Throughput time control and due date reliability in tool & die shops

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Ton (A.)M. van de Wakker

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Throughput Time Control and Due Date Reliability in Tool & Die Shops

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Eindhoven,
op gezag van de Rector Magnificus, prof.dr. J.H. van Lint,
voor een commissie aangewezen door het College van Dekanen,
in het openbaar te verdedigen op vrijdag 26 maart 1993 om 16.00 uur

door:

Antonius Maria van de Wakker

Geboren te Arnhem

Dit proefschrift is goedgekeurd door de promotoren:

prof.dr.ir. J.W.M. Bertrand

en

prof.dr. J. Wijngaard

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The completion of this thesis denotes the completion of the study performed by this author into the production planning and control approaches required by component manufacturing units of tool & die shops. This research was initiated in 1986 as the result of the production planning and control problems encountered in practice at the Central Tool & Die Shop of Philips Electronics in Eindhoven (Netherlands).

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SUMMARY

Summary

The results of a study into the production planning and control issues involved in manufacturing multiple discrete products in the component manufacturing units of tool & die shops are presented in this book. Special attention in this study has been paid to designing approaches to the following three planning and control decisions:

- due date assignment: how to be able to promise short and reliable throughput times;
- order release: when should the manufacturing unit receive an order;
- work sequencing: which manufacturing order should be given the highest priority at a given work station.

The study presented here focuses on designing a set of planning and control rules to be used as the basis for making the planning and control decisions mentioned above. These decision rules are intended to provide an optimal performance mix with respect to achieving a high level of due date reliability and a short average throughput time for assembly orders.

The subject of the research in this study has been based upon the production planning and control problems encountered in practice in the Central Tool & Die Shop ("CGM") of Philips Electronics in Eindhoven (Netherlands).

◆ *Assembly order structures*

A complicating factor with respect to designing the decision rules arises when assembly orders are processed in a tool & die shop with network characteristics. Multiple products

are normally manufactured in the component manufacturing units of tool & die shops. A set of different components belonging to a single assembly order may be manufactured during the same period of time within such a component manufacturing unit. It can be assumed that the methods of processing will also be different when different components are to be manufactured. The type, duration, sequence and total number of operations needed to produce these components can all be different. In particular, the number of operations required to manufacture a given component will determine the throughput time. The manufacturing order for the component requiring the largest number of operations becomes the critical path. The other manufacturing orders for components belonging to the same assembly order will normally require fewer operations and will therefore have a shorter required minimum throughput time. This means that there will be more slack per operation in the throughput times of these other orders as compared to the critical path. A manufacturing order for the production of a component is referred to here as a work order. The number of work orders per assembly order and the number of operations per work order generally can be represented by geometric distribution functions. This has been verified in practical situations (CGM). The operation times can be represented by a negative exponential distribution. In view of this, it can be said that the assembly orders have a geometrical structure.

◆ *Reducing the throughput time*

The planned throughput times of assembly orders can be reduced by using the Operation Start Date (OSD) priority rule to swap the planned slack between the work orders. This planned slack is referred to here as allowance time. Allowance time is swapped in such a way as to reduce the allowance time within the critical work orders while keeping the total average allowance time constant. This means that the allowance time associated with the non-critical work orders will increase. It turns out that the shortest average throughput times for assembly orders can be realized by swapping the allowance times between the work orders, separately, for each assembly order.

In comparison with the traditional due date assignment rules which have been published in the literature, the new due date assignment rule developed as part of the study presented here, in which the allowance times are swapped between the work orders belonging to a single assembly order, leads to a shorter average throughput time (i.e., a reduction of 20%) for the large assembly orders. Large assembly orders are considered to be orders consisting of ten work orders in this case. Three work orders per assembly order was used as the average for this study.

◆ *Improving the due date reliability*

Completion interference occurs when a assembly order consists of multiple work orders. This results in a completion delay at the work order level. At the same time, this type of completion interference leads to a structure delay at the assembly order level when the work orders belonging to a assembly order all have the same scheduled due date. The expected completion date for a assembly order is defined as being the scheduled due date plus the estimated structure delay time (the structure allowance). The structure delay time represents, on the average, 17% of the average throughput time of a assembly order. A method for determining the structure allowance is presented as a part of this study.

The dynamic assignment of due dates leads to a significant reduction in the spread of the distribution of the lateness. A distinction is made between symmetrical and asymmetrical dynamic due date assignment. In the case of symmetrical dynamic due date assignment, the waiting time allowance is a function of the workload in the shop and the work orders are released for production immediately upon arrival. With an asymmetrical dynamic due date assignment the waiting time allowance is kept constant, provided that there is a sufficient workload. In this case the waiting time allowance is reduced when the workload falls below a certain level. In addition, a release date is scheduled dynamically for each work order. The work orders must be held in a buffer until they can be released to the shop, exactly on their respectively scheduled release dates. This is referred to as the work order release. The use of work order release in combination with asymmetrical dynamic due date assignment leads to a further reduction in the spread of the distribution of the lateness.

The use of asymmetrical dynamic due date assignment can produce an extremely poor performance when allowance swapping is not used and the planned throughput times of the work orders belonging to a given assembly order are all different. This poor performance is caused by a characteristic lumpy pattern which results from an unbalanced distribution of the workload between the buffer and the shop.

◆ *Workload control*

Workload control is a technique used at the work order release point for keeping the workload for a shop at a fairly constant level. With this technique, the scheduled work order release date is used to determine the release priority. Workload control can be used to counteract the negative side-effects of asymmetrical dynamic due date assignment. When allowance swapping is not used, then the combination of workload control and asymmetrical dynamic due date assignment provides a better performance than symmetrical dynamic due date assignment with respect to the average throughput time and the due date reliability.

Workload control does not provide any improvement when allowance swapping is used. In practice, however, it generally makes sense to always use workload control in releasing work orders since all of the necessary conditions for the full use of allowance swapping are rarely satisfied.

◆ *The contribution of this study*

This study has been able to provide a contribution to the literature on this subject in three areas:

- it is demonstrated why traditional planning and control decision rules are not sufficient in situations with geometrical assembly order structures;
- a new set of planning and control decision rules is developed which takes the characteristics of the assembly order structure into account;
- the effectiveness of the different planning and control rules for assigning due dates and releasing orders are evaluated for several circumstances giving insight in the consequences of order structure characteristics on control behaviour in specific situations.

SAMENVATTING

Samenvatting

In dit boek worden de resultaten van het onderzoek naar het produktiebesturingsvraagstuk van de fabricage van discrete meervoudige produkten in onderdelen produktieafdelingen van gereedschapmakerijen gerapporteerd. In het onderzoek is met name aandacht besteed aan de inrichting van de volgende drie besturingsbelissingen:

- de leverdatumafgifte: hoe kunnen betrouwbare en korte levertijden worden beloofd;
- de ordervrijgave: op welk moment moet de produktieafdeling over een order beschikken;
- de prioriteitsstelling: de keuze welke fabricage-opdracht bij een werkplek de hoogste prioriteit krijgt.

Het onderzoek heeft zich gericht op het ontwerp van een set besturingsregels op basis waarvan de eerder genoemde besturingsbeslissingen uitgevoerd kunnen worden en waarbij het ontwerp resulteert in een optimale performance-mix van hoge leverbetrouwbaarheid en korte gemiddelde doorlooptijd van assemblage-orders.

De probleemstelling van het onderzoek is afgeleid uit de praktijkproblematiek van de produktiebesturing in de Centrale Gereedschapmakerij (CGM) van Philips in Eindhoven.

