types, (p(*i*)-1) extra unmanned shifts are required to complete a work order.
The external waiting time can be expected to be (almost) equal to the case where p(*i*)=1 and half of the pallets are used. The reason for this expectation is that the internal flow time for p(*i*)=1 is identical to the internal flow time for the first type of product set-up in case p(*i*)=2. Also, the time the first cycle will be loaded on a pallet will be (almost) identical in both situations.
In consequence, we expect the flow time of an order to grow with p(*i*)-1 shifts. For a large N there is hardly any difference between mounting two product set-ups on one pallet or mounting these set-ups on separate pallets. Therefore, in case there is no limitation on the number of pallets, the order flow times in the multiple pallet set-up case will be almost equal to the flow times in this single pallet set-up case.

Input
We have repeated the experiment described under *a)*, assuming that the two types of product set-ups required to complete a part are mounted on separate pallets.

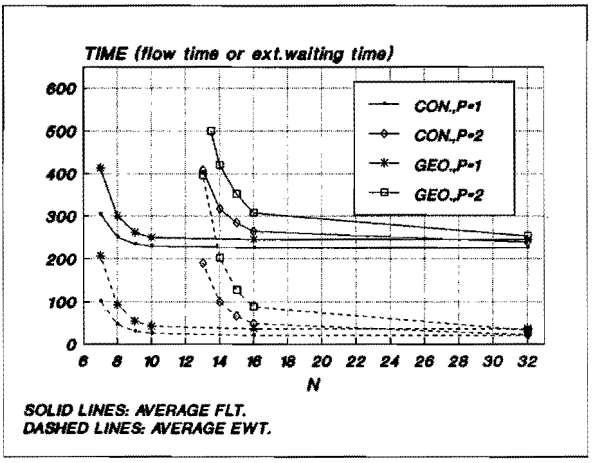

Figure 7.13:
Average flow time and external waiting time in single pallet set-up case as function of N in case of constant cycle-size and geometrical cycle-size, resp. for p(*i*)=1 and p(*i*)=2 (ρ_{pre}=60%).

Results
The results are shown in Fig.7.13. As we can see, the external waiting time in case p(i)=2 is comparable to the external waiting time for p(i)=1 and N/2. Also, if we compare these results with the results shown in Fig.7.12 for the multiple pallet set-up case, we see that indeed for a large N the flow times are almost equal.

Conclusion
In case of the single pallet set-up case, increasing p(i) will increase the order flow time. Also, if the product set-ups are mounted on separate pallets, the number of pallets required to complete all parts increases proportionally with p(i). Therefore, in case of unmanned production, the number of product set-ups required to complete a part, should be limited. If more than one type of product set-up is required, these product set-ups should be mounted on one pallet in order to reduce the number of pallets required to complete all work orders.

7.6 Conclusions

The conclusions from the analysis and experiments can be summarized as follows.
First of all, we have seen that the internal flow time of an order, in case of a limitation in the maximum number of identical product set-ups, depends on the number of cycles of that order, and the length of the unmanned shift. Clearly, the influence of the internal flow time on the order flow time is stronger for low utilization rates than for high utilization rates.
Secondly, as opposed to the manned case, the influence of the order cycle-size on the flow time does not depend on the distribution of the cycle-size. In all cases the flow time decreases rapidly for a larger N. As soon as the pallet utilization rate becomes negligible, increasing N hardly has any influence on the flow time anymore.
Thirdly, the order flow time in unmanned production heavily depends on the average cycle-size. Decreasing the cycle-size by increasing the number of parts in one product set-up, will reduce the average flow time. On top of that, the number of pallets required to complete all parts can be reduced proportionally to such a reduction in cycle-size.
Fourthly, due to the large impact of the internal flow time on the total flow time, increasing the number of identical product set-ups will reduce the average flow time of an order.
Finally, decreasing the number of product set-up types will decrease the average flow time. Also, the number of pallets required to complete all cycles will be reduced proportionally to the reduction in the number of product set-up types. If more than one type of product set-ups is required to complete a part, combining the product set-ups on one pallet will not only reduce the average flow time for a small N, but also reduce the number of pallets required to complete all parts.

Chapter 8
ESTIMATING FLOW TIMES

In the previous two chapters (Chapter 6 and Chapter 7) we have studied the flow time behaviour of work orders in case several work orders are produced simultaneously. In this chapter we will introduce flow time estimators for these situations that can be applied in practice.

Before a work order is released by Order Release, the flow time of the order is estimated in order to set the order due date, the order release date, and/or the operation due dates or start dates (see §4.1.2). It is not required to estimate the flow time very accurately, since the estimate is not used for a detailed deterministic schedule, but merely as a basis for Production Unit Control to determine priorities among work orders (see §2.3.3). The estimator for the flow time of an order at a particular work station should take into account the specific flow time characteristics of that work station (e.g. utilization rate, number of servers). In other words, the estimated flow time must be realistic, otherwise the estimates will not be accepted both by the planners and by the operators. In Chapter 6 and 7 we have studied the impact of the simultaneous production of work orders on the flow times. We conclude that in the flow time estimator for operations on a FAM-Station, the flow time effects of this simultaneous production of work orders have to be accounted for. Secondly, the estimator used must be kept simple, otherwise the estimation process will not be understood and because of that possibly also not accepted by the planners and/or operators. Finally, the estimators must take into account possible changes in flow time characteristics in the (near) future. These changes may be caused e.g. by different order characteristics. It should be clear in what way such a change in characteristics will affect the flow time estimates. To summarize, important demands on flow time estimators for operations on FAM-Stations are:

- the flow time effects of the simultaneous production of work orders have to be accounted for;
- the structure of the estimator must be simple, in order to make the estimation process acceptable;
- the structure of the flow time estimator must be logical, in order to make it possible to cope with changes, e.g. in order characteristics.

All flow time estimators introduced in this chapter distinguish two parts in the flow time of a work order, viz.:

- the external waiting time, i.e. the time the work order is waiting for the loading of the first cycle of the order;
- the internal flow time of the work order, i.e. the time between the loading of the first cycle of the work order and the unloading of the last cycle.

As we will see, the flow time estimators for the simultaneous production of work orders (on FAM-Stations) are different from the flow time estimators for work orders produced in a sequential way.

In the following paragraphs we will concentrate on simple flow time estimators that can be used in practice. In the first paragraph, we will start with a short discussion on the the structure of flow time estimators frequently used in case work orders are produced one after the other (the sequential case). In the second paragraph we will study the impact the simultaneous production of work orders has on the structure of these flow time estimators. The general structure given in this second paragraph will hold for all the estimators introduced in this chapter. In §8.3 we will introduce flow time estimators for orders that are completed during the manned production mode. In §8.4 we will concentrate on work orders with unattended operations, in particular for the case where the orders are completed entirely in unmanned shifts.

8.1 Flow time estimators in case of sequential production of orders

Usually in low volume component manufacturing shops, work orders are taken into operation and completed one after the other. A general estimator of the order flow time at a work station often used for this sequential case is:

$$\hat{\underline{t}}(i) = \hat{\underline{w}} + (s(i)+O(i)) \qquad (8.1)$$

where:

$\hat{x}$:	estimated value of x;
$\underline{t}(i)$:	flow time of work order i at the work station;
$\underline{w}$:	waiting time of a work order at the work station;
$s(i)$:	time required to set up the work station for work order i;
$O(i)$:	operation time required for work order i.

Sometimes the flow time estimator also includes transportation time to and from the work stations.
The structure of the estimator is quite simple. The waiting time can be regarded as the external waiting time, since no parts are loaded yet on the work station. This external waiting time is work station dependent (and thus will be different for different work stations). The set-up and operation time is operation dependent, and can be regarded as the internal flow time of the order.
In practice, often the external waiting time is estimated using historical data. In many cases it is also possible to estimate the waiting time using queueing models (see e.g. [Kleinrock, 1976]). In case of changes in the situation at the work station (e.g. a change in utilization rate, or a shift in average order operation time), the possible impact on the flow time can be predicted using these queueing models. Once the situation has stabilized again, new 'historical' data can be used in order to validate the waiting time estimates.

8.2 Flow times at FAM-Stations

In this paragraph we will study the impact of the simultaneous production of work orders on FAM-Stations on the models required to estimate the flow time of an order. We will start with a discussion on the external waiting times at FAM-Stations. In the second subsection we will discuss the internal flow times of the work orders on FAM-Stations. In §8.2.3 we will come to a conclusion regarding the general structure of the flow time estimator(s) required.

8.2.1 External waiting time at FAM-Stations

As long as no structural higher priority is given to a work order with particular characteristics above other work orders, the average external waiting time of an order will depend on the characteristics of the entire set of orders completed on the FAM-Stations, not on individual order characteristics. An example of a priority rule with this property is the FCFS-rule (First Come, First Served).
Usually, the characteristics of the set of orders to be completed during manned production on a FAM-Station differ from the characteristics of the set of orders completed during unmanned production. For instance, in order to gain as much capacity from an unmanned shift as possible, we prefer parts requiring long operation times for the unmanned production mode, whereas parts requiring short operation times are to be produced during the manned shifts. On top of that, as we have seen in the previous chapter, the characteristics of the two production modes are different. For instance, during an unmanned shift we aim to load as much pallets as possible, whereas during the manned shift the number of orders simultaneously in operation should be limited. Due to these differences in the characteristics of the set of orders to be completed in each production mode, and due to the different operation characteristics of the manned and the unmanned production mode, the external waiting time will depend on the production mode in which the order is going to be completed.
We conclude that the same estimate can be used for the external waiting time for each work order that is completed in the same production mode. However, the estimated external waiting time of orders produced during the unmanned production mode will be different from the estimated external waiting time of orders produced during manned production.

8.2.2 Internal flow time on FAM-Stations

As soon as a pallet set-up is prepared for a particular work order and the first cycle of this order can be loaded, the internal flow time of the order starts.
As we have seen in the Chapters 6 and 7, the internal flow time of an order is highly dependent on the cycle-size of the order. On top of that, the internal flow time of orders also depends on the production mode, since the cycle flow time in the unmanned shift will be different from the

cycle flow time in the manned shift. In case of manned production, a run batch containing one or more cycles can and usually will be unloaded as soon as the required operation process is completed. In case of an unmanned shift, after the completion of the operation process, the run batch will have to wait for the manning of the mounting/loading place. Consequently, the cycle flow time will be different for these production modes. As a result, also the internal flow time of the work orders will be different.
We conclude that the internal flow time of an order will depend both on the order characteristics (i.e. the order cycle-size) and on the production mode during which the order is completed.

8.2.3 General structure flow time estimator for FAM-Stations

From the discussion in the previous subsections, we conclude that each flow time estimator for an operation of a work order i at a FAM-Station will have the following structure:

$$\underline{t}(i,m) = \underline{t}_{int}(i,m) + \underline{t}_{ext}(m)$$

with:

$\underline{t}(i,m)$:	flow time of work order i at the FAM-Station if completed in production mode m;
$\underline{t}_{int}(i,m)$:	time between loading first cycle and unloading last cycle of work order i in production mode m (the internal flow time of work order i);
$\underline{t}_{ext}(m)$:	waiting time of a work order in front of FAM-Station with no cycles loaded on the station in production mode m (the external waiting time).

The flow time estimators given in §8.3 and §8.4 are all expressed in the time available for each production mode. Therefore, in order to translate these flow times into flow times based on a production calendar, the time available for each production mode during each working day should be taken into account. For instance, if according to the flow time estimator the flow time should be set 24 hours, and during each working day 8 hours will be spent in the production mode in consideration, the expected flow time will be 3 working days.

8.3 Flow time estimator for manned production

Based on the general structure introduced in the previous paragraph, we will study the flow time estimator for operations that are completed during manned shifts. We will start the discussion with a further specification of the general structure of the estimator. Having introduced this general structure for the estimators in case of manned production, we

will discuss in the second subsection the estimation of the external waiting time of an order. In subsection §8.3.3 we will study the estimator of the internal waiting time of an order in the basic case of simultaneous production of work orders. In the more complex cases we need a new concept, i.e. the concept of a 'cycle–train'. This concept will be introduced and discussed in §8.3.4. Finally, in the last subsection the flow time estimator for manned production will be given and tested.

8.3.1 General structure

In Chapter 6 we have seen that the internal flow time of a work order in the manned production mode, can be split up into two parts. Assuming that the cutting tools required for the machining process on the work order are loaded in only one machine tool, the internal flow time may consist of pallet preparation time, cycle loading and unloading times, machine set–up time, and order operation time. Clearly, this part of the internal flow time is fully dependent on the work order considered. For instance, in case of a FAM–Station with one pallet (N=1), the internal flow time of a work order consists entirely of the work order dependent operation and set–up time (where the set–up time can be regarded as the sum of the times required for all preparation and (un)loading activities). The order flow time will have a similar structure as in case of conventional work stations. An example of the flow time of a work order in such a case is given in Fig.8.1.
As soon as the number of pallets increases, we can expect that also the number of work orders simultaneously in operation will grow. In

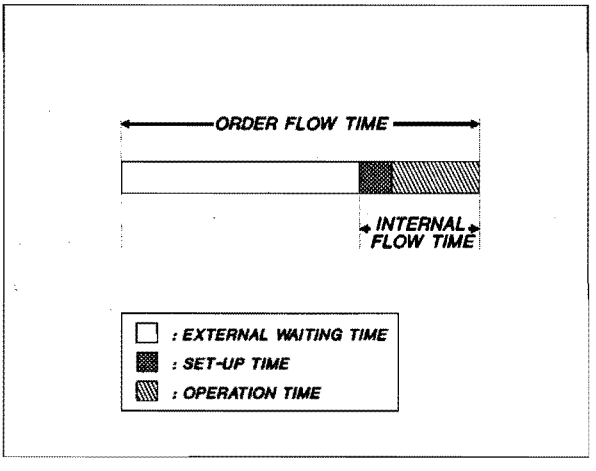

Figure 8.1:
Expected flow time of an order in case N=1, in manned production mode.

consequence, apart from the order operation time and set-up time, the internal flow time of a work order will also include some (internal) waiting time. During this internal waiting time the machine tool is processing parts of other work orders. Also, usually most of the preparation and (un)loading activities can take place during the time the machine tools is processing other parts. Therefore, the expected flow time of a work order in case N>1 will look like is shown in Fig.8.2.

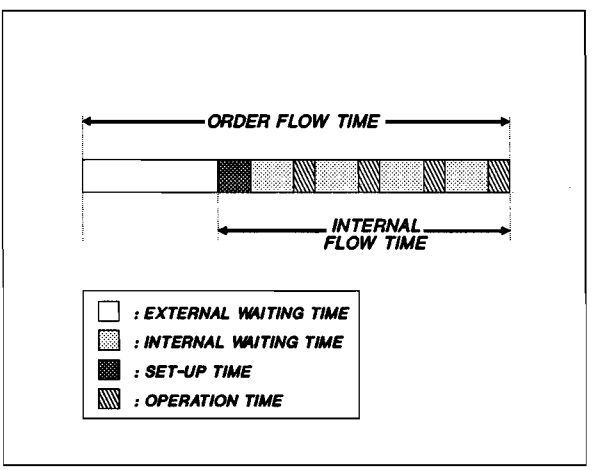

Figure 8.2:
Expected flow time of an order in case N>1, in manned production mode.

In other words, we may conclude that in case of the manned production mode, all flow time estimators will have the following structure:

$$\hat{\underline{t}}(i,M) = \hat{\underline{w}}_{ext}(M) + \hat{\underline{w}}_{int}(i,M) + (s(i) + O(i))$$

where:

$\underline{w}_{ext}(M)$:	external waiting time of a work order in front of the FAM-Station in the manned production mode (M);
$\underline{w}_{int}(i,M)$:	internal waiting time of work order i on FAM-Station in production mode M;
$s(i)$:	time required to set up the FAM-Station for work order i;
$O(i)$:	operation time required for work order i.

To summarize, the flow time estimator for manned production is built up from three parts. The first part of the estimator (the external waiting time) is fully determined by characteristics of the set of orders completed on the work station in the manned production mode. The second part represents the time the FAM-Station is processing parts from other orders

while the work order is in operation (i.e. the internal waiting time of the work order). This part of the flow time depends both on the characteristics of the set of orders completed by the FAM–Station and on the characteristics of the concerning work order. The third part of the estimator represents the part that is fully dependent on the specific work order characteristics. The elements with index '*i*' can be derived directly from the process plan.

8.3.2 External waiting time

In order to estimate the external waiting time, we have to calculate the average number of work orders in the external queue. Unfortunately however, no exact analytical calculations for these values are available (see Chapter 6). Therefore, we can follow two approaches, viz.:
- apply an approximation like the one of Avi–Ithzak and Heyman (see §6.2.1);
- use historical data.

In case the expected internal and external waiting time at the FAM–Station is based on historical values, we have to record from all work orders (or a sample of work orders) two data, i.e. the arrival time of the order at the FAM–Station (a(i)), and the time the loading of the first cycle of the order starts (l(i)). In most cases these data are already recorded in order monitor the progress of work orders. An estimate of the external waiting time can now be derived from the difference:

$$w_{ext}(i,M) = l(i) - a(i)$$

Usually the operation characteristics of the set of orders to be produced on the FAM–Station is stable enough to use these historical values for estimates. However, we may apply insights from the approximation of Avi–Ithzak and Heyman in order to predict the impact of changes in these characteristics on the external waiting time. If required, these predictions can be adjusted according to the new flow time measurements.