◆ *Assemblage-orderstructuren*

Een complicerende factor bij het ontwerp waren de assemblage-orderstructuren in gereedschapmakerijen die netwerk-kenmerken bezitten. In de onderdelen produktieafdelingen van gereedschapmakerijen worden meervoudige produkten gefabriceerd. Binnen zo'n onderdelen produktieafdeling wordt een set van verschillende onderdelen in dezelfde tijdsperiode ten behoeve van één assemblage-order gefabriceerd. Als onderdelen verschillend zijn dan is de bewerkingswijze om die onderdelen te fabriceren ook verschillend. De bewerkingen die uitgevoerd moeten worden om onderdelen te fabriceren verschillen dan naar soort, naar bewerkingsduur, naar volgorde en naar aantal. Met name het aantal bewerkingen dat uitgevoerd moet worden bepaald de doorlooptijd die nodig is om een onderdeel te fabriceren. De fabricage-opdracht voor het onderdeel waar het grootste aantal bewerkingen voor uitgevoerd moet worden vormt het kritieke pad. De overige fabricage-opdrachten van onderdelen voor dezelfde assemblage-order hebben meestal een kleiner aantal bewerkingen en dus een kortere benodigde minimale doorlooptijd, zodat zij vergeleken met het kritieke pad als het ware extra ruimte in de doorlooptijd hebben. Een fabricage-opdracht voor de produktie van een onderdeel noemen wij werkorder. De verdelingen van het aantal werkorders per assemblage-order en het aantal bewerkingen per werkorder blijken in de praktijk (CGM) geometrisch van aard te zijn. De bewerkingstijden zijn negatief exponentieel verdeeld. Wij spreken daarom ook van de geometrische structuur van assemblage-orders.

◆ *Doorlooptijdreductie*

Door de Operation Start Date (OSD) prioriteitsstelling te gebruiken kunnen planmatig doorlooptijden van assemblage-orders gereduceerd worden door geplande speling, die wij toeslag noemen, tussen werkorders uit te wisselen. Daarbij moet de toeslag van de kritieke werkorders verkleind worden. Echter tegelijkertijd dient de totale gemiddelde toeslag constant te blijven. Dat kan bereikt worden door de toeslag van de niet kritieke werkorders te vergroten. Het blijkt dat de kortste gemiddelde doorlooptijden van assemblage-orders gerealiseerd kunnen worden door de toeslag tussen werkorders uit één assemblage-order uit te wisselen.

Vergeleken met de traditionele leverdatumafgifteregels uit de literatuur resulteert de in ons onderzoek ontwikkelde nieuwe leverdatumafgifteregel, waarbij toeslag tussen werkorders uit één assemblage-order uitgewisseld wordt, tot een kortere gemiddelde doorlooptijd van grote assemblage-orders (20 % reductie). Grote assemblage-orders zijn assemblage-orders met tien werkorders. Gemiddeld hebben assemblage-orders in dit onderzoek drie werkorders.

◆ *Verhoging van de leverbetrouwbaarheid*

Als een assemblage-order uit meerdere werkorders bestaat, dan treden completeringseffecten op die resulteren in completeringswachttijden op werkorderniveau.

Tegelijkertijd resulteren deze completeringseffecten in structuurtijden op assemblage-order niveau als de werkorders uit een assemblage-order dezelfde geplande leverdatum hebben. De verwachte leverdatum van de assemblage-order is gelijk aan de geplande leverdatum plus de geschatte structuurtijd, de structuurtoeslag. De structuurtijd maakt gemiddeld 17% van de gemiddelde doorlooptijd van assemblage-orders uit. In dit onderzoek is een methode voor het bepalen van de structuurtoeslag uitgewerkt.

Dynamische levertijdafgifte geeft een aanzienlijke reductie in de spreiding van de levertijdafwijking. Wij maken onderscheid naar symmetrische en asymmetrische dynamische levertijdafgifte. Met symmetrische dynamische levertijdafgifte is de wachttijdtoeslag een functie van de werklast in een produktieafdeling en worden werkorders direct op het aankomst moment vrijgegeven aan de produktieafdeling. Met asymmetrische dynamische levertijdafgifte wordt de wachttijdtoeslag constant gehouden als er voldoende werklast is. In dit geval wordt de wachttijd toeslag wel verlaagd als er te weinig werklast beschikbaar is. Daarnaast wordt dan voor iedere werkorder een dynamische geplande vrijgave datum vast gesteld. De werkorders worden vervolgens precies op hun geplande vrijgave datum vrijgegeven aan de produktieafdeling en moeten tot aan de vrijgave wachten in een buffer. Dit noemen wij werkorder vrijgave. Het gebruik van werkordervrijgave in combinatie met asymmetrische dynamische levertijdafgifte leidt tot een verdere reductie in de spreiding van de levertijdafwijking.

Als toeslaguitwisseling niet wordt toegepast en de geplande doorlooptijden van werkorders uit één assemblage-order onderling verschillen, dan leidt asymmetrische dynamische levertijdafgifte tot een zeer slechte performance. Deze slechte performance wordt veroorzaakt door lumpy-effecten die het gevolg zijn van een onbalans in de werklastverdeling tussen de buffer en de produktieafdeling.

◆ *Werklastbeheersing*

Werklastbeheersing is een methode om bij de werkordervrijgave de werklast in een produktieafdeling zoveel mogelijk constant te houden. De geplande vrijgave datum van een werkorder wordt dan als prioriteitsgetal gebruikt. Werklastbeheersing heft de negatieve bijeffecten van asymmetrische dynamische levertijdafgifte op. De combinatie van werklastbeheersing met asymmetrische dynamische levertijdafgifte geeft een betere performance ten aanzien van gemiddelde doorlooptijd en leverbetrouwbaarheid, dan symmetrische dynamische levertijdafgifte als toeslaguitwisseling niet toegepast wordt.

Als toeslaguitwisseling wel toegepast wordt dan heeft werklastbeheersing geen toegevoegde waarde. Echter omdat in de praktijk bijna nooit volledig voldaan is aan alle voorwaarden om toeslaguitwisseling volledig toe te kunnen passen, is het in de praktijk verstandig om altijd werklastbeheersing bij de werkordervrijgave te hanteren.

◆ *De bijdrage van het onderzoek*

De bijdrage van het onderzoek is drieledig:

- er wordt aangetoond waarom traditionele besturingsregels in situaties met assemblage-orderstructuren niet voldoen;
- er wordt een ontwerp gemaakt van een nieuwe set besturingsregels waarbij gebruik gemaakt wordt van orderstructuurkenmerken;
- de effectiviteit van verschillende besturingsregels, die gehanteerd kunnen worden bij de levertijdafgifte en de ordervrijgave, wordt voor verschillende omstandigheden geëvalueerd zodat inzicht verkregen wordt in de gevolgen van orderstructuurkenmerken voor het besturingsgedrag in verschillende voorkomende situaties.

Chapter
1 PREFACE

1.1 Introduction

A great deal has been published on the subject of production planning and control in job shops where single, discrete products are manufactured. Often in practice, however, job shop production planning and control must deal with the manufacturing of multiple rather than single products. The assembly of components is carried out after the parts are manufactured. This implies that a set of different components belonging to a single customer order are manufactured during the same period of time. A number of studies have been described in the literature which deal with the production planning and control problem with respect to composite products in job shop environments. The subject of the study presented here is the total production planning and control problem in job shop environments in which multiple, discrete products are manufactured. This type of environment is referred to as a component manufacturing unit.

The motivation for this study is presented in the first section of this chapter. The subject of this study is described and the problem description is formulated in the second section. A summary of how this dissertation is structured is provided at the end of this chapter.

1.2 Motivation for this study

The motivation for this study originated within the equipment manufacturing plants of Philips N.V. where day-to-day problems associated with the production planning and control in the component manufacturing units have been identified. The Philips equipment manufacturing organization encompasses a number of professional manufacturing plants for various types of machinery and a single tool & die shop. Advanced production planning and control techniques are used.

Multiple products are produced in the component manufacturing units of these plants. A short explanation of the composition of the order structure is provided as a basis for discussing the production planning and control issues. As mentioned above, a set of different components belonging to a single customer order are manufactured during the same period of time in this type of component manufacturing unit. When the components are different, then each of the processes used to manufacture these components may also be different. The manufacturing operations to be performed to produce these components will typically differ in terms of type, duration, sequence and quantity. In particular, the number of operations to be performed will determine the throughput time required to manufacture a given component. The critical path is defined as being the work order for the component with the largest number of operations in its manufacturing process. The work orders for the other components belonging to the same customer order will typically have fewer operations and therefore a shorter throughput time. When compared to the throughput time of the critical path, the throughput times of these other work orders can be extended without adversely affecting the total order.

Two aspects of the production planning and control approach used in the Philips equipment manufacturing organization are particularly noteworthy. Firstly, a procedure is normally followed whereby large orders are scheduled optimistically, with a minimal margin for unexpected delay on the critical path. This is justified in practice by assuming that there is sufficient buffer time included within the order structure. In this way the manufacturing operations on the critical path can be treated as rush orders, so long as there are a sufficient number of other manufacturing operations and paths in the same customer order which do not need to be processed as rush orders. This particular approach to production planning has not been documented in the published studies. The literature often refers to a single total throughput time for manufacturing all of the components. This new approach is therefore analyzed and developed in more detail within the scope of the study presented here.

The second noteworthy aspect is that a number of production planning and control problems remained unresolved. These problems were related primarily to the implementation of an appropriate order release function. The existing literature similarly provides no solution for these problems. As a result, a major part of the study presented here is focused on the design of an effective order release function. This is described in more detail in Chapter 2.

The research objective has been determined based upon the day-to-day problems thus identified.

1.3 Subject of this study

The customer orders received by component manufacturing units, and by tool & die shops in particular, can be quite dissimilar. An analysis of the number of work orders per customer order as well as the number of operations per work order typically shows an extremely unbalanced distribution. Each order is actually unique because ultimately a specific product must be manufactured for the customer. It is not possible to initiate any of the manufacturing operations before the customer order has been placed and the product and manufacturing specifications are fully known. The work content of the customer orders and the work orders can vary widely. The utilization of production resource capacities in this type of manufacturing situation is extremely variable because of the dependence on an irregular arrival of customer orders and a non-standard composition with respect to the work content of these customer orders.

The study here concentrates on the total problem of production planning and control of multiple, discrete products in component manufacturing units of tool & die shops. Research is carried out with respect to the planning and control decisions which need to be made involving the following three aspects:

- assigning due dates: determining how reliable and short throughput times can be promised;
- releasing orders: determining the point in time at which a manufacturing unit should receive a work order;
- sequencing orders: determining which work order is to be given the highest priority at each work station.

The research results are used to develop a set of decision rules to support the planning and control decisions mentioned above. These decision rules have been designed to provide an optimal performance mix with respect to high due date reliability and short average throughput times for customer orders.

These results are based upon the investigation and analysis of the effect of different order structure characteristics on the production planning and control decisions. Maxwell (e.g., [Maxwell, 1969]) and Adam (e.g., [Adam et al., 1991]) also have studied such aspects, however, their research was not sufficiently comprehensive and not applicable to practical situations (also refer to Chapters 3 and 7). The decision rules which have been developed based upon the results of the research presented here take the structure characteristics of individual orders into account.

The results of this study provide new insights in three specific areas:

- it is demonstrated why the traditional decision rules are inadequate for practical use in situations with parallel paths in the customer order structures;
- a new set of planning and control decision rules is developed which take the order

structure characteristics into account;
- the effectiveness of the different planning and control rules for assigning due dates and releasing orders are evaluated for several circumstances giving insight in the consequences of order structure characteristics on control behaviour in specific situations.

1.4 Structure of this study

This study is presented in three parts. The first part is an introduction in which the case study is described which has provided the basis for the research objective of this study. In addition, the research results published in the literature relevant to this study are reviewed. The chosen approach for carrying out this study is described in more detail in the last chapter of this part.

The theoretical research component of this study is described in four chapters and forms the second part of this study. Each chapter covers a separate research issue.

The third part of this study focuses on deriving conclusions from the theoretical research results and translating these to practical situations. The conclusions are summarized in the final chapter.

Chapter

2 CASE STUDY OF A CENTRAL TOOL & DIE SHOP

2.1 Purpose of the case study

The research study presented here deals with production planning and control problems typically found in the component manufacturing units of equipment manufacturing plants. This type of manufacturing unit is seen to be an independent shop (see [Bertrand et al., 1991]) which typically produces mechanical components used in the construction of machinery. An equipment manufacturer often makes production equipment which is, in turn, used by customers to manufacture their own products. Production equipment is almost always made-to-order to meet numerous customer specifications. This means that manufacturing operations cannot be started until the customer order and specifications are known. In general, a customer order passes through five phases in a manufacturing plant:

- the engineering design phase in which the customer specifications are translated into product specifications. The equipment to be manufactured is designed and detailed in the form of blueprints and bills of materials;
- the process planning phase in which the manufacturing specifications are developed from the product specifications. The manufacturing specifications describe how a product is to be produced and which initial materials are necessary. Most of the results of the process planning activities are recorded in the manufacturing documentation;
- the component manufacturing phase in which the internally-manufactured components are produced by the various manufacturing units. At the same time, a large number of components are typically contracted out to external suppliers who manufacture the parts according to the specifications provided. In some instances only the manufacture of semi-finished components is contracted out to third-parties;
- the assembly phase in which the internally or externally produced components as well as other parts purchased from third-parties are assembled into a single finished unit. The assembled equipment is also tested and calibrated in this phase;

- the installation phase, starting with the quality assurance and approval of the assembled equipment. In many cases, the manufactured and tested equipment is then partially dismantled for shipment to the customer site where it is reassembled and installed. Manufacturing equipment which is to be included within a customer's production system then usually needs to be recalibrated and adjusted to ensure optimal performance as an integral part of the total production system.

This study focuses particularly on the problems faced by complex component manufacturing units which may typically be found within large tool & die shops. A tool & die shop can be seen as a special type of equipment manufacturing plant. A tool & die shop manufactures specialized tooling products, such as stamps and moulds for manufacturing equipment. State-of-the-art manufacturing technology and special expertise is often required in the manufacture of tooling products. Advanced manufacturing technology and expertise must be available. Assembly activities, on the other hand, rarely occur within a tool & die shop; the fourth phase in the manufacturing process associated with a customer order (as described above) therefore does not exist within a tool & die shop. Any simple assembly activities which may be required are typically carried out as the last operation in the component manufacturing phase. This means that the component manufacturing phase in a tool & die shop is likely to be somewhat more complex than in a normal equipment manufacturing plant.

The subject of the research here is the planning and control of the manufacturing operations in component manufacturing units. The research objective as well as a number of the basic premises are derived from real-life situations. A case study of the component parts manufacturing unit of the Central Tool & Die Shop of Philips Electronics in Eindhoven (Netherlands), the "CGM" (from the Dutch: Centrale GereedschapMakerij), has served as a motivating force behind this research.

The CGM case has been used in three ways:

- the subject of this study originated from problems of current interest within the CGM;
- the CGM situation demonstrates that the subject of this study is relevant in real-life;
- the practical feasibility of implementing the findings and conclusions from the theoretical research has been tested for the CGM situation.