8.3.3 Internal waiting time – the basic case

In Chapter 6 we have seen that the internal waiting time of a work order heavily depends on the cycle–size of the work order. In case only one product set–up is required to complete a part and always only one cycle of each work order is loaded on the FAM–Station at the same time (i.e. the basic case of the simultaneous production of work orders), the internal waiting time seemed to be almost proportional to the cycle–size. In other words, if we denote the cycle waiting time in manned production as $\underline{w}_{cyc}(M)$, we can derive an estimate of the internal waiting time of an order with cycle–size q(i) by (see also eqn.(6.4) in §6.2.1):

$$\hat{\underline{w}}_{int}(i,M) = q(i) \times \hat{\underline{w}}_{cyc}(M) \qquad (8.2)$$

In this estimation, we neglect both the effect of the order cycle-size and the effect of the cycle operation time on the cycle waiting time (see §6.4.1 resp. §6.5.2). However, since these effects are small, especially in case of high utilization rates, we may expect that the error made by this estimate will be small too. On top of that, the flow time estimator will be much more complex and difficult to implement in practice if we would incorporate these effects in the estimator.
The remaining problem is the estimation of the cycle waiting time. Such an estimate can be obtained by recording the cycle waiting times of all cycles (or a sample of cycles). However, in practice this may be too time-consuming, especially if it is not possible to use the FAM-Station computer system for this purpose, and there is no direct link between the FAM-Station computer system and a central computer system. In such a case, the average cycle waiting time of the order can be calculated using the times already recorded in order to monitor the progress of a work order, viz. the time the loading of the first cycle of an order starts (l(*i*)), and the time the last cycle of the order is unloaded (u(*i*)). The internal waiting time of the work order can be obtained as follows:

$$w_{int}(i,M) = u(i) - l(i) - (s(i) + O(i))$$

If we divide this internal waiting time by the order cycle-size, we obtain the average cycle waiting time. In other words:

$$\bar{w}_{cyc}(i,M) = w_{int}(i,M) \;/\; q(i)$$

In case more product set-up types are required, and we assume:
- that of each set-up type only one product set-up is available,
- and that first all cycles are completed in one product set-up type before they are being re-loaded one after the other in the product set-up of the next type,

we may apply a similar estimator. In such a case we have to multiply the estimated internal flow time given in eqn.(8.2) with the number of product set-up types required (p(*i*)), or:

$$\hat{\bar{w}}_{int}(i,M) = p(i) \times q(i) \times \hat{\bar{w}}_{cyc}(M) \qquad (8.3)$$

However, this situation is quite rare. Usually all product set-up required by one work order are mounted on pallets as soon as possible (see §6.6). As a result, during the cycle waiting time of one cycle of the work order, the FAM-Station will produce not only cycles of other orders, but also other cycles of the same work order. As a result, the internal waiting time of the order will be much shorter than estimated according to eqn.(8.2). Clearly, the estimate will even get worse in case it is possible to mount several product set-ups of one set-up type concurrently on pallets. For these situations, we will introduce a new concept, i.e. the 'cycle-train'. The purpose of this concept is to be able to estimate the internal flow time of an order using an estimator similar to eqn.(8.2) and eqn.(8.3).

8.3.4 Cycle–trains

In this subsection we will introduce the concept of the 'cycle–train' and apply this concept to estimate the internal waiting times of work orders in several cases.

The concept
Let us assume that if several cycles of the same work order are loaded on the FAM–Station at the same time, then these cycles will be taken into operation one after the other. In other words, these cycles are supposed to be linked like wagons of a train. Consequently, we will call this concept a *cycle–train*. Notice that a cycle–train is a mental concept. It differs from the situation in real life, since the 'train' can be spread out over several non–connected pallets.
With this concept, the time bar for the real flow time drawn in the first part of Fig.8.3 can also be represented by an alternative time bar based on cycle–trains (the second part of Fig.8.3). As we can see, the internal waiting time for both cases is the same.

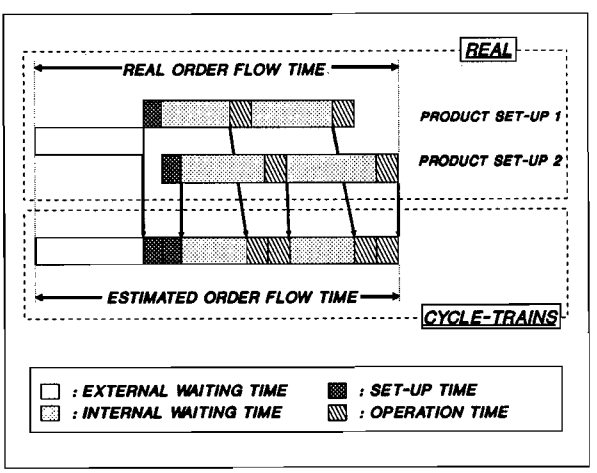

Figure 8.3:
Flow time estimate based on cycle–trains.

As we will show, with this concept of a cycle–train, we can derive an estimate of the internal waiting time based on the flow time effects we have studied in Chapter 6.

Estimating internal waiting times
Based on Fig.8.3, we assume that the internal waiting time of each order is proportional to the number of cycle–trains of the order ($q'(i)$). The number of cycle–trains required is fully dependent on the characteristics of order i. The average waiting time of each cycle–train is assumed to be independent of the work order considered. In other words, if we denote the

waiting time of a cycle–train in manned production as $\underline{w}_{tr}(M)$, we assume the following equation will hold:

$$E(\underline{w}_{int}(i,M)) = q'(i) \times E(\underline{w}_{tr}(M)) \qquad (8.4)$$

Similar to the estimation of the cycle waiting time, we can derive an estimate of the cycle–train waiting time by dividing the internal waiting time of a completed work order by q'(*i*), or:

$$w_{tr}(i,M) = [u(i) - l(i) - (s(i)+O(i))] \;/\; q'(i)$$

What remains to be studied is the number of cycle–trains required to complete a work order for a number of different cases.

Number of cycle–trains

In the basic case of simultaneous production of work orders, we have assumed that the number of product set–up types required to complete all operation processes on parts of a work order, is limited to one. Also, the number of identical product set–ups is assumed to be limited to one (e.g. due to a fixture limitation). In this basic case, only one cycle per work order can be loaded on the FAM–Station at a time. Therefore, one cycle–train consists of exactly one cycle. As a result, the number of cycle–trains required equals the cycle–size of the order, or:

$$\hat{q}'(i) = q(i) \qquad (8.5)$$

where:
q(*i*): cycle size of work order *i*.

In other words, in this special case the waiting time of a cycle–train can be interpreted as the cycle waiting time (see also eqn.(8.2)).

In case several cycles belonging to the same work order are loaded on the FAM–Station concurrently, it may become possible to reduce the number of orders simultaneously in operation to only one without a loss in productive use. This increase in the number of identical cycles concurrently on the system can be achieved by increasing the number of identical product set–ups and/or by increasing the number of product set–up types required to complete a part. As a result, there will be no internal waiting time at all. In other words, in such a case:

$$\hat{q}'(i) = 0 \qquad (8.6)$$

The flow time can be estimated as in the conventional case, i.e. based on the external waiting time and the order operation time (see eqn.(8.1)).

The next case we will study is the case where the maximum number of identical product set-ups may be larger than one, while at the same time also the number of orders simultaneously in operation may be larger than one. As a result, the number of cycles of one work order loaded concurrently on the FAM-Station could be larger than one, and the internal waiting time will be larger than zero. We may expect that if possible all product set-ups of an order are mounted on pallets almost at the same time, since, as we have seen in the Chapter 6, in such a case the flow time effects of the simultaneous production of work orders are reduced. In that case, the number of cycle-trains required to complete the order will be reduced (almost) proportionally to the increase in the maximum number of identical product set-ups. For instance, in case two fixtures are used instead of one, the number of cycle-trains required is reduced with a factor 2. Such a situation is already illustrated in Fig.8.3, where we have drawn for a work order with cycle-size 4 the adjusted flow time bar using the concept of cycle-trains. Clearly, in that case two cycle-trains are required to complete the order.
In other words, the number of cycle-trains required to complete a work order can be estimated by dividing the cycle-size of the work order by the number of identical product set-ups (i.e. the number of fixtures). Or:

$$\hat{q}'(i) = [q(i)/f(i)]_{int} \qquad (8.7)$$

where:
$q(i)$: cycle-size of order i;
$f(i)$: number of fixtures for order i;
$[x]_{int}$: function giving the lowest integer equal or larger than x.

The most complicated situation is the case where several product set-up types are required to complete a part, while at the same time the number of orders simultaneously in operation is larger than one. As we saw in Chapter 4, preferably the number of parts loaded in a product set-up is equal for all product set-up types. In that case the operator can re-load each cycle at once. Therefore, it will not be required to store cycles at the FAM-Station with a special operation-status. Thus, we may assume that in such a situation each product set-up contains exactly one cycle.
For such a case, the flow time of a work order will look like is drawn in Fig.8.4. In the example given in the figure, two types of product set-ups are required to complete a part, and the maximum number of identical product set-ups is one. As we can see, the time bar for the internal flow time of the order starts at the time the first cycle is loaded on the FAM-Station in the product set-up of the first type required (*ProS1*). In order to prevent the cycle from being stored in front of the station, the operator will make sure that the product set-up *ProS2* of the second type required is mounted on a pallet at the time this first cycle is completed and returns to be unloaded. Sometimes it is possible to mount this second set-up on the same pallet as the first product set-up, which makes the re-loading logic even more simple (the multiple pallet set-up case, see §6.6.3). After the first cycle is unloaded from *ProS1*, the second cycle is loaded in *ProS1*, and the first cycle can be re-loaded in *ProS2*. The next time the pallet(s) return(s) at the mounting/loading place, the first cycle is unloaded, the second cycle is re-loaded in the second set-up, and the third cycle is loaded in the product set-up of the first type.

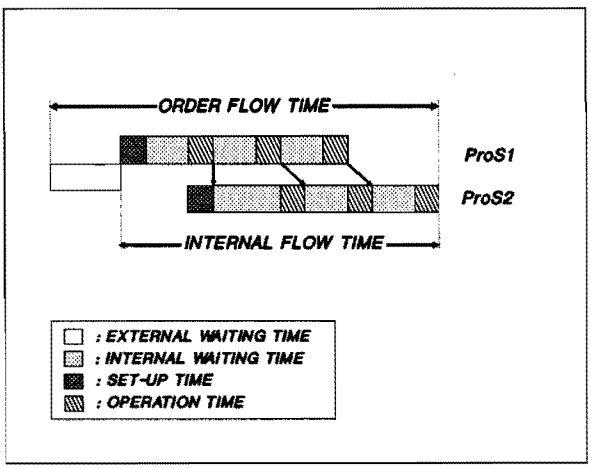

Figure 8.4:
Example of flow time in case of two product set–up types required to complete a part.

The number of cycle–trains required in the example of Fig.8.4 is equal to the cycle–size of the order plus one. This extra cycle–train (consisting of only one cycle) is required to get the first cycle in the second product set–up. We can generalize this (see also §6.6.3): in case p(i) product set–up types are required to complete a part, it will take (p(i)–1) cycle–trains for the first cycle to be re–loaded in the last set–up type. Once the first cycle is loaded in the last product set–up, it takes q(i) cycle–trains before the last cycle of the work order is unloaded, assuming that only one fixture is available for this last product set–up type. In case it is possible to mount several product set–ups of the same type simultaneously on the FAM–Station (say f(i)), it will take $[q(i)/f(i)]_{int}$ cycle–trains before the last cycle can be unloaded (see eqn.(8.7)). In other words, the estimate of the number of cycle–trains required to complete the work order is:

$$\hat{q}'(i) = [q(i)/f(i)]_{int} + p(i) - 1 \qquad (8.8)$$

where:

q(i):	cycle–size of order i;
f(i):	number of fixtures for each product set–up type of order i;
$[x]_{int}$:	function giving the lowest integer equal or larger than x;
p(i):	number of product set–up types required to complete a cycle of order i.

In the discussion it is assumed that the number of product set-ups available is the same for each product set-up type. This is a reasonable assumption considering the loading logic given above. Under this assumption, the rate of completion is equal for each type of product set-up. Any other case requires the storage of non-completed parts at the FAM-Station. However, even in some of these other cases a similar flow time estimate can be applied if the following constraints hold:

$$q'(i,j-1) \leq q'(i,j) \qquad \forall i,\ \forall j \in \{2,\ldots,j^*\}$$
$$q'(i,j-1) \geq q'(i,j) \qquad \forall i,\ \forall j \in \{j^*+1,\ldots,p(i)\}$$

where

$q'(i,j)$: the number of cycle-trains required to complete all cycles of order i in the j-th product set-up type ($j \leq s(i)$);
j^*: the product set-up type with the largest $q'(i,j)$.

For these cases we have to replace $[q(i)/f(i)]_{int}$ by $q'(i,j^*)$. However, since these cases differ from the re-loading logic described above, we will not consider them any further.

Notice that the estimated number of cycle-trains in previous cases all can be deduced from eqn.(8.8). Eqn.(8.7) can be obtained by assuming that $p(i)=1$, whereas in eqn.(8.5) it is assumed that also $f(i)=1$. Consequently, equation (8.8) can be regarded as the general estimator for $q'(i)$.

8.3.5 The flow time estimator

All the ingredients required for the flow time estimator are now introduced. Following the general structure of the flow time estimator for manned production, and using the concept of the 'cycle-train', the estimated flow time for manned production is:

$$\hat{t}(i,M) = \hat{w}_{ext}(M) + \hat{w}_{tr}(M) \times \left[\left[\frac{q(i)}{f(i)} \right]_{int} + p(i) - 1 \right] + (s(i)+O(i)) \qquad (8.9)$$

where:

$w_{ext}(M)$: external waiting time of a work order in front of FAM-Station in manned production mode;
$w_{tr}(M)$: waiting time of a cycle-train on FAM-Station in the manned production mode;
$q(i)$: cycle-size of work order i;
$f(i)$: number of fixtures for order i;
$p(i)$: number of product set-up types required to complete a cycle of order i.
$s(i)$: time required to prepare all pallet set-ups for work order i;
$O(i)$: operation time required for work order i.

Clearly, this flow time estimator is not as simple as the flow time estimators applied in case of conventional work stations. However, still the

estimator is not very complex, and from the real life cases we studied it seems to include the effects of the simultaneous production of work orders on the flow times in a clear and acceptable way. Nevertheless, the estimator does simplify the flow time behaviour of orders on FAM–Stations, especially concerning the internal waiting time of a work order. If the estimated flow times of particular work orders consistently differ substantially from the real flow times, these work orders may get unintended higher or lower priority at the FAM–Station or at the next work station, e.g. in case operation start dates are applied. Therefore, we have to check the validity of the flow time estimator.

In order to test the flow time estimator, in particular the cycle–train concept, a number of simulation experiments have been performed, using the simulation model described in §6.3. In these experiments we have distinguished six classes of orders. Orders belonging to the same order class are identical in every respect (i.e. the same operation time, the same cycle size, etc.). However, each order is assumed to require an order–specific type of fixture. We assume negligible mounting, dismounting, loading and unloading times. The order characteristics of the input per simulation run are given in Appendix 1. The Appendix gives for each order class in the simulation run:

- the cycle–size;
- the cycle operation time in the first product set–up type;
- the cycle operation time in the second product set–up type (if required);
- the maximum number of identical product set–ups for each product set–up type (assumption: this number is the same for both set–up types).

If two product set–up types are required, it is assumed that these set–up types are mounted on different pallets (i.e. the single pallet set–up case; see §6.6.3). Furthermore, the average inter–arrival time is assumed to be the same for all order classes. As a result, also the expected number of orders of each class is the same for all classes. The input values chosen are largely based on the order characteristics in the real life cases we have studied.

Each set of order characteristics is used in simulation runs with four settings, viz. a single FAM–Station with four pallets (N=4), or a single FAM–Station with ten pallets (N=10), with a pre–set utilization rate of 80% or 90%. The priority rule used both in the external queue and in the internal queues is the FCFS–rule. For each setting, ten simulation runs have been performed with different random input. The length of each simulation run was set at 100,000 time units (excluding the starting–up period).

The detailed results of the experiments are given in Appendix 1. In most production control information systems, a flow time estimator similar to eqn.(8.1) is used (i.e. the flow time estimator for the sequential case). The Tables 8.1 and 8.2 compare for a pre–set utilization rate of 80% resp. 90% the results of the flow time estimates based on the cycle–train concept, with the flow time estimates obtained by applying the flow time estimator for the sequential case. For this latter flow time estimate, we used the overall average total order waiting time as an estimate for the total waiting time of each order. The tables give for each experimental setting the relative differences over the ten simulation runs between the estimated and the measured average flow times per order class, where the relative difference $\underline{e}_{frlt}(i)$ of order class i is defined as:

$$\underline{e}_{frlt}(i) = 100\% \times (\underline{\hat{t}}(i,M) - \underline{t}(i)) \; / \; \underline{t}(i).$$

Clearly, the flow time estimator based on the concept of a cycle–train gives a better flow time estimate than the more common flow time estimator based on eqn.(8.1). Due to the fact that the latter estimator does not take into account the effects of the simultaneous production of work orders, especially the estimates for flow times of the orders with extreme cycle–sizes (both large and small) are poor.
The mean relative estimation errors of the estimator based on eqn.(8.9) are quite acceptable in real life situations. Only a few times the relative difference exceeds the 10%. However, Appendix 1 shows that in some cases the estimator systematically underestimates or overestimates the internal order waiting times. A more detailed analytical approach is required to overcome these estimation errors.

Table 8.1:
Mean relative estimation error (in %) of order flow times in manned production when using eqn.(8.9) resp. eqn.(8.1) (ρ_{pre}=80%).

Order Set	N	Eqn.	CLASS i 1	2	3	4	5	6
01	4	(8.9)	– 2.	0.	0.1	2.	1.	3.
		(8.1)	33.	13.	0.8	– 8.	6.	–23.
	10	(8.9)	– 3.	2.	1.3	– 2.	– 4.	11.
		(8.1)	88.	30.	2.8	–17.7	7.	–32.7
02	4	(8.9)	– 3.3	2.	– 3.	2.	1.	8.
		(8.1)	20.	12.	9.	–11.	2.	–16.
	10	(8.9)	– 5.	4.	– 3.	7.	– 4.2	8.
		(8.1)	62.	28.	26.	–16.	0.2	–32.5
03	4	(8.9)	– 1.	– 9.	5.	10.	5.	2.9
		(8.1)	39.	29.	8.	– 3.	–14.	–20.0
	10	(8.9)	– 0.	– 5.	3.	7.	2.	– 1.9
		(8.1)	93.	89.	11.	– 7.	–23.	–31.3
04	4	(8.9)	– 2.	– 2.	2.	4.	5.	3.
		(8.1)	37.	6.	20.	– 9.	7.	–25.
	10	(8.9)	– 2.	– 2.	2.	– 0.	5.	7.
		(8.1)	115.	16.	47.	–21.3	10.	–37.2
05	4	(8.9)	3.	– 8.	3.	3.	1.	8.
		(8.1)	44.	21.	4.	– 5.	–13.	–17.
	10	(8.9)	2.	– 6.5	3.	– 1.	– 1.	11.
		(8.1)	117.	70.	6.	–13.1	–22.	–28.
06	4	(8.9)	– 2.	– 2.	– 0.	2.	3.	3.
		(8.1)	33.	10.	– 1.	–11.	–13.	2.
	10	(8.9)	– 2.	– 2.	– 0.	8.	– 0.	– 0.
		(8.1)	98.	26.	– 0.	–14.	–27.1	– 0.

Table 8.2:
Mean relative estimation error (in %) of order flow times in manned production when using eqn.(8.9) resp. eqn.(8.1) (ρ_{pre}=90%).

Order Set	N	Eqn.	CLASS i 1	2	3	4	5	6
01	4	(8.9)	− 1.	0.2	− 1.0	1.	3.	− 0.
		(8.1)	20.	9.	− 0.3	− 5.	7.	−19.
	10	(8.9)	− 2.	1.7	− 0.7	0.	− 0.	3.
		(8.1)	60.	23.	1.1	−14.	10.	−32.
02	4	(8.9)	− 2.8	0.	− 2.	0.	1.	7.
		(8.1)	11.	6.	6.	− 8.	3.	−11.
	10	(8.9)	− 3.3	1.	− 2.	3.	− 1.	6.
		(8.1)	38.	17.	19.	−14.	3.	−28.
03	4	(8.9)	− 3.	− 5.	4.	6.	4.	4.5
		(8.1)	22.	19.	6.	− 3.	−11.	−15.
	10	(8.9)	− 2.	− 5.	3.	5.	2.	1.3
		(8.1)	66.	63.	9.	− 8.	−21.	−29.
04	4	(8.9)	− 1.	− 1.	− 0.2	4.	4.	1.
		(8.1)	20.	4.	11.	− 6.1	5.	−19.
	10	(8.9)	− 2.	− 1.	− 0.1	3.	4.	4.
		(8.1)	68.	13.	30.	−17.1	7.	−34.
05	4	(8.9)	2.	− 4.	2.	3.	1.	5.
		(8.1)	23.	12.	2.	− 2.9	− 9.	−13.
	10	(8.9)	2.	− 5.	2.	1.4	− 0.	6.
		(8.1)	64.	42.	4.	− 8.8	−18.	−24.
06	4	(8.9)	− 2.	− 2.	0.	1.	2.	2.
		(8.1)	18.	6.	0.	− 7.	−11.	2.
	10	(8.9)	− 2.	− 2.	0.	3.	1.	0.
		(8.1)	60.	19.	1.	−13.	−24.0	0.

We conclude that the estimator given in eqn.(8.9) is a good basis for estimating flow times in real life, especially since the estimator is simple and logical. The estimation error may be reduced if a more detailed analytical approach is applied, particularly taking into account:
- the probability that product set-ups belonging to one order can be mounted on pallets at the same time;
- the differences in cycle(-train) waiting times caused by the differences in order cycle-sizes and/or the differences in cycle operation times.

However, such a more detailed approach is likely to create a more complex flow time estimator.

8.3.6 Conclusion

In this paragraph we have introduced a flow time estimator to be applied in real life situations for estimating flow times of orders on FAM-Stations in the manned production mode. The estimator, given in eqn.(8.9), simplifies the real flow time behaviour of orders on a FAM-Stations in order to be acceptable and logical. In the estimator the flow time effects of the simultaneous production of work orders have been accounted for. In particular, the estimator distinguishes external waiting times from internal waiting times, and clearly shows the dependency of the internal waiting time on the order cycle-size. In most cases the estimator provides a fairly accurate estimate of the order flow time. Improvement of the estimation quality requires a more detailed approach, thus creating a more complex estimator.

8.4 Flow time estimator for unmanned production

In Chapter 5 we concluded that in case of a high utilization rate and a large number of attended operations, almost all unattended operations are to be performed during the unmanned production mode. On top of that, due to the large number of attended operations, it is impossible to predict when it will be possible to perform unattended operations during manned shifts. As a result, the possibility of performing unattended operations in the manned production mode must be regarded as volume flexibility that only in exceptional cases will be applied. In the flow time estimator it is not possible to take these exceptional cases into account. Therefore, in most subsections of this paragraph we will discuss flow time estimators for orders with operations performed entirely during the unmanned shifts. Only in §8.4.5 we will discuss briefly the hypothetical situation that all operations of all orders can be regarded as unattended operations.
As we did in §8.3, we will start the discussion with a further specification of the general structure of the estimators. In §8.4.2 we will discuss the estimation of the external waiting time of a work order. In the next subsection we will study the estimator of the internal waiting time of an order. The flow time estimator for unmanned production will be given and tested in §8.4.4. In §8.4.5 we will extend our view to the hypothetical case where all operations of all orders are regarded as unattended operations. The main conclusions will be summarized in the last subsection of this paragraph.

8.4.1 General structure

In Chapter 7 we noticed that the flow time of a work order in the unmanned production mode, can be split up into two parts. First of all an order will wait in front of the FAM-Station without a cycle loaded on the station. Similar to the manned case, this waiting time is called the external waiting time.

Once the order is chosen to be loaded on the station, the set-up activities required for the order can start. All these activities have to be performed during manned production periods. In this paragraph we will assume that in between two unmanned shift there will be a change-over period. During this change-over period the operator has to perform activities like pallet preparation, cycle loading and unloading, and setting up the machine. The change-over period should be long enough to perform all of these activities. Usually, a manned shift can be regarded as such a change-over period. Under the assumption that these preparation activities can be performed during the change-over period, the time required for these activities no longer is of interest for estimating the flow times. Independent of the work order in consideration, we can regard the change-over period as a part of the unmanned shift.
After the loading of run batches at the beginning of the shift, it will take exactly the length of one unmanned shift before the run batches that are completed during the unmanned shift, can be unloaded. Therefore, under the assumption that the work load on the FAM-Station at the beginning of the unmanned shift does not exceed the machine capacity during this unmanned shift, we know the cycle flow time will be exactly one unmanned shift (see also §7.2.1). The number of unmanned shifts required to complete an entire work order will depend on the cycle-size of the order, the number of fixtures available, and the number of times a cycle has to be re-loaded in another product set-up. Consequently, in the flow time estimator, the work order characteristics will not influence the cycle flow time, but only the expected internal order flow time. Therefore, the expected flow time of a work order for all values of N will look like is shown in Fig.8.5.

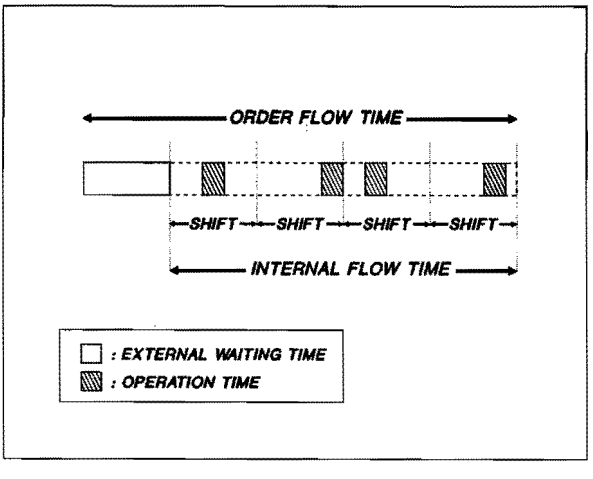

Figure 8.5:
The expected flow time of an order in unmanned production mode.

In other words, we may conclude that in case of the unmanned production mode, all estimators will have the following structure:

$$\hat{t}(i,U) = \hat{\underline{w}}_{ext}(U) + T\hat{q}''(i)$$

where:

$\underline{w}_{ext}(U)$: external waiting time of a work order in front of FAM-Station in the unmanned production mode U;
T: length (in time) of one unmanned shift;
$q''(i)$: the number of unmanned shifts required to complete order i.

8.4.2 External waiting time

In order to estimate the external waiting time of a work order in the unmanned production mode, again we have to calculate the average number of work orders in the external queue. Similar to the manned case, we can follow two approaches, viz.:
- apply the approximation of Avi-Ithzak and Heyman (see §7.2.1);
- use historical data.

In case the expected external waiting time at the FAM-Station is based on historical values, we can apply the same method as in the case of manned production (see §8.3.2). However, as we have stressed in §8.2.2, the average external waiting time for the unmanned production mode will differ from the external waiting time in the manned production mode.

8.4.3 Internal flow time

Deriving an estimator for the internal flow time means estimating the number of unmanned shifts required to complete a work order.

In the basic case of simultaneous production of work orders, we have assumed that both the number of product set-up types required to complete all operation processes on parts of a work order, and the number of identical product set-ups (e.g. due to a fixture limitation) is limited to one. In that case, only one cycle per work order can be loaded on the FAM-Station at a time. As a result, the number of shifts required to complete the order equals the cycle-size of the order. In other words:

$$\hat{q}''(i) = q(i) \qquad (8.10)$$

where:

$q(i)$: cycle size of work order i.

In case the number of identical product set-ups concurrently on the system is increased, the number of unmanned shifts required to complete a work

order will be reduced. In such a case, we may expect that, if technically possible, all product set–ups of an order will be mounted on pallets simultaneously. With this mounting discipline, we will both decrease the number of shifts required to complete a particular work order (see also §7.4.3) and may increase the productive use of the machine capacity. In that case, the number of cycles loaded on the system at the beginning of the shift will equal the number of identical product set–ups. As a result, the number of shifts required to complete the order will be reduced (almost) proportionally to the number of identical product set–ups. Therefore, the number of shifts required to complete a work order can be determined by dividing the cycle–size of the work order by the number of identical product set–ups (i.e. the number of fixtures). Or:

$$\hat{q}''(i) = [q(i)/f(i)]_{int} \tag{8.11}$$

where:

$q(i)$:	cycle–size of order i;
$f(i)$:	number of fixtures for order i;
$[x]_{int}$:	function giving the lowest integer equal or larger than x.

Finally, let us assume that several product set–up types are required to complete a part. In case the number of parts loaded in a product set–up is equal for all product set–up types, during each change–over period the operator can re–load an entire cycle at once. Therefore, it will not be required to store a part at the FAM–Station with a special operation–status. For such a case, the flow time of a work order will look as shown in Fig.8.6. In the example given in the figure, two types of

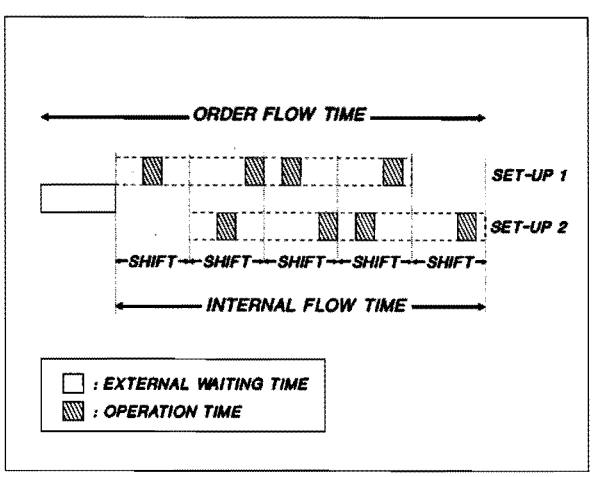

Figure 8.6:
Example of flow time in unmanned production mode in case of two product set–up types required to complete a part.

product set-ups are required to complete a part. The internal flow time starts when the first cycle is loaded on the FAM-Station in a product set-up of the first type required. In order to prevent the cycle from being stored off the station, the operator will make sure that a product set-up of the second type required is mounted on a pallet during the next change-over period. Thus, once the first cycle is completed and is unloaded during the change-over period, it can be re-loaded at once in the second product set-up type. During the same change-over period, the second cycle can be loaded in the first product set-up. The next time the pallet(s) return(s) at the load/unload station, the first cycle is unloaded, the second cycle is re-loaded in the second set-up, and the third cycle is loaded in the product set-up of the first type.
As we can see, the number of shifts required in this example equals the cycle-size of the order plus one. To generalize this observation: in case $p(i)$ product set-up types are required to complete a part, it will take $(p(i)-1)$ shifts for the first cycle to be loaded in the product set-up of the last type required. In case only one fixture is available for each type of product set-up, it takes $q(i)$ shifts after the first cycle is loaded in the last product set-up, before the last cycle of the work order is unloaded. In case it is possible to mount several product set-ups of the same type simultaneously on the FAM-Station (say $f(i)$), it will take $[q(i)/f(i)]_{int}$ shifts before the last cycle can be unloaded. Therefore, the estimated number of unmanned shifts required to complete the work order, is:

$$\hat{q}''(i) = [q(i)/f(i)]_{int}+p(i)-1 \qquad (8.12)$$

where:
$q(i)$: cycle-size of order i;
$f(i)$: number of fixtures for order i;
$[x]_{int}$: function giving the lowest integer equal or larger than x;
$p(i)$: number of product set-up types required to complete a part.

Notice that in all cases $q''(i)$ is identical to $q'(i)$ in the similar case in the manned production mode (see §8.3.4). This is not a surprising observation, since the concept of a 'cycle-train' can also be used in case of unmanned production. Therefore, we conclude that $q''(i)$ in case of unmanned production can be chosen equal to $q'(i)$ in case of manned production. The values can easily be derived from the work order characteristics.

8.4.4 The flow time estimator

Following the general structure of the flow time estimator for unmanned production, and using the results of the previous subsections, the estimator for the flow time of work order i in unmanned production is:

$$\hat{f}(i,U) = \hat{w}_{ext}(U) + T\times\left[\left[\frac{q(i)}{f(i)}\right]_{int}+p(i)-1\right] \qquad (8.13)$$

where:

$\underline{w}_{ext}(U)$:	external waiting time of a work order in front of FAM-Station in the unmanned production mode U;
T:	length (in time) of one unmanned shift;
q(i):	cycle-size of work order i;
f(i):	number of possible identical product set-ups for order i;
p(i):	number of product set-up types required for order i.

Obviously, this flow time estimator is different from the estimator in case of manned production. The flow time effects of unmanned production are shown clearly in the estimator.

In order to test the flow time estimator, again some simulation experiments have been performed, using the simulation model described in §7.3.1. In these experiments we have simulated the same six classes of orders as in the manned case (see §8.3.5), assuming that all operation are to be carried out during unmanned production. The order characteristics of the input per simulation run are given in Table A.1 of Appendix 1. We have assumed that all mounting, dismounting, loading and unloading activities can be carried out in between two unmanned shifts during the change-over period. The length of this change-over period was assumed to be negligible. Each product set-up was mounted on a separate pallet (i.e. the single pallet set-up case; see §7.4.3). The priority rule used both in the external queue and in the internal queues was the FCFS-rule.
For each set of order characteristics we have performed ten simulation runs in two different settings, viz. a single FAM-Station with nine pallets (N=9) and a single FAM-Station with twenty pallets (N=20). In both settings the pre-set utilization rate was 60%.
The expected inter-arrival time was the same for all order classes in all simulation runs. Per simulation run we have simulated 12,750 unmanned shifts (excluding the starting-up period).

The detailed results of the experiments are given in Appendix 1. As we have said before, in most production control information systems, a flow time estimator similar to eqn.(8.1) is used (i.e. the flow time estimator for the sequential case). Table 8.3 compares the results of the flow time estimator using eqn.(8.13) with the flow time estimates obtained by applying eqn.(8.1) (using the overall average total order waiting time as an estimate for the total waiting time of each order). The table gives for each particular experimental setting the results over the ten simulation runs of the relative difference between the estimated and measured flow times per order class. This relative difference $e_{flt}(i)$ of order class i is defined as:

$$e_{flt}(i) = 100\% \times (\hat{t}(i,U) - \bar{t}(i)) \; / \; \bar{t}(i)).$$

Again, the flow time estimator based on the concept of a cycle-train gives a better flow time estimate than the more common flow time estimator based on eqn.(8.1). In this latter case, especially the estimates for flow times of the orders with extreme cycle-sizes (both large and small) are poor.

Table 8.3:
Mean relative estimation error (in %) of order flow times in unmanned production when using eqn.(8.13) resp. eqn.(8.1) (ρ_{pre}=60%).

Order Set	N	Eqn.	CLASS i					
			1	2	3	4	5	6
01	9	(8.13)	– 2.	– 3.0	– 0.3	– 2.5	– 4.0	0.0
		(8.1)	129.	26.8	1.9	–14.8	29.1	–45.1
	20	(8.13)	– 3.5	– 1.8	– 0.4	– 3.4	– 3.9	– 0.06
		(8.1)	152.	31.4	2.1	–16.4	32.3	–46.9
02	9	(8.13)	– 1.5	– 0.9	– 4.	– 0.	– 0.8	0.5
		(8.1)	13.	4.	5.	– 7.	6.	–15.
	20	(8.13)	– 2.4	– 0.0	– 6.3	–0.1	– 3.4	– 2.3
		(8.1)	139.	29.	55.8	–28.3	27.2	–47.6
03	9	(8.13)	– 5.1	–13.4	– 0.1	– 0.1	– 0.0	– 0.4
		(8.1)	129.	106.	10.5	–17.2	–27.0	–32.4
	20	(8.13)	– 5.5	– 4.4	– 0.3	– 0.3	– 0.3	– 0.5
		(8.1)	142.	141.	10.1	–18.5	–28.5	–33.7
04	9	(8.13)	–16.	– 1.4	– 3.1	– 4.7	– 1.7	– 0.2
		(8.1)	187.	32.	52.	–20.2	4.2	–46.6
	20	(8.13)	–20.	– 1.5	– 1.5	– 5.8	– 0.5	– 0.2
		(8.1)	205.	34.3	58.	–21.6	5.7	–47.6
05	9	(8.13)	1.	–14.9	– 3.	– 2.6	– 0.4	– 0.0
		(8.1)	96.	60.	2.8	– 7.0	–18.3	–35.3
	20	(8.13)	0.1	– 4.6	– 1.7	– 2.5	– 0.5	– 0.1
		(8.1)	171.	138.	3.4	– 9.6	–23.4	–42.7
06	9	(8.13)	– 0.	– 1.4	– 0.4	– 0.4	– 2.7	– 2.5
		(8.1)	124.	39.5	6.3	–29.7	–29.6	4.1
	20	(8.13)	– 1.	– 1.8	– 0.9	– 0.4	– 3.5	– 1.7
		(8.1)	135.	41.4	6.3	–30.4	–30.7	5.4

In most cases, the mean relative estimation errors of the estimator based on eqn.(8.13) are quite acceptable. However, in some cases, especially in case of small cycle–sizes, the flow time estimator clearly underestimates the order flow time. As it seems, the assumption that all product set–ups belonging to one order are mounted on pallets almost at the same time, is too optimistic. Clearly, violating this assumption has a larger relative impact on the estimation quality in case of small cycle–sizes than in case of large cycle–sizes. The estimation error may be reduced if a more detailed analytical approach is applied, particularly taking into account the probability that product set–ups belonging to one order can be mounted on pallets at the same time. Unfortunately, such a more detailed approach is likely to create a more complex flow time estimator.

8.4.5 Flow time estimator for both production modes

In this subsection we will assume that all operations can be regarded as unattended operations. Consequently, all operations can be performed in both production modes. In the real life cases we have studied, this situation was rather exceptional. Therefore, we will spend only a few lines on a possible flow time estimator in this special situation.
If the operations of all work orders indeed can be performed in both production modes, we cannot use the flow time estimators given above. However, we may use the results of §8.3.5 and §8.4.4 to calculate the number of cycle–trains that is being completed per unit of time in each production mode. In other words, we estimate the internal flow time of the work order in each production mode as if the operation is performed entirely in that particular production mode. Given this internal flow time, we can estimate the average number of cycle–trains that will be completed per unit of time by dividing the estimated internal flow time by the estimated number of cycle–trains. Thus:

$$\hat{\mu}(i,m) = \hat{t}_{int}(i,m) \;/\; \hat{q}'(i) \qquad (8.14)$$

with:

$\mu(i,m)$:	output rate of work order i in production mode m;
$t_{int}(i,m)$:	internal flow time of work order i assuming the operation is performed entirely in production mode m;
$q'(i)$:	number of cycle–trains of work order i (see eqn.(8.9) and eqn.(8.13)).