2.2 Organisation of this chapter

The CGM manufactures tooling products based upon customer specifications. This means that the CGM must wait until a fully specified customer order is available before preparations can be made for the manufacturing operations and before these operations can be initiated. The term "customer order" is defined here as the authorized order for the manufacture of a specific tooling product.

Customer orders are received by the CGM at irregular intervals. In addition, the tooling product orders placed by customers are almost never the same. This means that the resource capacity requirements with respect to the available manpower and machinery differ widely from one order to the next. The manufacturing resources required to handle all of the current orders can fluctuate greatly from one period to the next. The major focus of the production planning and control efforts within the CGM is concentrated on providing a close match between the available manufacturing capacity and the demand for these resources in each period.

A number of problem areas surfaced during the course of identifying the planning and control structure within the CGM. A certain amount of theoretical research is required to provide a definitive solution to the identified problem areas. These problem areas are described in this chapter. An explanation of the practical relevance of this study is provided at the end of this chapter. The following topics are discussed in the subsequent sections of this chapter:
- a brief description of, and general introduction to, the CGM situation;
- the production planning and control objectives;
- a description of the resource capacity structure used to define the availability of manufacturing resources;
- a description of the order structure used to define the demand for manufacturing resources;
- the production planning and control structure.

The case study will also serve as a basis for introducing and defining specific terms which have been used and developed during the course of this study.

2.3 Description of the CGM situation

Information about the organizational environment in which the CGM functions, the range of products produced, the internal organizational structure and the market is presented in this section.

The CGM is associated with the equipment manufacturing plants of Philips Electronics. These equipment manufacturing plants are the primary suppliers of several products to the Philips product divisions. The manufacturing plants produce manufacturing equipment, tooling products (stamps and moulds), spare parts and mechanical parts, components and plated parts for scientific, medical and business equipment. Each manufacturing plant operates as a separate profit center.

The machining of parts is the most important activity within these manufacturing plants. In recent years, electronics has become increasingly important. A number of centralized service units have been established to support the equipment manufacturing plants:
- the central equipment and tooling products shop;
- the materials department, including a central raw materials warehouse;
- the central measurement and calibration department.

There are also several staff departments such as the Information Systems and Automation (ISA) Department and the Organization & Efficiency (O&E) Department. The manufacturing plants have component manufacturing shops as well as assembly shops. The component manufacturing shops are suppliers to the assembly shops. There is very little assembly work involved in the manufacturing of the tooling products within the CGM. Because of this, the assembly activities are performed within the CGM component manufacturing shop.

The CGM manufactures stamps and moulds and employs approximately 250 people. The total turnover is 30 million guilders per year. The CGM is divided into three parallel production lines which operate as autonomous groups or manufacturing units within Philips. One group specializes in the manufacturing of moulds for display screens (Group G-2). Another group manufactures moulds (the "Mould Group") and the last group produces stamps (the "Stamp Group"). The organization chart is presented in Figure 2.1.

Moulds can be viewed as a special type of tooling used to shape plastic or glass products into their final form. Stamps and dies are used to stamp, cut or give a profile to (metal) parts and materials. A typical example within Philips is the tooling required for the manufacture of electric shavers. The plastic cover of the shaver is a component which has been shaped using a specific mould. Components such as this determine the appearance and distinctive characteristics of a product. Therefore, a great deal of attention is given to the accuracy of dimensions, the texture of the surface and the contour lines. The moulds must also be made of durable materials due to the fact that they may not wear down when they are used in the mass production processes. All of the surfaces which are subject to wear and tear must be hardened. The blades and various other components of the shaver are stamped out of metal strips. Durability is also very important here.

The CGM manufactures high-quality products which make use of advanced technology. Because of this, highly-trained specialists and skilled workers are needed. Workers must have an extensive amount of experience before they can be employed as qualified craftsmen. The CGM must utilize these skilled workers as effectively as possible since the cost of labor in this respect is relatively high.

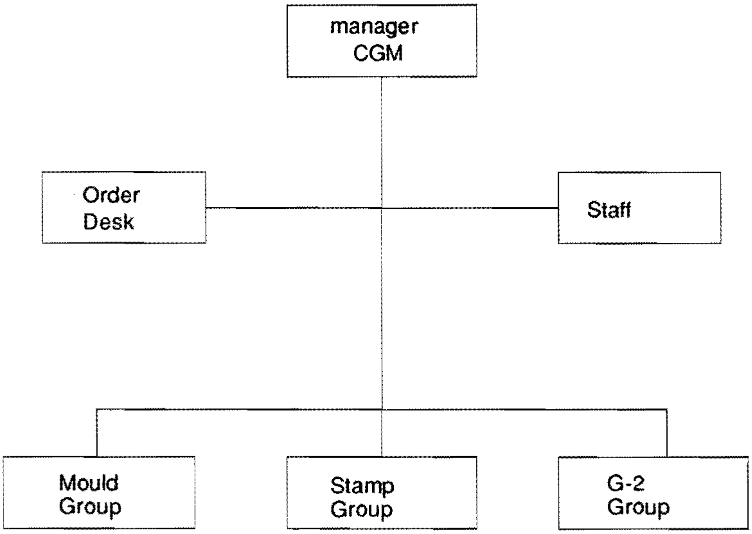

Figure 2.1: Organization chart of the CGM.

The CGM has five centralized departments, namely: the human resources department, the accounting department, the O&E department, the technical support department and the order processing department. The order processing department coordinates order acceptance and due date assignment. Each autonomous group has its own engineering department, process planning department and manufacturing unit.

In principle, the CGM accepts orders from the other Philips operating companies. The Philips companies are, however, not obligated to purchase solely from the other Philips manufacturing plants such as CGM. This means that the CGM must compete with the potential external suppliers. As a result, the price, quality and delivery lead time are extremely important factors. Orders are occasionally accepted from non-Philips companies in order to maintain a sufficient utilization of available manpower and resources. Tooling products are thus manufactured for third-parties in this case. The orders accepted from non-Philips companies generally do not incorporate the same high level of advanced technology as the normal work carried out by the CGM for the Philips companies. In this way, the work done for non-Philips companies is viewed as fill-work.

2.4 CGM production scheduling and control objectives

The average delivery lead times, and thus the throughput times, need to be reduced continually in order to remain competitive.

The CGM products are used as components in the customers' processing equipment. Production schedules, maintenance schedules and plans for new manufacturing activities are often coupled to the agreed delivery lead time for the required tooling products. In addition, there is enormous pressure to provide reliable estimates of the completion dates. The percentage of customer orders that are delivered too late and the average tardiness of these orders need to be kept to a minimum.

The average throughput time as well as the average tardiness and the number of tardy customer orders need to be minimized, but with the provision that the productivity of the human resources as well as the machines are maintained at high levels. Internal norms have been established within the CGM for this purpose.

2.5 Resource capacity structure

Resource capacity is defined as being both machine capacity and the processing capacity of the skilled workers. Capacity is available in the form of machines and skilled workers. A machine is always operated by skilled workers to provide the manufacturing capacity. A unique combination of a skilled worker and a machine can perform only one type of operation. A so-called "operation code" is used to identify the type of machine to be used for each operation within the CGM. A specific type of operation is defined by the combination of a number of interchangeable machines and a number of skilled workers which are qualified to operate those machines. As a result, each type of operation consists of one or more operation codes. In some instances, a specific type of operation may not involve the use of machinery and is thus carried out solely by one or more skilled workers; this is referred to as a manual type of operation.

Skilled workers are usually specialized in specific areas. As a result, a group of skilled workers generally performs a specific set of related types of operations. The skilled workers in a given group are consequently multi-skilled and can be used interchangeably within their own group, but are not sufficiently skilled and qualified to operate the machines within a different group. Such a group which incorporates related types of operations is referred to as a capacity group.

An autonomous group can be seen as a small, independent manufacturing plant. An autonomous group is a manufacturing department or unit (see [Bertrand et al., 1991]). The number and configuration of machines and skilled workers in each group is generally determined in such a way to enable each autonomous group to work independently from the other groups. An autonomous group is generally responsible for between 15 and 30 operation codes. An operation code represents a set of skills associated with a specific type of interchangeable machinery. A standard operation coding scheme is used at all of the Philips' manufacturing plants. An example of this is the operation code which represents "flash milling". Specialized machines are used for flash cleaning and only a limited number of skilled workers are qualified to operate these machines. A distinction is also made with respect to the skill levels of the skilled workers: craftsmen and apprentices. The skilled workers report to their respective section heads; each section head similarly reports to a group manager.

2.6 Order structure

A CGM customer order consists of an authorized requisition for manufacturing either a single mould or stamp or a batch of moulds or stamps. This type of tooling product has a limited number of components. Some of these components must be made simultaneously on the same machine to ensure, for example, that the cutting surfaces are exact opposite images of each other. In this way the discrete component manufacturing process can have batch-like characteristics.

When an order quotation is converted to a confirmed order, it is often necessary for the engineering department to complete the blueprints. When the engineering department has completed this task, the complete set of blueprints is then forwarded to the process planning department. The process planning department determines how the tooling product will be constructed, determines which materials will be required, prepares the work instructions, prepares any programs which may be required for the production machines, determines which production tools will be needed and completes the work order documentation.

The bill of materials for manufacturing a tooling product is rather simple. The bill of materials specifies which raw materials or parts are needed to make a specific component or sub-assembly. It rarely consists of more than three levels. Each "parent" (i.e., a separate assembly or sub-assembly) will normally have a maximum of ten components. A system to maintain the bill of materials information is not used in the CGM situation.

The structure of the processing operations is much more complicated. The processing structure specifies exactly how a component or a sub-assembly is to be made. In order to manufacture the specified high-quality, technologically-advanced components, a variety of complicated operations are often required. In some instances, certain operations cannot be handled by the tool & die shop. The hardening operations are good examples of this. These operations are carried out in a specialized hardening shop which is equipped with special facilities for this type of operation. In addition, some operations may need to be contracted out due to a shortage of internal capacity. It is also possible that a whole work order will be outsourced to one of the other Philips equipment manufacturing plants or even to a third-party contractor when there is insufficient internal manufacturing capacity.

A work order is a requisition issued to a shop to manufacture a (quasi-)batch of components. A batch consists of one or more components. A quasi-batch means that there are different components in a batch which are manufactured based upon the same work order and these components have essentially the same processing structure. This means that the sequence of the operations is the same for all of the components, but that the processing times may differ and certain operations may be skipped in manufacturing some of the components.

A work order consists of a sequence of operations to be performed. Associated with each operation is a processing time which is defined as being the sum of the set-up time and the total component processing time (the number of components multiplied by the processing time for a single component). A work order may additionally include transport times for moving the components from one work station to another. An allowance for waiting time is also allocated to each operation. The total of allowances, planned transport times and processing times is defined as being the normative throughput time for a work order. The actual throughput time is equal to the total of the realized processing times, transport times and waiting times. A set of blueprints and work instructions is prepared by the process planning department and added to each work order. All of the documentation pertaining to a specific work order is organized within a single file folder.

◆ *The concept of an assembly order*

Work orders are assigned to autonomous units within the Philips equipment manufacturing plants. These manufacturing units are also referred to as "shops" in this study. Work orders derived from a single customer order can therefore be allocated to different manufacturing units. All of the work orders belonging to a single customer order which are subsequently issued to a one shop for processing within a given period of time are referred to as an *assembly order*. In this way a customer order may consist of one or more assembly orders. Each assembly order is comprised of one or more work orders.

There are no significant assembly activities performed within the CGM. The component manufacturing as well as the assembly of the tooling products take place within a single autonomous group or shop. There is usually only one assembly operation defined within the manufacturing process for a tooling product. Quality assurance with respect to the completed product is then carried out. This usually means that the manufacturing of all of the components generally needs to be completed at the same point in time so that the assembly operation can be started immediately thereafter. In the CGM situation, the internal due date for the associated work orders is generally the same date as the scheduled start date for the assembly operation.

Customer orders issued to the CGM often have only one assembly order. Nevertheless, there are some situations in which these customer orders have more than one assembly order. For this reason, this study deals with assembly orders rather than customer orders.

An assembly order generally includes a number of work orders which are interrelated. An example of an assembly order is presented in Figure 2.2 (see for the drawing conventions Appendix A). All of the interrelationships between the work orders in a given assembly order are defined in the network structure of the respective assembly order.

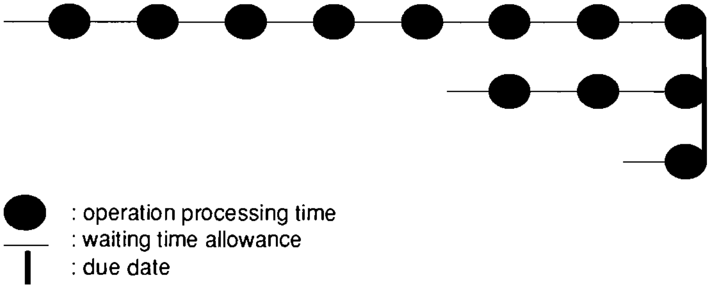

Figure 2.2: An example of an assembly order.

In some instances, a given work order may be merged with another work order. This occurs in the case of welding operations. Such an operation is represented as a convergent node in the network structure. A convergent node in the network structure of an assembly order is essentially an operation in which two or more work orders are combined into a single work order. This is a rare occurrence within the CGM. The occurrence of multiple convergent nodes in a single assembly order is more common within other types of manufacturing plants, however. In addition to the above-mentioned welding operation as an example of a convergent node, there is also a second type of convergent node operation which is often found within the CGM; this is described below. Complex equipment is often assembled step by step. Such equipment is ultimately assembled from sub-assemblies; each sub-assembly is in turn assembled from component parts. A different assembly start date may be assigned to each of these sub-assembly operations. For example, the equipment frame may need to be assembled first. The other sub-assemblies would then be assigned later assembly start dates and the assembly order components used in the individual sub-assemblies would then have different internal due dates. These different due dates would be represented by separate convergent nodes within the assembly order.

This aspect of multiple convergent nodes is not relevant for the case study presented here. For this reason, the problems related to multiple convergent nodes are not considered here. This limits the basic research objective of this study but does not substantial affect the practical relevance of the results of this study for this kind of situations. Therefore, for the purpose of this study, an assembly order is defined as having a single convergent node which is associated with the due date for the assembly order.

Operations may occur where the raw materials are divided into two or more components. In this case, one work order may be split into two or more work orders. An example of this is when a mould consists of two parts which are exact mirrored images of each other. Such matching pairs of moulds are often referred to as upper and lower moulds. Since the points of contact between these two moulds must correspond exactly, both of these components are often made from a single piece of material and processed simultaneously. At a certain point in the routing, each of these components must be processed individually. In this way the original work order is effectively split into two separate work orders, one for the upper mould and one for the lower mould. This type of splitting operation can be represented in the form of a divergent node in the network structure of the assembly order. One of the work orders which is formed at a divergent node will be on the critical path with respect to the assembly order throughput time. This work order can be viewed as the extension of the original work order. An arrival date can be assigned to the other, non-critical work order(s) which is the same as the completion date of the divergent operation. In this way the divergent nodes do not pose any special problems for the production scheduling and control. For this reason, the aspects of divergent nodes are not addressed in the remainder of this study. In addition, divergent nodes rarely occur in the CGM situation.