Then, an estimate of the output rate for order i per working day is:

$$\hat{\mu}_{day}(i) = \hat{\mu}(i,M)c_{day}(M) + \hat{\mu}(i,U)c_{day}(U) \qquad (8.15)$$

where:
$c_{day}(m)$: available capacity in production mode m per working day.

Consequently, an estimate of the internal flow time of a work order i is:

$$\hat{t}_{int}(i) = \hat{q}'(i) \;/\; \hat{\mu}_{day}(i)$$

In case all operations can be regarded as unattended operations, clearly the expected external waiting time will be the same for all work orders. In other words, we can use one estimate for the external waiting time for all work orders (expressed in working days). This estimate can be obtained in a similar way as described for the manned and unmanned production mode. In consequence, an estimator for the order flow time in this hypothetical situation is (expressed in working days):

$$\hat{t}(i) = \hat{w}_{ext} + ([q(i)/f(i)]_{int}+p(i)-1) \; / \; \hat{\mu}_{day}(i) \qquad (8.16)$$

8.4.6 Conclusion

In this paragraph we have introduced a flow time estimator to be applied in real life situations for estimating flow times of orders on FAM-Stations with unattended operations. The estimator distinguishes external waiting times from internal flow times, and clearly shows the dependency of the internal flow time on the order cycle-size and the length of an unmanned shift. The internal flow time is independent of the cycle operation time. Furthermore, clearly the estimator in case of unmanned production differs from the estimator in case of manned production. In most cases, the flow time estimate provided by the estimator is quite accurate. A further improvement of the estimation quality may be obtained if a more detailed approach is applied. However, such an approach is likely to create a more complex estimator.

Chapter 9
PRODUCTION CONTROL FUNCTIONS IN CASE OF FAM-STATIONS

In the previous chapters, we have discussed in detail the capacity and flow time aspects of FAM-Stations. In this chapter we will apply the results obtained in these chapters in order to determine for each relevant production control function in the framework presented in §4.1.2, the implication(s) of producing on a FAM-Station.
Successively we will discuss the Goods Flow Control function, the Order Release function, and the Production Unit Control function. Fig.9.1 gives the complete production control structure in case of FAM-Stations (see also §4.1.2). In every paragraph, each of the production control functions will be introduced briefly, based on their description in §2.3.

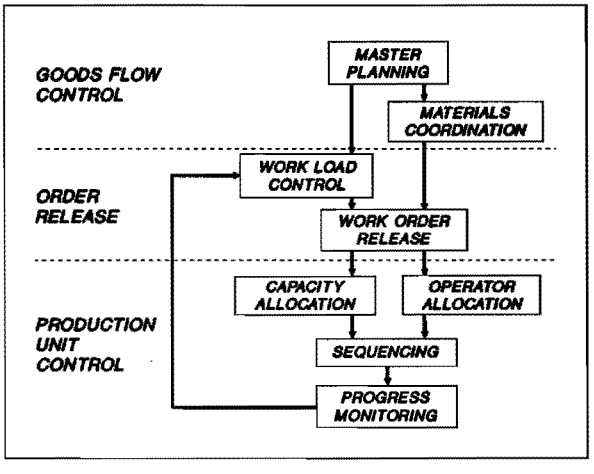

Figure 9.1:
Overview of production control functions in case of FAM-Stations.

9.1 Goods Flow Control

In the first subsection of this paragraph we will re-introduce the Goods Flow Control functions. In the second subsection we will discuss the consequences of the distinctions in operation mode (attended or unattended) and in production modes (manned or unmanned) for Goods Flow Control.

9.1.1 Introduction

In §2.3.2 we have described the Goods Flow Control problem as how to realize for each Production Unit the agreed environmental conditions, while at the same time the overall production control objectives should be achieved. Goods Flow Control can be decomposed into two control functions, i.e. Master Planning and Materials Coordination. Master Planning is concerned with aggregate capacity decisions. Materials Coordination initiates and coordinates the goods flow between the Production Units. Fig.9.2 gives the Goods Flow Control functions as part of all production control functions required in case of FAM-Stations.

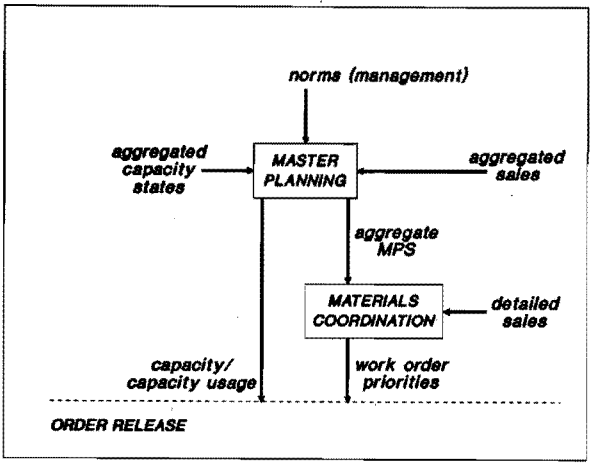

Figure 9.2:
Goods Flow Control functions.

9.1.2 Operation mode and Production mode

In Fig.4.2 the relationship between the operation mode and the production mode has been shown. As we have seen, one of the potential benefits of FAM-Stations is volume flexibility. This flexibility is obtained by the possibility of an unmanned shift. If the work load at a certain moment at the FAM-Station is high, and all operations can be regarded as unattended operations, the unmanned shift can be used to increase the capacity of the station. The time required to organize for this increase in capacity is negligible, since no overtime of operators is required. In such a case, the unmanned shift merely is an extension of the manned capacity. There is no reason for Goods Flow Control to distinguish explicitly the two different production modes.
However, in Chapter 5 we have seen that the distinction between manned and unmanned production indeed is important, especially in case many operations should be regarded as attended operations. In such a case, the volume flexibility should come from the unattended operations, since only these operations can be performed during the unmanned shift. If the capacity of the manned production mode is highly utilized by attended operations, there is only limited flexibility left for the unattended operations. In such a case, all unattended operations should be performed in the unmanned production mode. As a result, it is required for Goods Flow Control to consider the distinction between the manned and the total capacity of the FAM-Station (see e.g. eqn.(5.1) and (5.2) in §5.2).
On top of that, a distinction in production modes and operation modes is required to make it possible for Goods Flow Control to apply the flow time estimators introduced in Chapter 8. Similar to the registration of expected waiting times for conventional work stations, it becomes possible to register distinct expected external waiting times for the manned resp. unmanned capacity mode. Also, with such a distinction in production mode, for the unmanned capacity mode the length of one unmanned shift can be denoted, while for the manned capacity mode an estimate of the cycle-train waiting time can be denoted (see §8.3.4). Based on the operation modes, these data can be used to estimate the flow times of work orders.
Sometimes it is not possible for a firm to use the flow time estimators given in the previous chapter, given the existing information systems in the firm. Especially the cycle-size dependent internal waiting time requires an adaptation of the existing flow time estimator(s). One way of avoiding a required (and possibly expensive) change in these information systems is to limit the differences in flow time effects between the work orders. This can be achieved in two ways, viz.:

- limiting the flow time effects for all work orders by increasing the number of identical product set-ups (clearly this possibility of limiting the flow time effects requires a possibly high investment in positioning tools);
- limiting the differences in flow time effects between work orders by creating more or less equal cycle-sizes; in this case it is possible to regard the sum of the external waiting time and the order internal waiting time as one waiting time estimate, comparable to the waiting time estimate at conventional work stations.

9.2 Order Release

The second set of production control functions lie at the interface between Goods Flow Control (see previous paragraph) and Production Unit Control (to be discussed in §9.3). In the first subsection of this paragraph we will describe briefly these so-called Order Release functions. In the next two subsections (§9.2.2 and §9.2.3) the impact of FAM-Stations on each of the two Order Release functions will be discussed.

9.2.1 Introduction

In Fig.9.3 we see that the Order Release level of the production control structure can be split up into two control functions, viz. Work Load Control and Work Order Release.

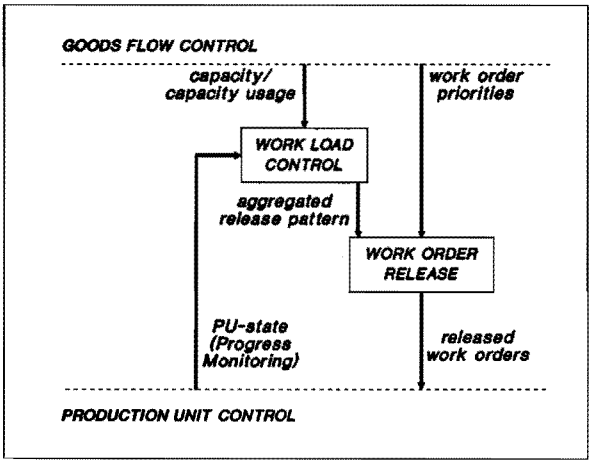

Figure 9.3:
Order Release functions.

Work Load Control determines the aggregate work order release patterns or opportunities. As we recall from §2.3.2, by controlling the work load in a Production Unit, the average flow times of work orders in the Production Unit are controlled also. Based on the work load information given by Work Load Control, and on the order priorities set by Material Coordination, the Work Order Release function releases work orders to the Production Unit.

9.2.2 Work Load Control

From Master Planning the Work Load Control function receives information on the capacity utilization norms (translated into work load norms, see [Bertrand and Wortmann, 1981]). From the PU, information is required on the actual remaining work load. This remaining work load information is based on the actual progress of all work orders in the shop. Usually only the time at which a work order has been taken into operation, and the operation completion time are recorded. Consequently, during the operation time the *real* remaining work load of the order on the server considered diminishes gradually in time, while the *registered* remaining work load of the order is being reduced only after the operation (see Fig.9.4).

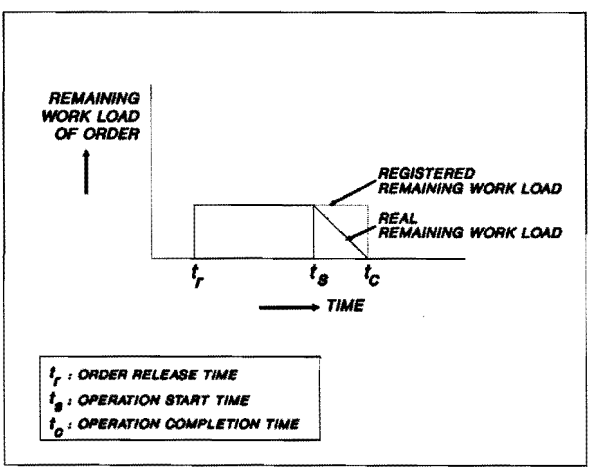

Figure 9.4:
Registered versus real remaining work load per order in case of order progress monitoring based on operation start date and completion date.

Sequential case
In case orders are taken in operation sequentially, an expression for the average difference between real and registered work load per machine can be obtained as follows.
Let us assume that all orders belonging to the same class (say class i) have the same operation time ($O(i)$). Let $p(\underline{i}=i)$ be the probability that an order belongs to class i. Furthermore, let $E(\underline{O})$ be the expected operation time of an arbitrary order. In other words:

$$E(\underline{O}) = \Sigma_i \; p(\underline{i}=i)O(i)$$

Let $\lambda(i)$ be the average arrival rate at the machine of orders of class i. Using Little's result (see e.g. [Kleinrock, 1976]), we know that the expected number of orders in operation belonging to class i is:

$$E(\underline{n}_{op}(i)) = \lambda(i)O(i)$$

Let λ be the average arrival rate of an arbitrary order at the machine. We know that:

$$\lambda(i) = p(\underline{i}=i)\lambda,$$

and also:

$$\lambda = \rho/E(\underline{O})$$

where:
ρ: the utilization rate of the machine.

Combining these expressions, we get:

$$E(\underline{n}_{op}(i)) = \rho p(\underline{i}=i)O(i)/E(\underline{O}) \qquad (9.1)$$

During the operation of an order of class i, the average difference between real and registered remaining work load of the machine is $O(i)/2$. The average difference between real and registered work load can now be obtained as follows:

$$E(\underline{d}_{seq}) = \Sigma_i\ E(\underline{n}_{op}(i))(O(i)/2)$$

In other words:

$$E(\underline{d}_{seq}) = \rho E(\underline{O}^2)/2E(\underline{O}) \qquad (9.2)$$

In case of a constant order operation time (i.e. $O(i)=E(\underline{O})\ \forall i$), we know that $E(\underline{O}^2)=E(\underline{O})^2$, thus $E(\underline{d}_{seq})=\rho E(\underline{O})/2$. In case of negative exponentially distributed operation times (in which case $E(\underline{O}^2)=2E(\underline{O})^2$), we get $E(\underline{d}_{seq})=\rho E(\underline{O})$.

In any case, we know that the maximum difference between registered and real work load is:

$$Max(\underline{d}_{seq}) = Max_i(O(i))$$

However, usually the number of work orders that already are released to the shop and still require an operation on a bottleneck server (denoted as '$\underline{r}$'), is large. Therefore, the expected difference between real and registered remaining work load is relatively small compared to the registered total work load for a server, viz.:

$$E(\underline{d}_{seq,rel}) = [\rho E(\underline{O}^2)/2E(\underline{O})] \;/\; [E(\underline{r})E(\underline{O})] =$$

$$= [\rho/2E(\underline{r})][E(\underline{O}^2)/E(\underline{O})^2] \qquad (9.3)$$

For instance, in case of an utilization rate of 0.9, negative exponentially distributed operation times, and $E(\underline{r}) = 20$, the expected relative difference between registered and real remaining work load is less than 5%. Combining this fact with the inaccuracy of the data used, in most real situations this difference is negligible.

Simultaneous case, manned production

In case several orders may be in operation simultaneously, as in the case of a FAM-Station, the difference between registered and real remaining work load will grow. We will show this in detail for the manned production mode.

Let us assume that all orders of class i have an operation time of $O(i)$ and require $q'(i)$ cycle-trains ($\underline{O}$ and $\underline{q}'$ are independent). Furthermore, let us assume that the expected cycle-train waiting time is the same for all classes, viz. $E(\underline{w}_{tr})$ (see also §8.3.4). Then we know that the expected internal flow time of an order of class i will be:

$$E(t_{int(i)}) = q'(i)E(\underline{w}_{tr}) + O(i) \qquad (9.4)$$

Again applying Little's result, we obtain for the average number of orders of class i in operation at the FAM-Station:

$$E(\underline{n}_{op(i)}) = \rho(M)p(\underline{i}=i)E(t_{int(i)})/E(\underline{O}) \qquad (9.5)$$

where:

$\rho(M)$: the utilization rate of the FAM-Station in manned shifts

Again, during the operation of an order of class i, the average difference between real and registered remaining work load of the order at the machine is $O(i)/2$. The average difference between real and registered work load of the FAM-Station can now be obtained as follows:

$$E(\underline{d}_{sim}) = \Sigma_i \; E(\underline{n}_{op(i)})(O(i)/2)$$

In other words:

$$E(\underline{d}_{sim}) = \frac{\rho(M)}{2}(E(\underline{q}')E(\underline{w}_{tr}) + E(\underline{Q}^2)/E(\underline{Q})) \qquad (9.6)$$

As we can see, the difference between registered and real remaining work load in the simultaneous case is $\rho E(\underline{q}')E(\underline{w}_{tr})/2$ larger than in the sequential case (assuming that $\rho=\rho(M)$). Especially in case of a large number of cycle-trains and a large number of orders in operation simultaneously, this difference may get large.
Even more striking is the maximum difference between registered and real work load. The upper limit of the maximum difference can be expressed as follows:

$$Max(\underline{d}_{sim}) = N \times Max_i(O(i))$$

where:
N: the number of pallets on the FAM-Station

Simultaneous case, unmanned production
In case all orders are completed in the unmanned production mode, the expected internal flow time of an order of class i will be (cf. eqn.(8.13) in §8.4.4):

$$E(t_{int}(i)) = q'(i)T \qquad (9.7)$$

where:
T: length in time of one unmanned shift

Then, clearly the average number of orders of class i in operation is:

$$E(\underline{n}_{op}(i)) = \rho(U)p(\underline{i}=i)q'(i)T/E(\underline{Q}) \qquad (9.8)$$

where:
$\rho(U)$: the utilization rate in unmanned shifts.

In other words, in this case:

$$E(\underline{d}_{sim}) = \rho(U)TE(\underline{q}')/2 \qquad (9.9)$$

Again, especially in case of a large number of cycle-trains and long unmanned shifts, this difference can get quite large. Also in this unmanned case, the upper limit of the maximum difference between registered and real work load can be expressed as:

$$Max(\underline{d}_{sim}) = N \times Max_i(O(i))$$

Conclusion
We conclude that in many cases adjusting the registered work load of a work order after the completion of the operation on the entire work order will not be sufficient anymore. Therefore, in these cases it is required to adjust the registered work load of a work order in operation more frequently. In real life situations, usually a simple solution can be found in order to register the remaining work load more accurately. All that is required is a registration from time to time (e.g. once a day) of the number of cycles already completed. Using the calculated operation time norms, this number can easily be translated into work load information.

9.2.3 Work Order Release

As we recall, the Work Order Release function releases individual work orders to a Production Unit. As we will see, the important characteristics of work orders with operations on a FAM-Station are not only the work load of the orders, but also the operation mode. Also, for this control function it should be clear which set of processing activities on the FAM-Station will be called an operation.

Operation modes
In Chapter 5, we noticed that the normative capacity and the capacity constraints of FAM-Stations differ for the two production modes. Also, we noticed that not all operations of work orders can be performed in both production modes. Consequently, when releasing work orders, such a distinction between manned and unmanned capacity is required also. In other words, the Work Order Release function has to make a distinction in the work load of both production modes, and a distinction between the operation modes of the work orders.
On top of that, usually, with the release of work orders, also flow time estimates are required, for instance to determine the planned operation start dates. Similar to Goods Flow Control, it should be possible for Work Order Release to apply both the estimator for manned production and the estimator for unmanned production.