◆ *Summary of the order and processing structures*

The concepts introduced here can be described in a more rigorous manner in the form of an entity model (see appendix B). A short summary of the model of the order structure and processing structure within the CGM is presented here. In this way it is possible to easily and quickly check to ensure that these structures have been defined in a consistent manner.

A customer order (B[1]) is a requisition issued to the CGM to manufacture a (batch of one) tooling product for a given price to be completed by a certain due date and meeting a defined set of specifications regarding the technical requirements and the product quality. A customer order can be split into one or more assembly orders (2). An assembly order (C) is an order for the manufacturing of a specific set of components required to make the tooling product ordered by the customer. This set of components is to be processed within a single shop, whereby all of the components are to be completed at the same time. Multiple assembly orders belonging to several customer orders may be processed simultaneously within a given shop (1). A shop (A) is an independent organizational unit which is equipped to process and complete manufacturing orders. Components of an assembly order which have a similar routing and incorporate similar operations can be combined in work orders. A work order (D) is a manufacturing order issued to a shop. Each work order consists of a sequence of operations to be completed. Included with each work order are blueprints and manufacturing instructions as well as instructions regarding which machines are to be used for which operations. A work order always belongs to a single assembly order (3). An assembly order is always divided into one or more work orders (3). One or more different components are always processed based upon the instructions in a work order (4). A work order consists of operations (5). An operation (F) consists of instructions to be given to a skilled worker to perform a number of manufacturing tasks to work on one or more components (E), with or without the use of specific machinery. Operations are sequenced and, as such, are defined as having a "previous" and "next" operation. The start and the finish operations are exceptions in the sense that they have no "previous", respectively "next", operations (6).

Various components included in a (quasi-)batch can be processed using only one operation (7). This is referred to as a component processing operation (G). A component processing operation is thus a part of a manufacturing operation which is required for a single component (8).

The entity diagram is presented in Figure 2.3.

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[1] With characters is referred to the entities in figure 2.3, with figures is referred to the relations in figure 2.3.

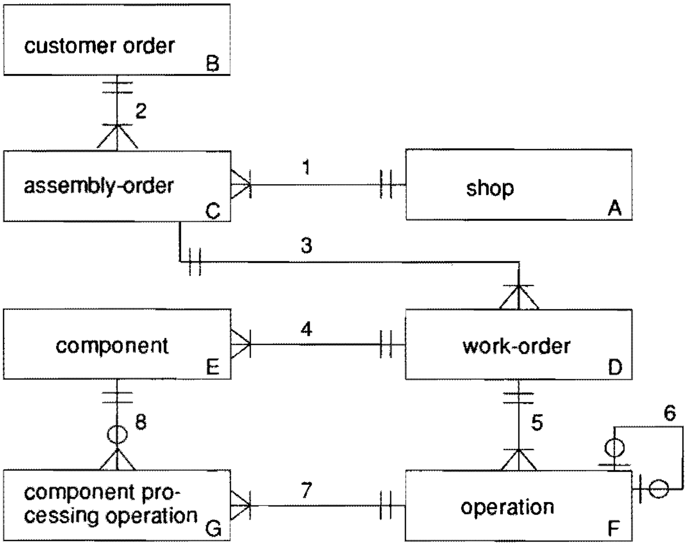

Figure 2.3: Entity diagram of the order structure and processing structure in the CGM.

♦ *Quantitative elements*

There are three aspects of the order structures which can be described in a quantitative sense using distribution functions for:

- the number of work orders per assembly order;
- the number of operations per work order;
- the processing time per operation.

From the various published studies (see Chapter 3) it is clear that a geometric distribution function is often chosen to represent the number of operations per work order and a negative exponential distribution function to represent the processing time per operation. A random distribution of values is generated by these functions. These distribution functions are convenient for use in modelling and analyses.

Data has been collected from actual assembly orders processed by the CGM Mould Group with respect to the first two aspects listed above. This data is based upon a random sample consisting of 193 assembly orders processed and completed in 1988 in the Mould Group. This Group also accepts a relatively large amount of fill-work which is taken on to ensure an adequate utilization of the available resource capacity in the shop. Of the 193 orders, 148 could be classified as fill-work. Fill-work generally consists of isolated, single work orders. An analysis of the number of work orders per assembly order was performed to determine whether the distribution of the work orders can be represented accurately by a geometrical distribution function. The conclusion is that a geometrical distribution function cannot be used to accurately model the total population of work orders in the sample analyzed (see Table 2.1). If the fill-work is ignored, however, then it appears that use of the geometric distribution function is appropriate (see Table 2.2). The frequency distribution is presented graphically in Figure 2.4.

Table 2.1:
Results of the analysis of the number of work orders per assembly order.

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency (prop.= 0.31)	Chisquare
≤ 2	2	154	101.1	27.66
2	3	4	28.5	21.05
3	4	2	19.7	15.86
4	5	4	13.6	6.74
5	6	2	9.4	5.79
6	7	2	6.5	3.08
7	9	3	7.5	2.72
9	> 9	22	6.8	33.58
total:		193	193	116.48

$116.48 > \chi^2_6 = 12.6$; significance level $= 0 < 0.05$

Table 2.2:
Results of the analysis of the number of work orders per assembly order, without fill-work.

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency (prop. = 0.1)	Chisquare
≤ 2	2	6	8.6	0.76
2	4	6	6.9	0.12
4	6	6	5.6	0.03
6	10	5	8.2	1.26
10	14	5	5.4	0.03
14	> 14	17	10.3	4.37
total:		45	45	6.57

$6.57 < \chi^2_4 = 9.5$; significance level = 0.16 > 0.05

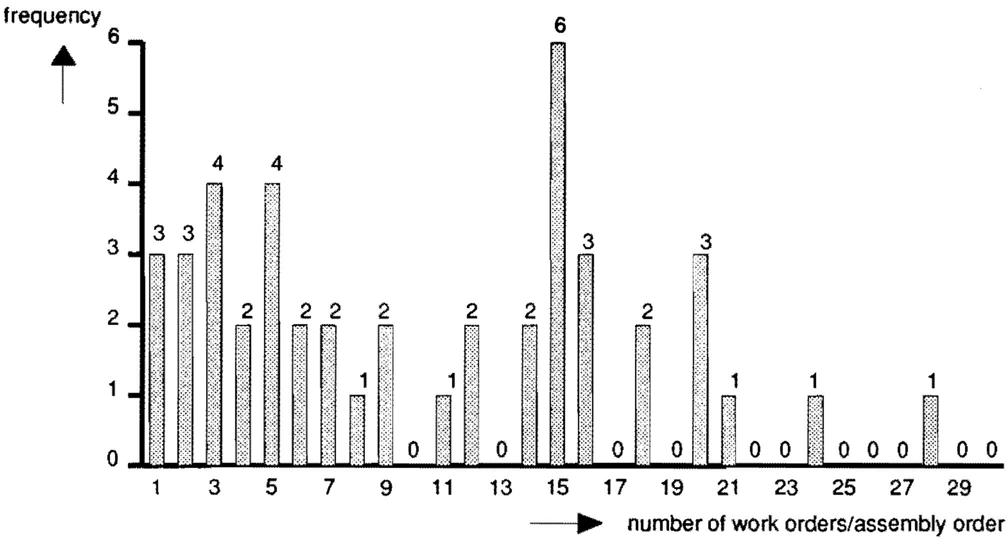

Figure 2.4: The frequency distribution of the number of work orders per assembly order.

An average of three work orders per assembly order was observed. When the fill-work is excluded, the average number of work orders per assembly order is then 10.

The hypothesis that the number of operations per work order can be modelled accurately by a geometric distribution function is therefore correct. This conclusion is valid for the situation in which the fill-work is included (where the average is 7) (see Table 2.3) as well as when the fill-work is excluded (where the average is 6) (see Table 2.4). The frequency distributions are presented graphically in Figure 2.5 and Figure 2.6.

Table 2.3:
Results of the analysis of the number of operations per work order.

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency (prop.= 0.163)	Chisquare
≤ 7	7	451	440.1	0.27
7	8	30	29.0	0.04
8	9	22	24.3	0.21
9	10	14	20.3	1.96
10	11	28	17.0	7.12
11	12	11	14.2	0.73
12	13	11	11.9	0.07
13	14	7	10.0	0.88
14	> 14	44	51.2	1.01
total:		618	618	12.29

$12.29 < \chi^2_7 = 14.1$; significance level = 0.09 > 0.05

Table 2.4:
Results of the analysis of the number of operations per work order, without fill-work.

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency (prop. = 0.145)	Chisquare
≤ 8	8	345	335.8	0.25
8	9	20	19.5	0.01
9	10	13	16.6	0.80
10	11	24	14.2	6.71
11	12	11	12.2	0.11
12	13	11	10.4	0.03
13	14	7	8.9	0.40
14	> 14	39	52.4	3.44
total:		470	470	11.75

$11.75 < \chi^2_6 = 12.6$; significance level $= 0.07 > 0.05$

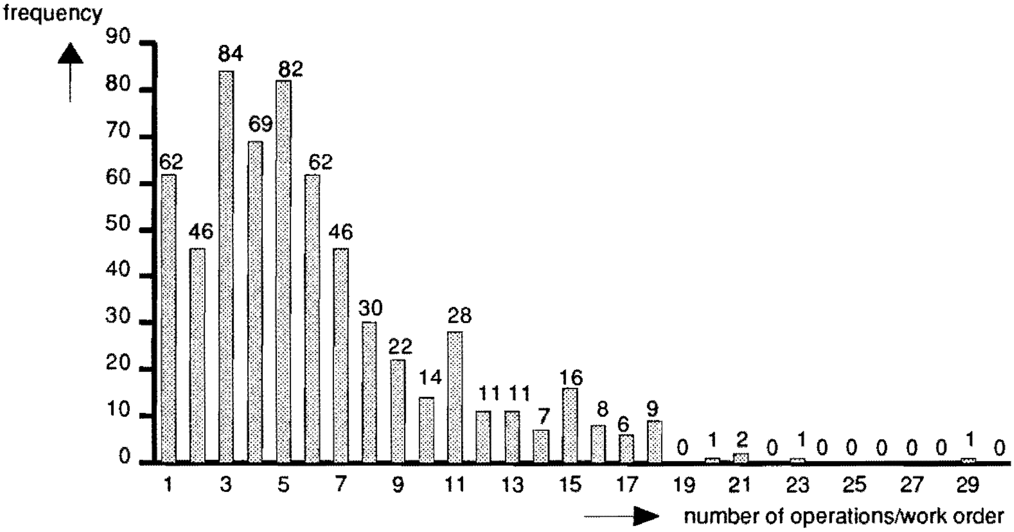

Figure 2.5: The frequency distribution of the number of operations per work order.

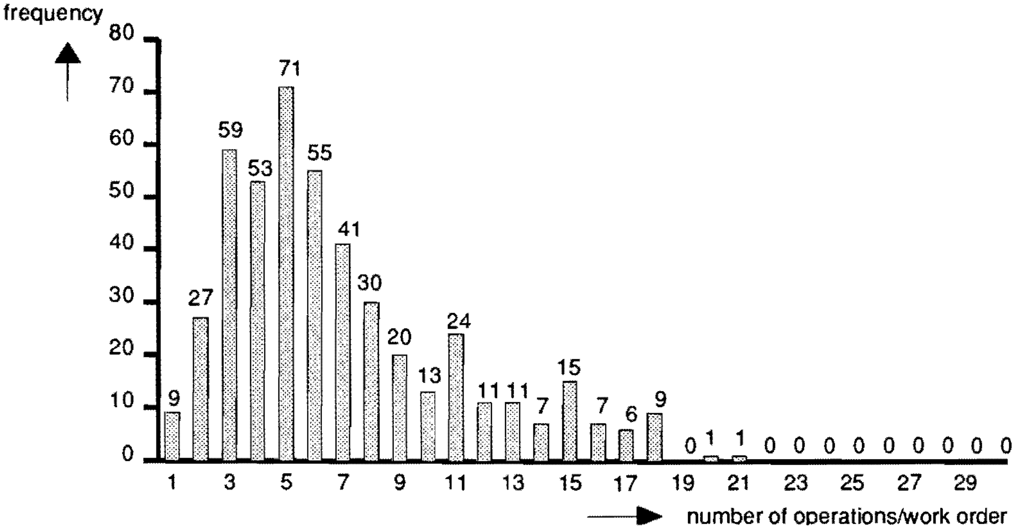

Figure 2.6:
The frequency distribution of the number of operations per work order, without fill-work

Based upon these findings and the acceptance of this approach in the literature (see Chapter 3), a geometrical distribution function will be used to model the number of work orders per assembly order and the number of operations per work order in the theoretical research associated with this study.

Data has also been compiled with respect to the third aspect regarding the distribution of processing times based upon the operations performed in the Mould Group. The Mould Group has 38 operation codes. The 193 assembly orders sampled in 1988 were analyzed with respect to the frequency distribution of the processing times to determine whether a negative exponential distribution function can be used to accurately represent this aspect.

There was insufficient data to make reliable conclusions for 19 of the 38 operation codes. For 15 of the 19 remaining operation codes it was apparent that a negative exponential distribution function provided accurate results. In four cases, however, this distribution function did not provide an accurate representation of the processing times (see Table 2.5). With a level of significance of 0.025 only in one case did the negative exponential distribution not provide an accurate representation.

Table 2.5:
Results of the operation time analysis.

operation codes	average	standard-deviation	variance coefficient	number	number of clasess	chi-square calculation	chi-square critical points (0.05)	conclusion possible conform the N.E.D.
GM	97.89	140.88	1.44	683	10	208.37	15.5	FAULT
1GRA	45.13	44.46	0.99	77	7	4.35	11.1	GOOD
C06B	71.23	52.20	0.73	173	8	13.33	12.6	FAULT
C0SL	43.25	36.04	0.83	87	7	9.71	11.1	GOOD
H1SL	100.95	100.44	0.99	156	8	7.41	12.6	GOOD
H3SL	63.28	63.68	1.01	329	9	12.75	14.1	GOOD
HD8	90.91	60.98	0.67	99	7	12.38	11.1	FAULT
HDSL	110.48	94.20	0.85	105	7	7.57	11.1	GOOD
HV4F	125.70	87.94	0.70	57	6	8.03	9.5	GOOD
M2DR	102.38	119.62	1.17	86	7	4.30	11.1	GOOD
MGM	77.01	95.51	1.24	207	8	13.91	12.6	FAULT
NB2F	127.32	98.45	0.77	72	7	9.43	11.1	GOOD
NB2V	254.00	224.37	0.88	81	7	1.30	11.1	GOOD
NB3F	97.99	85.23	0.87	161	8	5.05	12.6	GOOD
NB4V	288.52	335.34	1.16	84	7	10.99	11.1	GOOD
NB6F	91.78	87.38	0.95	167	8	10.06	12.6	GOOD
PRGR	49.82	57.88	1.16	116	7	5.44	11.1	GOOD
R1B0	63.25	52.54	0.83	174	8	10.44	12.6	GOOD
R1SL	61.22	71.00	1.16	159	8	9.98	12.6	GOOD

These findings and similar findings presented in published studies with respect to the distribution of processing times provide sufficient justification for using a negative exponential distribution function to model the processing times in the theoretical research performed in this study.