Operations
The flow time estimators presented in Chapter 8, are based on the assumption that all processing activities on a part on the FAM-Station are regarded as one operation. However, as we have seen in Chapter 4, it also is possible to regard all processing activities of one single type of product set-up as one operation. In such a case, if $p(i)$ product set-up types are required to complete a part, also $p(i)$ operations will be distinguished in the process plan. Consequently, we need $p(i)$ flow time estimates instead of one. Clearly, for each of these estimates we may assume that the number of set-up types required for the operation is equal to one.
One of the advantages of defining separate operations for the product set-up types is, that it is possible to differ the operation mode for each type of product set-up. For instance, a simple milling operation can be performed during the unmanned shift, while more complicated milling operations are performed during the manned shifts. Also, it becomes possible to perform the operation in one or more product set-up types on work stations other than the FAM-Station, for instance because these other work stations are idle. For example, in the MF-Case (§1.3.2), sometimes it

was possible to perform operations both on the FAM-Stations and on two other Machining Centres. On top of that, it no longer is required to make the general assumption that the product set-ups of the different types required for a particular work order, are mounted on pallets more or less simultaneously. In fact, it becomes possible to apply the operation overlapping techniques already available in many software packages. In these packages it often is possible to adjust the amount of overlap between two subsequent operations for each individual work order (see also §2.1, Fig.2.6). Finally, the short term planning of the tools preparation activities usually is based on the information on the progress of a work order in operation. Defining a separate operation for each product set-up type makes it possible to monitor the progress of the work order in more detail. As a result, first of all it becomes possible to determine the required availability of tools for the next product set-up type(s) of the work order more accurately. Instead of assuming that all tools have to be available at the time the work order is taken into operation, the priorities between the tools become clear. On top of that, it becomes possible to anticipate with tool preparations on the start of the first operation of a next work order.

9.3 Production Unit Control

In subsection §9.3.1 we will re-introduce the basic task of Production Unit Control and the production control functions required to perform this task in case of FAM-Stations (based on the discussion in §4.1.2). In the next subsections of this paragraph we will discuss successively each of these control functions.

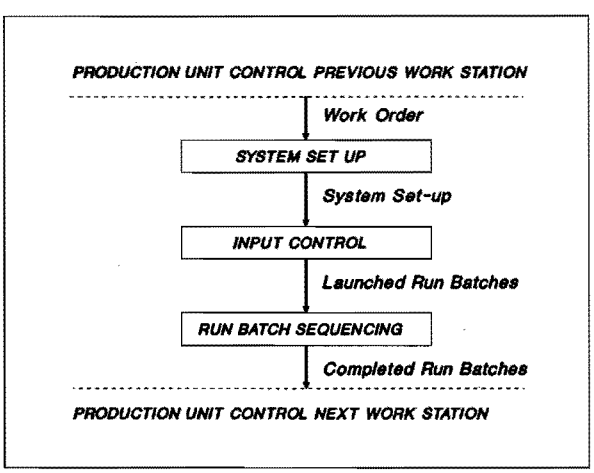

Figure 9.5:
Production Unit Control functions.

9.3.1 Introduction

Given the set of released work orders in a Production Unit, the sequence in which the orders should be taken into operation should be determined. It is the task of Production Unit Control (PUC) to control the progress of work orders through the Production Unit in such a way that the delivery performance of the Production Unit is according to the norms (see §2.3.3). In §4.1.2 we noticed that the PUC functions required in case of FAM–Stations are somewhat different compared to more conventional work stations. These PUC functions for FAM–Stations are given in Fig.9.5.

9.3.2 System Set–up

On of the major benefits of FAM–Stations is the reduction of machine set–up time. Most preparation activities can be performed before the processing activities on the machine start. As long as at least one run batch is loaded on a pallet and the required cutting tools are loaded in the tool magazine, the machine will not get idle.
The set–up of the FAM–Station can be changed either by the loading of tools, or by the unloading of tools.

Loading tools
In the simulation experiments described in the previous chapters we have assumed the following priorities of activities at the mounting/loading place:
1. Unloading of cycles;
2. (Re–)loading of cycles;
3. Mounting of pallet set–ups;
4. Dismounting of pallet set–ups.

Furthermore, once a pallet set–up is mounted on a pallet, we assumed that this set–up remained mounted until it no longer was required for cycles of the work order.
In other words, the highest priority is given to loading and unloading activities within a particular system set–up. With these priority settings we achieve that:
- the machine tools stay idle as short as possible;
- the flow time effects of the simultaneous production of work orders are limited, since the number of work orders in operation is limited;
- the required operator capacity is minimized, since each product set–up is mounted only once; as a result the operators are more likely to be able to perform all operator activities required;
- the required machine capacity is minimized by the fact that for each product set–up only once set–up capacity is required;
- once the required position accuracy is achieved, there will be no changes in the set–up that might deteriorate this accuracy.

From Chapter 6 we know that the flow time effects of the simultaneous production of work orders in the manned production mode can be influenced by the set of pallet set–ups loaded on the FAM–Station. In case several identical product set–ups can be mounted on pallets concurrently, the flow time effects will be reduced as compared to the case where only one product set–up is mounted for each set–up type. If possible, during manned production these product set–ups should not be combined on one

pallet. In that case, the flow time effects may disappear completely since it no longer is necessary to have more than one order in operation to keep the machine running. In case more types of product set-ups are required to complete a part in the manned production mode, these product set-up types should also be distributed over several pallets. Again, such a set-up policy will reduce the number of orders that should be in operation simultaneously in order to prevent the machine from getting idle.
The other pallets on the FAM-Station, which are not being used during the manned shifts, can be prepared for the unmanned shift. Combining several product set-ups in one pallet set-up usually is an advantageous strategy for the unmanned production mode, because this increases the work load on one pallet and thus the work load that can be loaded on the system at the beginning of the unmanned shift. Given the cycle-size of an order and the number of product set-up types required to complete the product, the flow time of an order completed in the unmanned production mode can be reduced either by changing the system set-up more frequently (i.e. dividing the unmanned shift into two or more unmanned shifts by increasing the number of change-over periods), or by increasing the possible number of identical product set-ups. The first option will be less expensive if the operators also are required for the attendance of other work stations during the unmanned shift.

Unloading tools
After the completion of a work order, the (cutting) tools required for this order can be unloaded and even dismounted. Sometimes it is possible to reduce the preparation time for an operation by taking advantage of the similarity in tools required. At conventional work stations this is usually achieved by adapting the sequence in which orders are taken into operation. At FAM-Stations it also is possible to achieve some of this advantage with the unloading and dismounting of tools. If the FAM-Station operator has information on the orders that will arrive at the station in the near future, he can choose to remove those tools that are not required by these orders. In principal this would mean that for each individual tool the information system should give information on its possible future use. However, as we have seen in §4.1.2, the overlap in tools required by different products in low volume component manufacturing can be very limited. Therefore, in those cases it is sufficient to have insight in the short term future demand for the same part type. The entire set of tools required for the processing of the part type can thus be regarded as having the same priority. In the example case of this study, an exception was made for a small set of cutting tools. The tools belonging to this set were used in most NC-programs, and thus were kept in the tool magazine as long as possible.

9.3.3 Input Control

In Chapter 4 we concluded that in case non-launched run batches are stored on the FAM-Station, it should be possible either to withdraw pallets located on the system from the automatic control system, or to give the pallets a special status. Otherwise the control system will regard these pallets as pallets containing run batches that are competing for machine capacity (see §4.1.2).
With such a possibility, decisions on the system set-up can be distinguished from the decisions on the launching of run batches. Consequently, it is

possible for instance to prepare during the manned shift the pallets for the unmanned shift. In the cases we have studied, this was achieved by:
- unloading pallets from the FAM-Station and storing them elsewhere (i.c. in a special preparation area). This possibility may create an extra position inaccuracy, viz. the position of the pallet itself.
- sequencing operations on the system by the operator instead of using the automatic control system. However, this way of sequencing requires the presence of the operator at least on the moment a machine tool has completed all processing activities of a run batch.
- registering a pallet as 'empty' after the the pallet has been (re-)loaded. As a result, the FAM-Station control system will treat these pallets as if they were empty.

In Chapter 6 we noticed that for the manned production mode about three pallets are sufficient to keep the machine going, while at the same time the flow time effects of the simultaneous operation of work orders are limited. With three pallets it should be possible for the operator to unload and re-load a run batch, while the machine is processing a second run batch, and a third run batch is waiting at the machine.
In case most manned production capacity is required for attended operations, attended operations should be given the highest priority during the manned shifts. As a result, an unattended operation performed during manned shifts will be an exception.
For the unmanned production mode, we have to launch as much run batches as possible, that is, as long as the work load on the pallets does not exceed the machine capacity during an unmanned shift. Of course, only run batches with unattended operations should be launched.

9.3.4 Run Batch Sequencing

The criteria to be used in the decision on the sequence of operation of the launched run batches are different for the manned and the unmanned production mode.

Manned production
In the manned production mode, usually a FCFS-priority will be applicable. Sometimes a higher priority should be given to operations in a particular type of product set-up. By doing so, a difference in production rate between product set-up types of one order will be compensated. This is illustrated in Fig.9.6. In the example there is only one product set-up available for the first product set-up type. Since for the second type of product set-up two identical product set-ups can be mounted at the same time on different pallets, the possible production rate of this second product set-up type is twice as high as the production rate of the first set-up type. If all loaded run batches are given equal priorities (FCFS), the pallet containing the second product set-up of the second set-up type is not really required. In the example, as a result, pallets containing cycles of other work orders will be taken into operation in order to prevent the spindle from getting idle. In other words, only one of the two product set-ups of the second type is required in order to maintain the production rate. However, by increasing the priority of the operation in the first set-up, the production rate of this set-up type is increased with a factor two. Consequently, in such a case both the product set-ups of the second type are required to maintain the (higher) production rate.

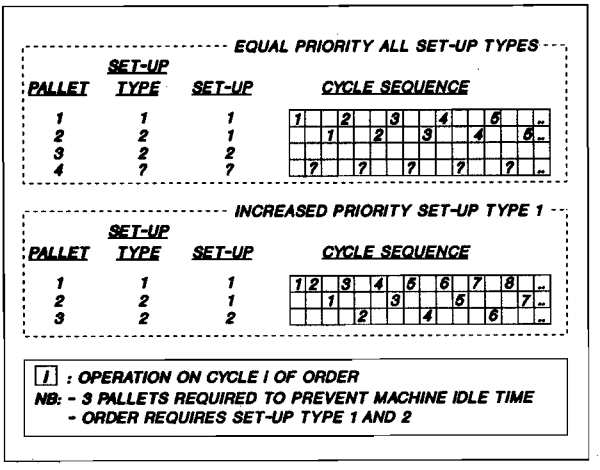

Figure 9.6:
Example of effect of increasing the priority of an operation on the production rate.

Another reason to differentiate the priorities of run batch operations may be a required reduction in internal flow time of a particular order. An example of such an order can be a rush order. Another example may be an order with a large cycle–size. Increasing the priority of such an order will have a similar effect as decreasing the cycle–size of the order by increasing the number of parts loaded on one pallet (see §6.6.1). However, as in the case of conventional work stations, reducing the internal flow time of one order will increase the (internal) flow time of the other work orders. Therefore, the use of increased priorities for rush orders should be limited.

Unmanned production

In the unmanned shift the sequence in which the operations are performed, is irrelevant for the cycle flow time: independent of this sequence, all cycles will have an internal flow time of exactly one shift. However, usually some operations have a higher processing risk than others. Depending on the automatic control system and the NC–programs, a processing problem during the unmanned shift may:

- prevent the present operation from being completed; however, other operations on other run batches can still be performed;
- prevent all operations requiring the particular cutting tool that caused the problem, from being completed;
- cause a major problem and thus a system break–down.

Especially this last possible consequence of processing problems will cause a major loss in machine capacity. In order to prevent this from happening, the run batch with the least probability of the occurrence of these problems should be taken in operation first.

9.4 Conclusions

From the above discussion, we conclude that:
- it should be possible for almost all production control functions to make a distinction in production mode and operation mode;
- based on the distinctions just mentioned, it should be possible to use different flow time estimators for attended and unattended operations;
- the number of orders simultaneously in operation during the manned shift(s) should be limited in order to limit the negative flow time effects; usually this will mean that the number of run batches launched to the FAM-Station is kept low;
- the aim for the unmanned shift should be the full use of the machine capacity as long as work is available; usually this will result in the launching of many run batches, and, due to the limitation in the number of concurrent identical product set-ups, in a large number of work orders simultaneously in operation;
- in the manned production mode work load should be spread out over several pallets (for as long as mounting and loading times remain negligible), whereas in the unmanned production mode the work load of one pallet should be as high as possible;
- the priorities between run batches in the unmanned shift should be based on processing risks, whereas during the manned shift(s) the priorities should be set such that the machine will not get idle unnecessary and that all production rates of the product set-up types required for a work order are equal.

Chapter 10
ORGANIZING FOR FAM-STATIONS

As we know from previous studies, the efficient and effective use of FAMSs usually requires several changes in the organization (see e.g. [Hartley, 1984], [Krabbendam, 1988], [Meredith, 1989]). In Chapter 9 we have concentrated on the changes required for the production control functions. In this chapter we will extend our view and discuss some important implications of the use of FAM-Stations for other functions in a production organization. We will especially focus on the impact of the changes in order flow time behaviour, capacity characteristics, and production control problems on these other functions.
The functions considered in this chapter are:
- Production, i.e. the function that performs the actual transformations required;
- Tool Management, i.e. the function that is responsible for the management of all tools required in the manufacturing process (in particular cutting tools and positioning tools);
- Process Planning, i.e. the function that determines the process plans;
- Economics, i.e. the function that determines the costs of production and the prices of parts;
- General Management, i.e. the function that sets the targets and norms for each of the functions mentioned above, and determines the strategy of the organization.

In the paragraphs of this chapter we will discuss consecutively each of these functions.

10.1 Production

In this paragraph we will discuss the sequencing decisions (§10.1.1) and the necessity for a change in measuring operator performance (§10.1.2).

10.1.1 Sequencing

At most conventional work stations, the sequencing decision is a single-level decision. Once this decision is made, the system is set up for the order chosen, the product set-up required to perform the operation is mounted on the machine tool, and all parts belonging to the order are one by one loaded and processed. In case the set-up time required for a particular work order is independent of the sequence in which the orders are taken

into operation, the operator usually requires little freedom of choice. The priorities set by Production Unit Control (e.g. Operation Start or Due Dates) are sufficient for the operator to determine the work order to be taken into operation next. In many organizations, this results into the actual sequencing decisions being made by a centralized Production Control department within the Production Unit.
The decision on the sequence of work orders at FAM-Station is more complicated and often is hierarchical in nature. In our study we have distinguished three sequencing decisions, viz. the system set-up decision, the decision on the launching of run batches, and the sequence of taking launched run batches into operation. Apart from the considerations given in the previous chapter, these decisions also are highly influenced by technical considerations, and by the actual situation at the FAM-Station. This makes it impossible for a central Production Control department to determine exactly the work order sequence. Therefore, many of these decisions should be made by the FAM-Station operator or the foreman. For instance, in the MF-Case we noticed that the system set-up decision was made by the operators in the preparation area. In other words, the relation between the official Production Control department and the Production department changes. More actual production control decisions than before are made by Production, while Production Control merely determines delivery priorities instead of actual sequences.

10.1.2 Performance

The production rate of a FAM-Station is far less dependent on the activities of the operator than the production rate of conventional work stations. In other words, the operator has more freedom to determine his own work schedule. Also, for these kind of manufacturing systems, optimizing the production rate for each operator individually is very likely to be sub-optimal for the overall production rate. For instance, at the changing of shifts it is more important to have enough pallets loaded with cycles than to have completed a work order at the cost of all pallets being empty (especially at the start of an unmanned shift). On top of that, in case of strict individual performance measuring there is no necessity for a smooth change of shifts. In fact, shifting problems to the next shift will be an advantageous strategy. Due to the simultaneous production of orders, not only work orders will be in operation for a longer time (and thus also in more shifts), but also it will be easier to postpone the operation of a particular order without too much loss of machine capacity due to set-up activities. Finally, it is difficult for Production Control to determine whether the decisions made by the operator on the sequencing of work orders are right, since insight in the actual situation at the FAM-Station is required to do so. Consequently, instead of measuring individual operator performance, it is required to measure the overall FAM-Station performance.

10.2 Tool Management

With the use of FAM-Stations, often the number of tools available at the work station increases. The main reason for this fact is, that the number of orders simultaneously in operation increases. As a result, both the number of positioning tools and the number of cutting tools present at and on the work station will increase.
In the past, information on the work order priorities and the starting date of the order in operation was sufficient for Tool Management to determine which and when new tools should be prepared for production. Usually, the decision on the operation sequence of work orders also determined the sequence of loading and unloading of tools. Unloading tools meant unloading all tools (unless the next work order required the tool also). With the simultaneous production of work orders this is not the case anymore.
First of all, tools may be required for more than one work order at the same time. Therefore, some of the tools used for the operation of a particular work order that is just completed, may not be unloaded yet. This requires an adequate registration of the set of tools loaded on the system and required for the work orders in operation. For instance, in the MF-Case, a terminal connection with a computer was available in the preparation area for this 'local' tool management.
Secondly, since often more tools can be loaded on the system than actually are required for the work orders in operation, there is some decision freedom on whether tools should be unloaded or not, and if so, which tools. Keeping tools loaded on the system even though they are not required for the processing of the work orders in operation, may first of all reduce the preparation time in the near future (and thus reduce the operator capacity required). Also, especially in case of pallets and positioning tools, unloading tools may create a position inaccuracy once they are to be re-loaded. Usually gauging the exact position of these tools requires machine set-up time. In other words, keeping the right tools loaded may reduce the required operator and machine capacity. This requires not only knowledge on the effort of achieving the required tool accuracy, but also information on the near future, viz. which of the loaded tools are needed again soon. The level of detail required for this information depends on the overlap in sets of tools required for the processing of different parts. As we mentioned in §9.3.2, in case of a small overlap (e.g. the example given in Fig.4.8, §4.1.2), keeping a small group of standard tools loaded on the system may be sufficient. The information on the need for tools in the near future can be limited to information on the future arrival of work orders for the same part type the tools have been used for. As we know from other cases, only a small overlap in tools is not uncommon in low volume manufacturing.
Finally, sometimes tools are not dismounted once they have been unloaded. Both in case of cutting tools and in case of positioning tools mounted on pallets, keeping the tools mounted may reduce possible future accuracy problems and set-up time. However, not dismounting tools after they have been unloaded from the FAM-Station will create tool storage and registration problems. Usually, the non-automated central tool magazine of the machining department is not equipped to store mounted tools. In the example case some of these tools were stored in the preparation area. Also, if the tool measures are known only after the first part is processed, there is no guarantee that the same measures will be valid for other processes on other parts. Therefore, in these cases it is required to register for each

tool that is unloaded and stored, but not yet dismounted, the part type for which the tool has been used, and the tool offset values. Nowadays cutting tools are available with tool holders equipped with chips to store this kind of information, although these tools still are very expensive.

10.3 Process Planning

As we will see, Process Planning will be affected by the use of FAM-Stations. We first discuss briefly the change in the nature of process planning due to flexibly automated machinery equipment. The specific consequences of using FAM-Stations are discussed afterwards. As we will see, it is required for Process Planning to be aware of the distinction between attended and unattended operations. Also, the results mentioned in Chapter 6 and Chapter 7 impose some new guidelines for Process Planning, both concerning the design of product set-ups and concerning the choice of (cutting) tools.

10.3.1 Nature of process planning

With the introduction of flexibly automated machinery equipment, the nature of process planning changes. Since more transformations in the manufacturing process are controlled by automated controlling units, the process has to be planned more accurately and in more detail. Also, as we have seen in Chapter 4, in order to gain as much as possible from the flexibility of the FAM-Station, it is required to avoid other operations on non-flexible work stations. Often also the original organization structure of Process Planning changes, introducing a special programming department. Notice however that most of these changes already are required in case of other flexibly automated machines, like a Manufacturing Centre with or without an Automatic Part Changer (see the typology in §3.3.1). Therefore, in many cases a FAM-Station is regarded as 'just' one of the NC-machine tools.

10.3.2 Operation mode

In this study, we noticed that the set of operations to be performed by FAM-Stations should be split up into a subset of attended operations and a subset of unattended operations. It is the task of Process Planning to determine whether a particular operation should be regarded as an attended operation or as an unattended operation, and to take all precautions required for unattended operation.
In the example case of this study (the MF-Case), no detailed analysis had been carried out to determine whether certain operations could be performed unattended, even though several hours of unmanned production per day was assumed to be possible by Management. Since all operations

implicitly were regarded as attended operations (as was the case for all other machine tools), it was not required to optimize the NC-programs. As a result, hardly any operation could be performed unattended. However, an analysis of the NC-programs showed that several operations indeed could be performed unattended if some alterations were made in the programs. For instance, the sequence of drilling and milling operations had to be changed in order to prevent a milling tool from running into a broken drill that is stuck into a hole. In the discussion on the possibility of performing operations unattended, the operators mentioned some part-specific problems that were unknown to the Process Planning department.
Based on the explicit distinction in operation mode, and based on the distinction between manned and unmanned production mode, it is possible to determine the need for more detailed studies in order to transform an attended operation into an unattended operation. Of course, ideally all operations should be performed unattended. However, in low volume manufacturing it usually is not possible to optimize all operations. Therefore, those operations should be prepared for unattended production that:
- do not require a lot of effort to be prepared for unattended production at a low risk;
- are likely to be performed frequently in future;
- have favourable characteristics for unmanned production, viz. long cycle operation times through long part operation times and/or product set-ups containing many parts.

10.3.3 Product set-ups

Apart from the distinction in operation and production mode, Process Planning also should be aware of flow time consequences of a particular design of product set-up types and pallet set-up types. As we concluded in §9.3.2, some of these consequences will be different for the two distinct production modes. To summarize:
- in case of manned production, product set-ups should be mounted on different pallets, whereas in case of unmanned production combining product set-ups on one pallet will be an advantageous strategy;
- increasing the number of parts belonging to one cycle reduces the flow time both in unmanned and in manned shifts;
- (artificially) increasing the number of product set-up types in the manned production mode will reduce the flow time of work orders with large cycle-sizes in case of a small number of pallets, while in the unmanned production mode such a strategy will increase the flow time at all times;
- increasing the number of identical product set-ups reduces the flow time both in the manned shifts and in the unmanned shift.

10.3.4 Tools

Finally, as we have seen, many of the production control problems in case of FAM-Stations are caused by a limitation in the availability of identical tools (especially positioning tools). Therefore, most of these problems will disappear if more identical tools are available. This can be achieved either

by increasing the number of tools specially used for a particular part type, or by increasing the commonality of tools. The first possibility can be rather expensive, especially for low volume manufacturing. Consequently, if possible, emphasis by Process Planning on the commonality of tools is required.

10.4 Economics

Usually, in low volume manufacturing the fixed (machine- and operator-) costs are assigned to work stations as a fixed cost rate for one hour production. In the MF-Case this cost rate was used by the Process Planning department to select work stations for performing certain operations, and to determine the cost price of the product. We remark that in the cost rate many non-variable costs are included. Therefore, the cost rate is not a good criterion for a short term decision, such as the choice of capacity resources to perform an operation. For a more extensive discussion on the use of cost rates, we refer to [Muntslag and Ribbers, 1989]. In this discussion, we will accept the use of the cost rate in these decisions, since in most production organizations this is common practice.
If no distinction is made between manned and unmanned production, it also will not be possible to distinguish the cost rates for attended and unattended operations. As a result, the products requiring unattended operations will have the same cost rate as product requiring attended operations. The cost rate for attended operations can be rather high, especially if also the preparation costs (programming department, inspection department) are included. However, in the MF-Case these operations were very complex and accurate and hardly any alternative was available. Therefore, a high cost rate was not really a problem. Unattended production is only possible for less complex parts. These parts do not require as much attention of the operator and of other departments as the parts with attended operations. Usually these parts can also be produced on other capacity resources with lower cost rates. Therefore, if one cost rate is used for both manned and unmanned production, the Process Planning department will always choose these 'cheaper' other capacity resources to perform the required operations. As a result, the utilization of the unmanned shift will be (and in the case indeed was) low. Also, it will not be possible for an operator to attend other machines (unless in case of a multiple FAM-Station), since only attended operations are performed on the FAM-Station. With the introduction of the distinction in attended and unattended operations, it becomes possible to use different cost rates for these two operation modes. Clearly, unattended operations will have a lower cost rate, first of all because the operator costs will be lower, but also because the capacity required from other departments will be lower.

10.5 General Management

The investment required for FAM-Stations is high. A single FAM-Station may cost as much as DFl. 1,500,000.=, or even more, of which only less than half is required for the machine tool. The extra costs of an automated pallet buffer, including the required investment in the extension of the tool magazine, the software, and the number of tools, can be equal or even higher than the costs of the machine tool. This makes it necessary for Management to analyze the performance of the FAM-Station, compared to for instance a Manufacturing Centre with an Automatic Part Changer (see §3.3.1).
Frequently, the pallet buffer is used to store several pallet set-ups required for manned production. However, the major benefit of such a pallet buffer is the possibility to produce for several hours in an unmanned production mode. Production Control together with Process Planning should be able to analyze the set of parts to be produced on their possible advantageous characteristics for unmanned production. On top of that, once the FAM-Station is installed, it is required to evaluate the utilization of the FAM-Station, both in manned and in unmanned production mode. If no distinction is made between attended and unattended operations, it is not possible for Management to gain insight in the actual utilization of the unmanned shift and the operators, nor in the possible utilization in the future. In the MF-Case, gaining insight in these utilization rates required a new analysis of the set of parts produced in the past and to be produced in the future on the FAM-Stations. The registered utilization rates were of no use for this analysis. Therefore, even though the investment in the FAM-Stations was justified on, among others, an assumption regarding a substantial grow in capacity due to an unmanned shift, it was not possible to validate this assumption. With the distinction in the two production modes and the distinction in the two operation modes, it is no problem to get an overview of the utilization of the station.

Chapter 11
CONCLUSIONS AND FURTHER RESEARCH

In this last chapter we will summarize the main conclusions of our study. Subsequently we will discuss:
- the main differences between FAM-Stations and FAM-Shops from a production control point of view;
- the required FAM-Station capacity concepts;
- the flow time behaviour of work orders at FAM-Stations;
- the applicability of the flow time estimators;
- the FAM-Station production control functions;
- and some consequences for Process Planning.

When required, we will indicate the need for futher research.
In the last paragraph we will have a retrospective view on the aims and achievements of this study.

11.1 FAM-Stations versus FAM-Shops

The subject of our study is the production control for Flexible Automated Manufacturing Stations (FAM-Stations) in low volume component manufacturing. In literature, usually the production control problems in case of stand-alone Flexible Automated Manufacturing Shops (FAM-Shops) have been studied. The main differences between these two cases are:
- in low volume manufacturing the repeatability of orders is low;
- in case of FAM-Shops, work order lot-sizes are assumed to be very small (often only one), whereas the work order lot-sizes in case of FAM-Stations usually are larger (certainly larger than one);
- FAM-Stations are single-stage manufacturing systems, while a FAM-Shop is a multi-stage manufacturing system;
- in case of FAM-Stations, usually work orders also require operations on other work stations, whereas in case of FAM-Shops work orders often are completed entirely on the FAM-Shop.

Due to the first difference, the maximum number of identical (expensive) product set-ups that can be mounted simultaneously on pallets is low, usually only one. Because of this limitation in the number of identical product set-ups, and because of the fact that in case of FAM-Stations work orders have lot-sizes larger than one, work orders are no longer taken into operation in a sequential way, but more or less simultaneously. Consequently, the flow time behaviour of work orders at FAM-Stations is different from the order flow time behaviour at conventional work stations and at many FAM-Shops. In fact, in case of FAM-Shops flow times are considered to be negligible.
Furthermore, in case of low volume manufacturing it often is not possible

to optimize the NC-program and process control. Therefore, many operations on FAM-Stations are to be regarded as attended operations (requiring the attendance of a human operator), whereas all operations on FAM-Shops are regarded as unattended operations.
Since FAM-Stations are single-stage manufacturing systems, the set-up problems of these systems are less complex than the set-up problems in case of FAM-Shops. Also, FAM-Shops usually face severe mix problems, while on FAM-Stations there are no mix problems at all.
Finally, since FAM-Stations usually are part of a larger manufacturing system, and work orders also require operations on other work stations, the production control problem of FAM-Stations should be regarded as a stochastic dynamic problem. In case of FAM-Shops usually the production control problem is regarded as a deterministic static control problem.

11.2 FAM-Station capacity concepts

An important characteristic of FAM-Stations is their ability to produce several hours in an unmanned production mode. However, only unattended operations can be performed in the unmanned production mode; attended operations have to be performed in the manned production mode. Consequently, it should be possible to distinguish the operation modes of operations and the capacities in both production modes in order to be able to check the major capacity constraints of FAM-Stations.

11.3 Order flow time behaviour

At the FAM-Stations we studied, a part of the waiting time of a work order has become cycle-size dependent. As a result, work orders with a small cycle-size will have a short waiting time, whereas work orders with large cycle-sizes will have long waiting times. The main cause of this cycle-size dependent waiting time is the limitation in the number of identical product set-ups. In case of manned production, this limitation results into the simultaneous production of work orders. As a result, each cycle of a work order loaded on the FAM-Station will have to wait for the completion of operations on cycles of other work orders before it will be taken into operation. In case of unmanned production, due to the limitation in the number of identical product set-ups, each cycle will have to wait almost an entire unmanned shift before it is unloaded and a new cycle can be loaded.
In the manned production mode, in most cases an increase in the number of work orders simultaneously in operation results into an increase both in overall average flow times and in the variance in flow times. Consequently, given a number of pallets on the FAM-Station, increasing the number of product set-ups per work order will reduce the average flow times of the orders if these product set-ups are mounted on different pallets. Due to the (dis-)mounting and (un-)loading times required at the mounting/loading

place, usually the minimum average flow time will be obtained when three pallets are used.
In the unmanned production mode, increasing the amount of work loaded on the FAM-Station at the beginning of an unmanned shift usually decreases all order flow times, and thus also the overall average flow times and the variance in flow times. Therefore, in this case, mounting as much product set-ups on one pallet will be an advantegeous strategy. Also, if possible, especially work orders with cycles requiring long operation times should be completed during the unmanned shifts. The number of pallets used in an unmanned shift should be large enough to complete all work orders. The average flow times decrease rapidly with a small increase in the number of pallets used. The minimum average flow time is already almost obtained as soon as the pallet utilization rate is negligible (in most cases 60% or less).
The results obtained in this study are all based on a strict distinction in manned and unmanned production mode, i.e. work orders are supposed to be completed either in manned shifts or in unmanned shifts. Due to the fact that nowadays in most real life cases most operations should be regarded as attended operations, this assumption is realistic. However, if in the future the percentage unattended operations grows, further research is required on the case where some operations are completed entirely in the manned production mode, while others are completed in both production modes.

11.4 Flow time estimators

The flow time estimators presented in this study require three different waiting time estimates, viz. the estimated external waiting time in manned production, the estimated external waiting time in unmanned production, and the estimated cycle(-train) waiting time in manned production. Clearly, the first two waiting time estimates are used to estimate the time a work order will have to wait at the FAM-Station without a cycle being loaded yet on the station. The third estimate is required to estimate the internal waiting time of a work order in the manned production mode, i.e. the time the machine is not processing cycles of the work order between the loading of the first cycle of the work order on the station, and the completion and unloading of the last cycle of the order. Then, the internal flow time of a work order on the FAM-Station is estimated by multiplying the cycle(-train) waiting time with the number of cycle(-train)s of the order, and adding the work order operation time. In the unmanned shift the internal flow time of an order is estimated by multiplying the length of one shift with the number of cycle(-train)s of the work order.
Simulation experiments have shown that these estimators are more accurate in estimating work order flow times than the flow time estimators used in most component manufacturing shops. However, the waiting time estimates used in the experiments are based on historical data. Therefore, further research is required to obtain analytical results. On top of that, the experiments have shown that in some cases the estimators still are not very accurate. A further refinement of the estimators is required for these cases.

11.5 Production Control

In case of FAM-Stations, the Goods Flow Control function should distinguish attended from unattended operations, and manned from unmanned production capacity, in order to be able to check the capacity constraints.

In most cases, the information on the remaining work load at FAM-Stations to be used by Order Release should be more accurate than will be possible if the traditional progress monitoring procedures are used, i.e. registrating the start of an operation and the completion of the operation. In these cases, a more frequent report on the progress of work orders in operation is required.
If more than one product set-up type is required to complete the work order, an explicit distinction between these product set-up types as separate operations should be considered. In such a case, both Order Release and Production Unit Control have more options that can be considered, both concerning the capacity utilization and concerning the work order progress.

The sequencing decision at FAM-Stations can be split up into three interrelated, but separate decisions, viz. the System Set-up decision, Input Control, and Run Batch Sequencing.
The System Set-up decision is concerned with the (dis-)mounting and (un-)loading of tools and run batches. In case of manned production, if possible, product set-ups belonging to the same work order should be distributed over several pallets. The number of orders for which pallet set-ups are prepared, should be limited. Pallets that are not being used for manned production, can be prepared for the unmanned production. In the unmanned production mode, product set-ups should be combined on one pallet as much as possible. In the unmanned production mode, there is no limitation required on the number of work orders simultaneously in operation.
Input Control launches loaded run batches to the FAM-Station. The number of run batches launched during manned production should be limited to about three per machine in order to prevent the machine from getting idle. In case most manned production capacity is required for attended operations, these attended operations should be given highest priority.
Finally, the Run Batch Sequencing decision is concerned with the sequence in which run batches are taken into operation. In the manned production mode, usually a FCFS-priority rule will be applicable. Only in case the production rate of a particular work order should be increased, a different priority rule should be used. Reasons for increasing the production rate may be a rush order, different production rates between product set-up types required for an order if the FCFS-rule is used, and a required decrease in the order flow time of orders with large cycle-sizes. In unmanned shifts, the operation sequence of the launched run batches should be based on the probability that the operation will cause processing problems: risky operations should be performed after operations that are less risky.

11.6 Process Planning

The determination whether a particular operation can be regarded as an unattended operation, or should be regarded as an attended operation, should be the responsibility of Process Planning. If required, Process Planning should select attended operations that can be turned into unattended operations. Operations with the following characteristics are suited best for unmanned production in low volume manufacturing:
- the amount of effort required to prepare the operation for unmanned production is low;
- the repeatability of the operation in future is (relatively) high;
- the cycle operation times are long, either due to long part operation times, or due to the large number of parts per cycle.

11.7 Retrospect

As we stated in Chapter 2, the aim of this study was to determine:
1. how FAM-Stations should be described using the concepts introduced in this chapter;
2. whether a control structure as given in Fig.2.14 will still be applicable in case of component manufacturing shops using FAM-Stations;
3. whether specific control functions require new information on and/or insights in the capacity and flow time behaviour of FAM-Stations;
4. whether new control principles are required for Production Control.

In Chapter 4 we have discussed some difficulties in describing a FAM-Station using the concepts introduced in Chapter 2. In order to overcome these difficulties we have introduced several new concepts, i.c.:
- operation mode (attended or unattended);
- production mode (manned or unmanned);
- cycle and run batch;
- product and pallet set-up (-type).

We have shown that with some adaptations in the procedures (like the frequency of registrating the work order progress) most production control functions can be maintained. However, since a FAM-Station should be modeled as a server again containing one or more sub-servers (viz. the machine(s)), the sequencing decision at the FAM-Station should be split up into three sub-decisions, viz. a System Set-up decision, an Input Control decision, and a Run Batch Sequencing decision.
The main new information requirements and insights in capacity and flow time behaviour of FAM-Stations for each production control function are summarized in the previous paragraphs. Also it is indicated how and when the new concepts should be applied by Production Control.
Finally, we have shown that especially due to the distinction in production modes and due to the simultaneous production of work orders, indeed new control principles are required (see Chapter 9). An example of such a new control principle is the required limitation of the number of work orders simultaneously in operation during manned production.

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Appendix 1
SIMULATION EXPERIMENTS ON FLOW TIME ESTIMATORS

In Chapter 8 we introduced some estimators to be used in real life for estimating flow times of orders with operations on FAM-Stations in case of simultaneous production of work orders. In order to test the applicability of the cycle-train concept to estimate flow times, several simulation experiments have been performed. In the experiments, we varied both the 'fixed' experimental settings (in particular the production modes, the number of pallets, and the utilization rates), and the order characteristics. The characteristics of the order sets are given in Table A.1.

Table A.1:
Order set characteristics as input for simulation experiments.

SET	CLASS i: / $q(i)$:	1 6	2 12	3 18	4 24	5 30	6 36
01	$o(i,1)$	2.00	0.20	1.00	1.00	1.50	0.50
	$o(i,2)$	-.—	0.80	-.—	1.00	-.—	-.—
	$f(i)$	1	1	1	1	2	1
02	$o(i,1)$	1.50	0.20	0.80	0.50	1.50	0.20
	$o(i,2)$	-.—	-.—	0.20	-.—	-.—	0.80
	$f(i)$	1	1	2	1	2	1
03	$o(i,1)$	1.00	0.20	1.00	0.50	1.00	1.50
	$o(i,2)$	1.50	0.80	-.—	-.—	-.—	-.—
	$f(i)$	1	2	1	1	1	1
04	$o(i,1)$	2.50	2.00	0.50	1.50	0.50	1.00
	$o(i,2)$	-.—	-.—	-.—	1.00	-.—	-.—
	$f(i)$	2	1	2	1	2	1
05	$o(i,1)$	0.50	0.10	0.80	0.50	1.50	0.50
	$o(i,2)$	-.—	0.90	0.20	1.50	-.—	-.—
	$f(i)$	1	2	1	1	1	1
06	$o(i,1)$	1.00	1.80	2.00	0.20	0.20	1.00
	$o(i,2)$	-.—	-.—	-.—	-.—	1.80	-.—
	$f(i)$	1	1	1	1	1	2

NB: $q(i)$: cycle-size of order class i;
$o(i,j)$: cycle operation time for j-th product set-up type of order i; if no second set-up type is required, this is indicated as '-.—';
$f(i)$: maximum number of concurrent product set-ups for each product set-up type of order i.

As we can see in the table, we have used six different order sets. In each order set we distinguished six order classes. All orders belonging to the same order class have the same characteristics. In each experiment one particular set of orders of these six different order sets was used.

Manned Production

In case of manned production, each set of orders was used in simulation runs with four different settings, viz. a single FAM–Station with four pallets (N=4), or a single FAM–Station with ten pallets (N=10), with a pre–set utilization rate of 80% or 90%. The priority rule used both in the external queue and in the internal queue, was FCFS. Furthermore, every product set–up was mounted on a separate pallet (i.e. the single pallet set–up case). Loading and unloading times were assumed to be negligible. The expected number of orders simulated was equal for all classes. The length of each simulation run (excluding the starting–up period) was set at 100,000 time units.
In each simulation run, the order flow time was estimated for each order class using the flow time estimator given in eqn.(8.9) (see §8.3). As we recall from §8.3, the flow time estimator is based on the concept of a cycle–train. The estimator uses both order class characteristics, and estimates of the external waiting time and the cycle–train waiting time. In every flow time estimation, the overall results of the simulation run for the external waiting time and the cycle–train waiting time were used as waiting time estimates. These overall waiting times were determined as indicated in §8.3.2 and §8.3.4. The reason for using these measured values is that we wanted to test the applicability of the concept of a cycle–train, and not the estimates of the external or cycle waiting times. As an example of how an order flow time estimate was obtained, consider the following case. In one particular simulation run using the first order set (see Table A.1), the estimated flow time for order class 4 was 142.01. This estimate can be obtained as follows:

- number of cycle–trains per order of class 4:

$$q'(4) = [q(4)/f(4)]_{int}+p(4)-1 = [24/1]_{int}+2-1 = 25;$$

- order operation time per order of class 4:

$$O(4) = q(4) \times (o(4,1)+o(4,2)) = 24 \times (1.00+1.00) = 48.00.$$

- measured overall waiting times:
  - average external waiting time: $\bar{w}_{ext}(M) = 46.01$;
  - average cycle–train waiting time: $\bar{w}_{tr}(M) = 1.92$;

Therefore:

$$\underline{t}(4) = 46.01 + (25 \times 1.92) + 48.00 = 142.01$$

For each experimental setting, we have performed ten simulation runs with a different random input. For each run, we have determined for every order

class the relative difference between the estimated order flow time and the real (i.e. measured) flow times.
This relative difference for order class i is defined as:

$$\underline{e}_{flt}(i) = 100\% \times (\underline{\hat{t}}(i,M) - \bar{t}(i)) \; / \; \bar{t}(i).$$

The results of the experiment are given in Table A.2 and Table A.3, giving both the mean and the standard deviation of $\underline{e}(i)$ over the ten simulation runs (with ρ_{pre} set at 80% resp. 90%).

Table A.2:
Relative estimation error (in %) of order flow times in manned production (ρ_{pre}=80%).

Order Set	N	$\underline{e}_{flt}(i)$	CLASS i					
			1	2	3	4	5	6
01	4	Mean	− 2.	0.	0.1	2.	1.	3.
		StdDev	3.2	2.6	1.8	2.3	2.2	3.1
	10	Mean	− 3.	2.	1.3	− 2.	− 4.	11.
		StdDev	3.1	2.4	1.9	2.1	2.2	3.5
02	4	Mean	− 3.3	2.	− 3.	2.	1.	8.
		StdDev	1.4	5.5	3.2	2.2	2.7	3.4
	10	Mean	− 5.	4.	− 3.	7.	− 4.2	8.
		StdDev	2.0	5.4	3.0	3.0	1.7	3.4
03	4	Mean	− 1.	− 9.	5.	10.	5.	2.9
		StdDev	4.8	4.3	3.9	5.2	4.1	1.5
	10	Mean	− 0.	− 5.	3.	7.	2.	− 1.9
		StdDev	4.6	3.5	3.4	4.8	4.5	1.2
04	4	Mean	− 2.	− 2.	2.	4.	5.	3.
		StdDev	5.0	3.1	4.2	3.2	3.4	2.9
	10	Mean	− 2.	− 2.	2.	− 0.	5.	7.
		StdDev	5.2	2.7	4.3	2.4	3.6	3.5
05	4	Mean	3.	− 8.	3.	3.	1.	8.
		StdDev	4.3	2.1	4.4	2.4	2.6	4.7
	10	Mean	2.	− 6.5	3.	− 1.	− 1.	11.
		StdDev	4.3	1.8	4.5	2.2	2.9	5.0
06	4	Mean	− 2.	− 2.	− 0.	2.	3.	3.
		StdDev	5.8	3.1	2.3	4.7	2.8	3.1
	10	Mean	− 2.	− 2.	− 0.	8.	− 0.	− 0.
		StdDev	6.4	2.7	2.2	4.8	2.7	3.0

Table A.3:
Relative estimation error (in %) of order flow times in manned production (ρ_{pre}=90%).

Order Set	N	$\underline{e}_{flt}(i)$	CLASS i 1	2	3	4	5	6
01	4	Mean	− 1.	0.2	− 1.0	1.	3.	− 0.
		StdDev	2.2	1.7	1.8	2.5	3.1	2.2
	10	Mean	− 2.	1.7	− 0.7	0.	− 0.	3.
		StdDev	2.3	1.8	2.0	2.2	3.0	2.9
02	4	Mean	− 2.8	0.	− 2.	0.	1.	7.
		StdDev	1.8	3.1	2.6	2.5	2.6	3.2
	10	Mean	− 3.3	1.	− 2.	3.	− 1.	6.
		StdDev	1.8	3.0	2.7	2.1	2.1	2.9
03	4	Mean	− 3.	− 5.	4.	6.	4.	4.5
		StdDev	3.5	2.7	3.8	3.9	2.9	1.4
	10	Mean	− 2.	− 5.	3.	5.	2.	1.3
		StdDev	3.8	2.5	3.4	3.6	3.0	1.4
04	4	Mean	− 1.	− 1.	− 0.2	4.	4.	1.
		StdDev	4.2	2.6	1.8	3.3	3.9	2.8
	10	Mean	− 2.	− 1.	− 0.1	3.	4.	4.
		StdDev	4.7	2.2	1.9	2.1	3.8	3.0
05	4	Mean	2.	− 4.	2.	3.	1.	5.
		StdDev	2.8	3.7	2.6	2.5	2.2	4.1
	10	Mean	2.	− 5.	2.	1.4	− 0.	6.
		StdDev	2.9	4.0	2.6	1.9	2.3	4.4
06	4	Mean	− 2.	− 2.	0.	1.	2.	2.
		StdDev	5.5	3.2	2.5	3.8	3.5	2.5
	10	Mean	− 2.	− 2.	0.	3.	1.	0.
		StdDev	5.9	3.2	2.5	3.3	3.0	2.3

In Table A.4 and A.5 the results are given for the relative difference between the estimated internal waiting time of an order, and the real internal waiting time (with a pre-set utilization rate of 80% resp. 90%). In other words, the tables gives for each order class i the mean value and the standard deviation of $\underline{e}(i)$, where:

$$\underline{e}_{iwt}(i) = 100\% \times (q'(i)\bar{W}_{tr}(M) - \bar{T}_{int}(i) + O(i)) / (\bar{T}_{int}(i) - O(i))$$

with:

$q'(i)$: number of cycle-trains of an order of class i;
$\underline{w}_{tr}(M)$: overall waiting time of a cycle-train in manned production;
$\underline{t}_{int}(i)$: internal flow time of an order of class i;
$O(i)$: order operation time of order of class i.

Table A.4:
Relative estimation error (in %) of internal waiting times in manned production (ρ_{pre}=80%).

Order Set	N	$\varepsilon_{iwt}(i)$	CLASS i					
			1	2	3	4	5	6
01	4	Mean	− 7.8	− 3.	− 1.0	4.2	1.	9.
		StdDev	2.0	3.8	1.6	1.1	2.6	3.9
	10	Mean	− 4.9	3.	1.	− 3.	− 9.	15.
		StdDev	1.8	2.5	2.2	2.3	3.1	4.0
02	4	Mean	− 4.4	3.	−18.	6.	0.	22.
		StdDev	2.1	3.7	3.0	2.8	2.3	3.8
	10	Mean	− 3.9	4.	− 8.	11.	− 9.6	11.
		StdDev	1.5	3.6	2.4	4.0	1.2	3.4
03	4	Mean	− 7.	−25.8	13.	19.	11.	5.7
		StdDev	2.0	1.9	2.8	4.1	3.4	1.6
	10	Mean	− 2.	− 9.	4.	9.	3.	− 2.7
		StdDev	3.4	3.2	3.0	4.7	4.6	1.3
04	4	Mean	−23.	− 1.	4.	10.	17.	7.
		StdDev	2.2	3.5	4.7	3.2	3.7	3.2
	10	Mean	−13.	− 1.	3.	− 0.	7.	9.
		StdDev	2.2	3.2	3.2	2.8	3.7	4.1
05	4	Mean	10.	−31.2	10.	11.	3.	18.
		StdDev	2.2	1.5	3.5	2.9	2.7	4.8
	10	Mean	4.	−13.	5.	− 3.	− 2.	15.
		StdDev	2.4	2.5	4.4	2.5	3.5	5.7
06	4	Mean	− 6.	− 7.	− 6.	8.	8.	7.
		StdDev	2.3	2.6	2.5	4.7	2.5	3.2
	10	Mean	− 2.	− 3.	− 2.	10.	− 0.	− 1.
		StdDev	3.1	2.9	2.0	4.4	2.6	3.7

As we can see, in the simulation experiments the largest mean relative flow time estimation error was 11%. In most cases, the mean relative estimation error was 5% or less. Notice that the estimator tends to overestimate the internal waiting times of orders with large cycle-sizes, especially if such a large cycle-size is combined with a short cycle operation time and a low utilization rate. Vice versa, the estimator underestimates the internal waiting times of orders with a small cycle-size and a long cycle operation time. Presumably, the differences in these cases can be explained by the discussions in §6.4.1 and §6.5.2 on the impact of resp. the cycle-size and the cycle operation time on the average cycle waiting time. Also, as we can see, in case $p(i)=f(i)=2$ the estimator tends to underestimate the internal waiting time, and thus also the order flow time. Clearly, in such a case the assumption that all product set-ups belonging to one order can be mounted on a pallet more or less at the same time, is too optimistic, especially for a small N.

Table A.5:
Relative estimation error (in %) of internal waiting times in manned production (ρ_{pre}=90%).

Order Set	N	$\varepsilon_{iwt}(i)$	CLASS i					
			1	2	3	4	5	6
01	4	Mean	- 6.5	- 5.	- 2.0	7.2	6.	3.
		StdDev	1.9	3.2	1.4	1.4	2.1	2.9
	10	Mean	- 3.3	1.6	- 0.6	0.4	- 3.	6.
		StdDev	1.4	1.5	1.6	1.7	2.8	3.4
02	4	Mean	- 3.5	- 1.	-17.6	2.0	6.	22.
		StdDev	1.6	2.3	1.5	1.7	2.5	2.5
	10	Mean	- 2.2	1.1	- 7.7	5.6	- 4.2	9.
		StdDev	1.2	1.7	1.1	1.7	1.6	2.7
03	4	Mean	- 8.4	-26.5	13.3	17.	12.3	9.9
		StdDev	1.1	1.1	1.3	2.1	2.0	1.6
	10	Mean	- 3.1	-11.	5.0	7.	3.	1.3
		StdDev	1.4	2.1	1.8	2.4	2.4	1.2
04	4	Mean	-23.7	- 0.1	2.	13.	16.	4.2
		StdDev	1.8	1.9	2.0	2.4	2.7	1.8
	10	Mean	-15.3	1.8	2.2	4.5	6.	6.
		StdDev	1.6	2.4	1.6	1.9	3.0	2.5
05	4	Mean	8.4	-31.9	10.1	15.	6.	14.
		StdDev	1.5	1.0	1.8	2.3	3.2	3.3
	10	Mean	3.4	-16.2	5.	3.3	0.	9.
		StdDev	1.3	0.9	2.2	1.9	2.6	4.3
06	4	Mean	- 6.	- 6.7	- 5.	2.	10.3	9.
		StdDev	2.1	1.9	2.1	3.2	1.9	2.4
	10	Mean	- 2.	- 3.	- 0.7	5.	1.8	- 0.
		StdDev	2.3	2.3	1.5	3.0	1.7	2.2

Unmanned Production

In case of unmanned production, each set of order characteristics was used in simulation runs with two settings, viz. a single FAM-Station with nine pallets (N=9) and a single FAM-Station with twenty pallets (N=20). The utilization rate was pre set at 60%. The length of one unmanned shift was set at 10 (T=10). Product set-ups were mounted on pallets until the sum of the work load of the run batches was equal to or exceeded the machine capacity of one shift. The priority rule used both in the external queue and in the internal queue, was FCFS. Furthermore, every product set-up was mounted on a separate pallet. Also, the length of the change-over period between two unmanned shifts was assumed to be negligible.

Per simulation run we have simulated 12,750 unmanned shifts (excluding the starting-up period). The expected number of orders simulated was equal for all classes.
Table A.6 gives the results on the order flow times of ten simulations runs for each setting. The flow time estimates were obtained using eqn.(8.13) (see §8.4.5). In the flow time estimates, the overall results for the external waiting time, determined as indicated in §8.4.2, were used. For example, in a particular run using order set 01, the estimated flow time for order class 4 was 281.18. We have derived this estimate as follows:

- measured average overall external waiting time: $\bar{w}_{ext}(U) = 31.18$;

- number of cycle-trains: $q^*(4) = [q(4)/f(4)]_{int}+p(4)-1 = [24/1]_{int}+2-1 = 25$.

Therefore: $\hat{t}(4) = 31.18 + (25\times10) = 281.18$

Table A.6:
Relative estimation error (in %) of order flow times in unmanned production (ρ_{pre}=60%).

Order Set	N	$\epsilon_{iwt}(i)$	CLASS i					
			1	2	3	4	5	6
01	9	Mean	- 2.	- 3.0	- 0.3	- 2.5	- 4.0	0.0
		StdDev	2.4	1.0	0.65	0.58	0.63	0.48
	20	Mean	- 3.5	- 1.8	- 0.4	- 3.4	- 3.9	- 0.06
		StdDev	1.7	0.58	0.53	0.35	0.75	0.19
02	9	Mean	- 1.5	- 0.9	- 4.	- 0.	- 0.8	0.5
		StdDev	1.5	1.2	2.3	2.0	1.7	1.0
	20	Mean	- 2.4	- 0.0	- 6.3	-0.1	- 3.4	- 2.3
		StdDev	0.9	0.9	0.8	0.33	0.75	0.49
03	9	Mean	- 5.1	-13.4	- 0.1	- 0.1	- 0.0	- 0.4
		StdDev	1.4	1.4	0.66	0.62	0.70	0.37
	20	Mean	- 5.5	- 4.4	- 0.3	- 0.3	- 0.3	- 0.5
		StdDev	1.1	1.2	0.50	0.40	0.38	0.32
04	9	Mean	-16.	- 1.4	- 3.1	- 4.7	- 1.7	- 0.2
		StdDev	4.0	1.5	1.3	0.60	0.82	0.50
	20	Mean	-20.	- 1.5	- 1.5	- 5.8	- 0.5	- 0.2
		StdDev	2.5	1.1	1.1	0.48	0.59	0.44
05	9	Mean	1.	-14.9	- 3.	- 2.6	- 0.4	- 0.0
		StdDev	2.3	1.8	2.0	1.5	1.0	0.7
	20	Mean	0.1	- 4.6	- 1.7	- 2.5	- 0.5	- 0.1
		StdDev	1.3	1.3	0.68	0.45	0.38	0.21
06	9	Mean	- 0.	- 1.4	- 0.4	- 0.4	- 2.7	- 2.5
		StdDev	2.5	0.79	0.9	0.53	0.65	0.72
	20	Mean	- 1.	- 1.8	- 0.9	- 0.4	- 3.5	- 1.7
		StdDev	2.2	0.9	0.64	0.47	0.72	0.63

In Table A.7 the results are given for the internal flow times of the work orders. The estimates were obtained by multiplying the length of one unmanned shift with the number of cycle-trains required to complete an order of the concerning order class.

Table A.7:
Relative estimation error (in %) of internal flow times in unmanned production (ρ_{pre}=60%).

Order Set	N	$\varepsilon_{iwt(i)}$	CLASS i					
			1	2	3	4	5	6
01	9	Mean	− 2.5	− 4.1	− 0.11	− 2.9	− 4.6	− 0.007
		StdDev	0.36	0.42	0.043	0.29	0.37	0.011
	20	Mean	− 4.1	− 2.3	− 0.35	− 3.7	− 4.2	− 0.028
		StdDev	0.29	0.28	0.065	0.34	0.42	0.013
02	9	Mean	− 0.47	− 0.01	−27.2	− 0.010	− 7.5	− 3.1
		StdDev	0.17	0.020	0.62	0.013	0.38	0.26
	20	Mean	− 2.7	− 0.06	− 7.3	− 0.11	− 3.9	− 2.3
		StdDev	0.33	0.031	0.78	0.020	0.33	0.27
03	9	Mean	− 6.9	−16.6	− 0.20	− 0.020	− 0.13	− 0.29
		StdDev	1.0	0.9	0.062	0.017	0.043	0.064
	20	Mean	− 7.0	− 5.1	− 0.44	− 0.07	− 0.29	− 0.47
		StdDev	0.9	0.54	0.09	0.022	0.045	0.08
04	9	Mean	−26.3	− 1.2	− 3.6	− 5.3	− 2.14	− 0.075
		StdDev	1.2	0.24	0.29	0.47	0.17	0.016
	20	Mean	−28.2	− 1.8	− 1.1	− 6.2	− 0.73	− 0.14
		StdDev	1.2	0.21	0.23	0.57	0.09	0.024
05	9	Mean	− 0.06	−27.0	− 4.0	− 3.5	− 0.14	− 0.007
		StdDev	0.055	1.6	0.37	0.48	0.045	0.008
	20	Mean	− 0.34	− 5.5	− 1.9	− 2.5	− 0.54	− 0.06
		StdDev	0.12	0.66	0.34	0.38	0.071	0.026
06	9	Mean	− 0.94	− 1.19	− 1.07	0.000	− 3.0	− 2.8
		StdDev	0.19	0.13	0.11	0.000	0.25	0.23
	20	Mean	− 1.4	− 1.61	− 1.30	− 0.02	− 3.8	− 1.8
		StdDev	0.24	0.19	0.10	0.036	0.36	0.21

As we can see, in many cases the estimator is quite accurate. However, sometimes the estimator clearly underestimates the internal flow time, especially in case of a small cycle-size and long operation times, combined with two product set-up types and/or with two product set-ups per set-up type. The reason is that in such a case frequently it will not be possible to mount all product set-ups of the order at the same time without violating the work load constraint. Especially in case of a small cycle-size, the relative impact of the assumption that all product set-ups of the same order are mounted at the same time, will be large.

Appendix 2:
GLOSSARY

APC: see *Automatic Part Changer.*
ATC: see *Automatic Tool Changer.*
Attended operation: (see also §4.1.1)
Operation requiring the attendance of an operator.
Automated manufacturing system: (see also §3.2)
Manufacturing system in which all *transformation* functions are automated (i.e. no interference of human operators).
Automatic Part Changer (or: APC): (see also §3.3.1)
Automated handling equipment used for changing parts on a machine.
Automatic Tool Changer (or: ATC): (see also §3.3.1)
Automated handling equipment used for changing (cutting) tools.
Available capacity: (see also §2.2)
Capacity of a *capacity resource* during the time the resource is available for production.

Basic operation: (see also §2.2)
A (fixed) sequence of *transformations* that is the smallest entity considered by *production control.*
Bottleneck (capacity): (see also §2.2)
Capacity type or *resource* that is most scarce.

Capacity:
Amount of work that can be performed per unit of time.
Capacity resource: (see also §2.2)
Basic supplier of *capacity* (e.g. transportation vehicle, operator, machine).
Capacity resource allocation: (see also §2.2)
Allocation of *capacity resources* to *servers.*
Capacity type: (see also §2.2)
A particular type of *capacity resource.*
Controlled stock: (see also §2.2)
Deliberately created *inventory* used to decouple *production orders,* stored in controlled stock points.
Cycle: (see also §4.1.1)
Set of parts belonging to the same *work order,* always loaded together in a *product set–up* during the *FAMS*-operation; the number of parts per cycle is equal to the greatest common divisor of the numbers of parts that can be loaded in each *product set–up* of all *product set–up types* required to complete a part.
Cycle flow time: (see also §6.2.1)
The time spent by a *cycle* on a manufacturing system.
Cycle–size: (see also §4.1.1)
Number of *cycles* of a *work order.*
Cycle–train: (see also §8.3.4)
Mental concept assuming a linkage between *cycles* that are loaded on a *FAM–Station* and belong to the same *work order.*

Disturbance losses (in capacity): (see also §2.2)
Part of the *available capacity* lost due to disturbances in the availability of a certain *capacity resource*.
Disturbance rate: (see also §2.2)
[1 – (*usable capacity* / *available capacity*)].

Effective capacity: (see also §2.2)
Capacity of a *capacity resource* used to produce accepted output.
Effective use: (see also §2.2)
[*Effective capacity* / *productive capacity*].
Executable flexibility: (see also §3.1.2)
Flexibility of the system(–components).
External waiting time: (see also §6.2.1)
Waiting time of an order at a work station before the first *cycle* of the order is loaded (similar to: *server waiting time*).

FAMS: see *Flexible Automated Manufacturing System.*
FAM–Shop: (see also §3.3.1)
Multi–stage FAMS consisting of several computer controlled machines that are connected by *APC–*, *ATC–*, pallet storage equipment, and transportation devices.
FAM–Station: (see also §3.3.1)
Single–stage FAMS consisting of one or more *MCs&APCs* connected with a (common) pallet storage system.
Flexibility: (see also §3.1.1)
Ability to respond effectively to changes.
Flexibility range: (see also §3.1.2)
Range of changes in which the system is not rigid.
Flexible Automated Manufacturing System (or: FAMS): (see also §3.2)
Flexibly automated manufacturing system with *mix flexibility* and *volume flexibility.*
Flexibly automated manufacturing system: (see also §3.2)
Automated manufacturing system of which the automated functions are re–programmable.
Functional flexibility: (see also §3.1.2)
Possible variability in the output of a system.

Idle capacity: (see also §2.2)
Part of the *usable capacity* lost due to the absence of work to be performed.
Input Control: (see also §4.1.2)
Production control function concerned with the decision on the timing of the launching of *run batches* to a *FAM–Station.*
Internal flow time: (see also §6.2.1)
[*Order flow time – external waiting time*]
Inventory: (see also §2.2)
All stored materials (i.e. raw materials, parts, subassemblies, and products).

Machine set–up time: (see also §5.2)
The time it takes to perform all activities requiring machine *set–up capacity.*
Manned production mode: (see also §4.1.1)
Production mode of a *production system* during which operators are available.

Manufacturing Centre (or: MC): (see also §3.3.1)
Computer controlled machine capable of performing several distinct operation types.

Manufacturing process: (see also §3.2)
Series of *transformations* performed upon material to convert it from the raw or semifinished state to a state of further completion and greater value.

Manufacturing system: (see also §3.2)
Technical system required to perform a *manufacturing process.*

Master Planning: (see also §2.3.2)
Production control function concerned with decisions on the *available capacity* in *Production Units*, on the *effective capacity* stored in *controlled stock* points, and often also on norms on *capacity utilization.*

Materials Coordination: (see also §2.3.2)
Production control function concerned with the coordination of the goods flow between *Production Units.*

MC: see *Manufacturing Centre.*

Mix flexibility: (see also §3.1.2)
Functional flexibility in producing different mixes of products.

Mounting/loading place: (see also §6.3.1)
Place at a *FAM–Station* where *product set–ups* are mounted on and dismounted from pallets, and cycles are loaded in and unloaded from *product set–ups.*

Multi–functional capacity resource: (see also §2.2)
Capacity resource that is shared among several *servers.*

Multiple FAMS: (see also §1.2.1)
FAMS containing more than one machine.

Multi–stage manufacturing system: (see also §1.3.1)
Manufacturing system in which all *manufacturing processes* on a part are carried out on more than one machine.

Non–available capacity: (see also §2.2)
Amount of work a *capacity resource* could have performed per unit of time during the time the resource is not available for production.

Normative capacity: (see also §5.1)
Capacity that may be utilized according to *utilization* norms (set by *Master Planning*).

Operation (or server operation): (see also §2.2)
Set of *basic operations* to be performed on a *server* and considered as a unity by the *production control* function at hand.

Operational flexibility: (see also §3.1.2)
Executable flexibility of a system within the existing system structure.

Operation allocation: (see also §2.2)
Choice of the *server* to perform a particular operation.

Operation time:
Processing time required for a certain operation.

Order flow time: (see also §2.2)
Order flow time can have two meanings:
- time taken to complete a *production order*, starting at the instant the order is created (or released), and finishing with the completion of the last *operation* on the order;
- time between the arrival of the *production order* at a work station and the departure of the order from the work station after completion of the *operation.*

If the latter definition is meant, the term 'at the work station' is added.

Order–generating level of control: (see also §2.2)
Level of control generating a *production order.*
Order–receiving level of control: (see also §2.2)
Level of control receiving a *production order.*
Order transfer decision: (see also §2.2)
Decision on the creation of a *production order* for a lower level of control.

Pallet set–up: (see also §3.3.1)
Set of *product set–ups* mounted on one pallet.
Pallet set–up type: (see also §3.3.1)
Particular combination of *product set–up types* and a *pallet type.*
Process plan: (see also §2.2)
Sequence of *server operations* required to complete a *production order.*
Product flexibility: (see also §3.1.2)
Functional flexibility in producing different types of products.
Production control: (see also §1.3.1)
Function of management which plans, directs, and controls the material supply and manufacturing activities of a *production system.*
Production order: (see also §2.2)
Order for a particular *server* concerning the production of a batch of products.
Production system:
System aimed at the production of products with a certain quality at a certain place in a certain time at a certain cost.
Production Unit (or PU): (see also §2.3.1)
Combination of a set of *capacity resources*, a set of operations, and a set of materials, with the following properties:
- for each set of operations to be performed, it is only required to use materials from the set of materials, and to use *capacity* from the set of *capacity types*;
- each capacity type in the set of *capacity types* and each material item in the set of materials is only used for performing operations belonging to the operations set.

Production Unit Control: (see also §2.3.3)
Production control function concerned with the coordination of the production activities inside a *Production Unit.*
Productive capacity: (see also §2.2)
Capacity of a *capacity resource* used to produce output (or: *utilized capacity* minus *set–up capacity*).
Productive use: (see also §2.2)
[*Productive capacity / available capacity*].
Product set–up: (see also §3.3.1)
Set of tools required and prepared to position and hold one or more parts in a particular way.
Product set–up type: (see also §3.3.1)
Particular type of tool–set required and prepared to position and hold one or more parts in a particular way. Of a product set–up type several (identical) *product set–ups* may be available.
Progress Monitoring: (see also §2.3.3)
Function monitoring the progress of *work orders* in a *Production Unit.*
PU: see *Production Unit.*

Rigidity: (see also §3.1.2)
Inflexibility of a system.

Routing: (see also §2.2)
Sequence of *servers* required to perform a *process plan.*
Run batch: (see also §4.1.1)
Set of parts loaded on one pallet.
Run Batch Sequencing: (see also §4.1.2)
Production control function concerned with the decision on the operating sequence of *run batches.*

Sequencing: (see also §2.3.3)
Determination of the sequence of *server operations* on *servers.*
Sequential production: (see also §3.3.1)
Production sequence in which *work orders* are taken into operation only after the previous order has been completed.
Server: (see also §2.2)
Set of *capacity resources* that from the point of view of a particular *production control* function can be modeled as a unit of *capacity.*
Server waiting time: (see also §2.2)
Time a *production order* waits in front of a server because the *server* is occupied by other *production orders.*
Server operation: see *Operation.*
Server waiting time: (see also §2.2)
Waiting time of a *production order* at a certain *server.*
Service time: (see also §2.2)
Time required by a *server* to complete a certain *production order.*
Set–up batch: (see also §4.2.2)
Set of parts to be produced within one particular *set–up state* of a *manufacturing system.*
Set–up capacity: (see also §2.2)
Capacity of a *capacity resource* used to set up the resource for production.
Set–up state: (see also §2.2)
State of a *manufacturing system* in which it is suitable for the manufacturing a particular set of product types.
Simultaneous production: (see also §3.3.1)
Production sequence in which several *work orders* may be in operation simultaneously.
Single–stage manufacturing system: (see also §1.3.1)
Manufacturing system in which all *manufacturing processes* on a part are carried out on one machine.
Starting–up period: (see also §6.2.2)
Simulation time used to start up the actual simulation run; the orders that are completed during this time are not considered in the final output.
Structural flexibility: (see also §3.1.2)
Executable flexibility of a system in changing the system structure.
System Set–up: (see also §4.1.2)
Production control function concerned with the decision on the *set–up state* of a *FAM–Station.*

Transformation: (see also §2.2)
Basic activity performed on a part to change the characteristics of that part (physical appearance, position, time).
Transformation unit: (see also §3.2)
Subsystem of a *manufacturing system* carrying out a particular *transformation.*

Unattended operation: (see also §4.1.1)
Operation not requiring the attendance of an operator.
Unmanned production mode: (see also §4.1.1)
Production mode of a *production system* during which no operators are available.
Usable capacity: (see also §2.2)
Capacity of a *capacity resource* that can be used for production (or: *available capacity* minus *disturbance losses*).
Utilized capacity: (see also §2.2)
Capacity of a *capacity resource* actually utilized for production (or: *usable capacity* minus *idle capacity*).
Utilization rate: (see also §2.2)
[*Utilized capacity / usable capacity*].

Volume flexibility: (see also §3.1.2)
Functional flexibility in producing at different *capacity* levels.

Wasted capacity: (see also §2.2)
Capacity of a *capacity resource* used to produce output that can not be accepted (for quality reasons).
WIP: see *Work-In-Progress inventory.*
Work Load Control: (see also §2.3.2)
Production control function concerned with the determination for a particular *Production Unit* of the aggregate *work order* release pattern or release opportunities.
Work Order Release: (see also §2.3.2)
Production control function concerned with the acceptance and release of *work orders* to a *Production Unit.*
Work-In-Progress- (or WIP-) inventory: (see also §2.2)
Inventory used to decouple two subsequent *servers* in order to overcome an unbalance between these servers.
Work order: (see also §2.3.1)
Production order for a *Production Unit.*

Appendix 3:
FREQUENTLY USED SYMBOLS

$c(i)$:	Cycle flow time of a cycle of a work order of order class i.
$C(\underline{x})$:	Variation coefficient of '$\underline{x}$', i.e. $\sigma(\underline{x})/E(\underline{x})$.
$f(i)$:	Number of product set-ups available per product set-up type of a work order of order class i.
$f(i,j)$:	Number of product set-ups available for the j-th product set-up type of a work order of order class i.
M:	Number of machines in FAM-Station.
M:	Manned production mode.
n:	Number of orders that has arrived at the FAM-Station, and is not completed yet.
N:	Number of pallets.
N_{max}:	Maximum number of pallets utilized.
N_{min}:	Minimum number of pallets required.
N_{opt}:	Optimum number of pallets, i.e. the number of pallets at which the overall average order flow time is minimized.
o:	Cycle operation time of a cycle of an arbitrary work order.
$o(i)$:	Cycle operation time of a cycle of work order of order class i.
$o(i,j)$:	Cycle operation time of a cycle in the j-th product set-up of a work order of order class i.
O:	Order operation time of an arbitrary work order.
$O(i)$:	Order operation time of a work order of order class i.
$p(i)$:	Number of product set-up types required for a work order of order class i.
q:	Cycle-size of an arbitrary work order.
$q(i)$:	Cycle-size of a work order of order class i.
$q'(i)$:	Number of cycle-trains of a work order of order class i.
$s(i)$:	Set-up time required for a work order of order class i.
$t(i,m)$:	Order flow time of a work order of order class i at the FAM-Station in production mode m.
$t_{int}(i,m)$:	Internal flow time of a work order of order class i at the FAM-Station in production mode m.
T:	Length (in time) of one unmanned shift.
U:	Unmanned production mode.
$w_{cyc}(m)$:	Waiting time of an arbitrary cycle on the FAM-Station in production mode m.
$w_{ext}(m)$:	External waiting time of a work order at the FAM-Station in production mode m.
$w_{int}(i,m)$:	Internal waiting time of a work order of order class i at the FAM-Station in production mode m.
$w_{tr}(m)$:	Waiting time of a cycle-train of a work order of order class i on the FAM-Station in production mode m.
α:	Ratio of product set-up mounting time and cycle operation time.
γ_n:	Average rate of completion of orders if there are n orders in the system as a whole.
λ:	Average work order arrival rate at the FAM-Station.
ρ:	Machine utilization rate.
ρ_{pre}:	Pre-set machine utilization rate.

STELLINGEN

Behorende bij het proefschrift:

Production Control for Flexible Automated Manufacturing Stations in Low Volume Component Manufacturing.

Corné W.G.M. Dirne

I Een FAM-Station is zowel meer als minder flexibel dan een conventionele machine.

(Zie Hoofdstuk 3 van dit proefschrift).

II Een belangrijk deel van de geclaimde voordelen van het gebruik van FAMSs (met name: seriegrootte één, onbemande produktie, forse doorlooptijdverkorting) blijkt op dit moment in de praktijk, zeker in het geval van een niet al te hoge herhalingsgraad, niet of slechts ten dele haalbaar te zijn.

(Zie dit proefschrift).

III Een groot deel van de aan computers en programmatuur toegeschreven probleemoplossende werking heeft niet zozeer met computers of programmatuur te maken, als wel met de verplichting problemen op te lossen alvorens computers en programmatuur effectief en efficiënt te kunnen gebruiken.

IV Indien we een bepaald deel van de literatuur mogen geloven, dan maakt een produktiebedrijf geen schijn van kans meer te overleven indien het niet een MRP-II pakket toepast in een CIM-omgeving, daarbij gebruik makend van AI (Artificial Intelligence) of minimaal enkele Knowledge Based systems, terwijl het produktieproces grotendeels dient te bestaan uit FMS- en IR-toepassingen. Mocht dit het geval zijn, dan is in ieder geval het Nederlandse bedrijfsleven ten dode opgeschreven. Echter, in tegenstelling tot bovenstaande bewering, automatisering vergroot de overlevingskansen van een bedrijf alleen indien ze (slechts) selektief wordt toegepast. Indien niet selektief toegepast, verkleint zij juist de overlevingskansen.

(Zie bijvoorbeeld:
T.G. Gunn: "Manufacturing for Competitive Advantage". Ballinger Publishing Company, USA, 1987)

V Het zelf schrijven van een simulatieprogramma in plaats van het gebruiken van een pakket waarin het gedrag van de te bestuderen delen van het systeem is voorgeprogrammeerd, verhoogt het begrip van het te simuleren systeem.

VI Voor de Faculteit der Technische Bedrijfskunde van de Technische Universiteit Eindhoven is de uitspraak "...good fenches make good friends..." (R.Frost) van dubbele betekenis:
- vaststelling en erkenning van elkaars vakgebied en kennis is essentieel voor het funktioneren binnen en van de faculteit;
- enige isolerende werking van de 'muren' in het paviljoen (zowel voor wat betreft temperatuur als geluid) bevordert het leef- en werkklimaat van de faculteit.

VII Rationele besluitvorming sluit emotionele argumenten niet uit.

VIII Een grote categorie conflicten is oplosbaar zonder compromissen, daar bij juiste hantering deze conflicten geen conflicten blijken te zijn.

IX Arbeidstijdverkorting blijkt precies dat te zijn wat de term aangeeft; van arbeidsvermindering is in de meeste gevallen geen sprake.
(Voorbeeld: promotie-onderzoek aan universiteiten;
zie ook: "Rapportage fase 1 van het projekt Herverdeling van Werk". Ministerie van Social Zaken en Werkgelegenheid, 1985)

X Indien de prijs van een produkt gebaseerd zou zijn op de maatschappelijke integrale kostprijs van het produkt, dan zou een groot deel van de milieuproblematiek reeds opgelost zijn c.q. nooit ontstaan zijn. Assistentie van de overheid bij het bepalen van die maatschappelijke integrale kostprijs is op dit moment nog onontbeerlijk.

XI In bepaalde al dan niet individuele geloofsovertuigingen wordt een Godsbeeld gehanteerd waaruit men zou moeten concluderen dat God geschapen is naar het beeld van de mens. Een dergelijke conclusie is in tegenspraak met diezelfde geloofsovertuigingen.

XII Volgens Mark Twain is een klassiek boek een boek dat iedereen gelezen wil hebben en niemand wil lezen. Aangezien de helft van zijn bewering lijkt op te gaan voor dit proefschrift, is dit boek te classificeren als een semi-klassieker.