◆ *Routing*

Due to the customer-driven characteristics of the assembly orders processed by the CGM, very little uniformity is likely to be found in the routing structures. A large number of different routes are theoretically possible. Nevertheless, a number of common initial operations such as sawing, and common finishing operations such as polishing or cleaning, can be identified. In addition, the work scheduled for finishing operations will normally have been present in the shop for a longer period of time than the work scheduled for an initial operation. With this in mind, it is useful to create three operation categories:

- types of operations found at the beginning of the routing, referred to as initial operations,
- types of operations found in the middle of the routing, referred to as intermediate operations,
- types of operations found at the end of the routing, referred to as finishing operations.

Since the route length may vary greatly, it can be useful to know the relative position of a certain type of operation in a work order in this way. It is apparent that the spread of the distribution is considerable in the practice of the CGM.

In view of these findings, it is justifiable to assume that there is an equal probability of an operation occurring at any position within the routing of a work order. This assumption is used in the theoretical research study.

2.7 Planning and control structure

Certain limitations are defined in this section which have been applied to the research objective of this study. This leads to four explicit problem areas which are investigated in further detail in the next two chapters in order to fully define the research objective.

The planning and control decision rules used for production scheduling and controlling the operations form the basis of the planning and control structure. These planning and control rules are used to make decisions which are essential for planning and controlling the manufacturing activities, often referred to as the core decisions, needed to achieve the desired objectives. The decisions which directly influence the objectives of maintaining short and reliable throughput times and the achievement of established utilization levels are of particular importance. (See [Bertrand et al., 1992, a] and [Bertrand et al., 1992, b].)

A short description of the processes which are subject to the planning and control activities is presented first. The way in which these processes are planned and controlled in the current situation is also described. The core decisions are then discussed. In conclusion, the problems associated with defining the planning and control rules are covered.

2.7.1 Processes subject to planning and control

In many instances, a customer order must first be reviewed and completed by the engineering department and the process planning department after it is received by the CGM. The engineering department prepares the product design documentation based upon the customer specifications. This includes blueprints of the tooling product and a list of the required materials for production. The process planning department prepares additional details based upon the design documentation. This includes the tasks and instructions for the shop which are worked out in the form of work order documentation. The actual manufacturing operations can then be initiated, provided that the required materials are available. The physical production process consists of the manufacture and assembly of components.

This means that the total production process, the period between the order acceptance date and the order completion date, has an initial phase in which the "production of documentation" takes place before the actual manufacturing operations can be initiated. This production of documentation must be completed before the physical production processes can be started and may, as such, be a critical factor in determining the total throughput time.

This production of documentation has its own set of problems which need to be addressed and resolved. The global customer specifications are translated into detailed product and manufacturing specifications. It is during this process planning phase that the engineering and manufacturing details are defined. These processes need to be modelled and appropriate data needs to be collected before the planning and control of these processes can be studied and analyzed in more detail.

The study here is limited to the planning and control of the physical production processes. It is assumed here that all of the product and manufacturing specifications have been prepared. Requirements with respect to planning and controlling the production of documentation in order to ensure that the planning and control of the manufacturing processes can be adequately performed, are studied in Chapter 10.

2.7.2 Current planning and control approach

The current planning and control approach used within the CGM is described in this section and several comments are made. This description is presented in a logical order, following the normal route taken by a customer order when it is processed by the CGM.

The CGM first evaluates the resource capacity which is available in each shop when new customer orders are provisionally accepted, prior to final acceptance of a firm quotation. In connection with this it is important to be able to estimate the resource requirements of each new customer order. This means that required number of processing hours in the shop as well as the period of time during which this capacity will be needed must be estimated. Because it is usually unclear what the exact specifications will be for a new customer order at this point in time, use is made of historical information and typical models of tooling products for which the resource capacity requirements are already known from past experience. The average throughput time and the resource requirements per period associated with each of these tooling product models are used as reference points. The most appropriate model is chosen based upon the specified lead time for the customer order and the primary technical characteristics of the tooling product. The resource requirements can then be estimated based upon the chosen model. The resource capacity is subsequently reserved and included in the Shop Capacity Loading Summary for the relevant shop. (See also [Ooijen & Wakker, 1991].)

The CGM provides an optimal loading profile for each shop via the Shop Capacity Loading Summary. This loading profile should, in principle, never be exceeded. This means that before a due date is assigned to a new customer order, the various options for scheduling the order during a different period of time or outsourcing a part of the order to a different shop or to an external shop must all be evaluated. The optimal loading profile is determined in such a way as to ensure that sufficient work is always available and, at the same time, to ensure that a given amount of new work can still be accepted in each period. This is accomplished by scheduling a longer throughput time for some of the customer orders than would otherwise be necessary. The extra flexibility created in this way is needed to be able to accommodate unexpected disruptions and to be able to accept rush orders from special customers. The throughput time and capacity required for the engineering and process planning activities is derived from the shop scheduling.

The detail scheduling activity is initiated as soon as the customer order has been confirmed and the due date has been assigned. The order and processing structures are fixed in the detail scheduling activity. Also included are the specifications of the so-called "special" operations such as: engineering, process planning and the supply of materials. Plan dates are then determined based upon the scheduled due date. The waiting times and transport times are determined based upon special tables of norms for each operation code which have been drawn up for planning purposes. It is generally not known exactly which operation codes will be used and included in the processing structure for a new customer order. This information is added to the detail production schedule at a later point in time.

A work order is released for manufacturing in the shop after the process planning for this work order has been completed and the required materials are available. Operation sequencing lists (which include the plan dates) are then used in the shop to determine which operations and work orders are to be started. A notification of completion is registered whenever an operation is finished. The work which is currently being processed in the shop as well as any work which has been completed in the shop is noted on the capacity planning schedule.

The following comments can be made with respect to the current approach:

- only the resource requirements of the customer order are reallocated on the time axis at the moment of due date assignment. In a situation where the capacity utilization is low, however, the throughput times should also be shortened;
- based upon experience, it is "known" that the planned throughput times of certain unevenly distributed customer orders can generally be shortened significantly at the time of due date assignment. If it appears that the standard waiting time from the operation code table is excessive in these instances, then shorter waiting times are used. Planning and control decision rules have not been established to make optimal decisions which utilize the latitude in the order structure in a systematic and consistent way in these situations;
- the due date reliability is generally worse in the periods in which the resource capacity utilization is relatively high;
- the CGM does not make explicit decisions regarding the release of work orders. The release of work orders is only delayed in situations where the required materials or the necessary documentation is not available. This has resulted in an ongoing discussion concerning the usefulness of applying workload control techniques (see Chapter 3) and the advantages of keeping all of the work orders belonging to a single assembly order together.

2.7.3 Core decisions

Four essential "core" decisions need to be taken with respect to each customer order while it is being processed:

- accepting the customer order and assigning a due date;
  A technical evaluation must be made with respect to each potential customer order to determine whether the CGM is capable and willing to manufacture the requested

product. Upon the CGM's acceptance of the customer order, the price is established and the due date is agreed;
- allocation and possible outsourcing of the assembly order;
  The required manufacturing technologies are determined after the engineering department has completed and delivered the design documentation. As soon as the required documentation is made available, the decision can be taken with respect to which shop will produce which components, based upon the capacity loading situation and consequences. If insufficient capacity is available internally, then the operations may be contracted out to an external shop. The disposition of the assembly orders is thus determined and allocated to internal or external manufacturing units;
- releasing a work order;
  A work order can be released to the designated shop for processing after completion of the process planning activity and after the required documentation and materials have been made available;
- sequencing the operations;
  Each skilled worker receives instructions with respect to the sequencing of operations for each specific work order and the machine assignments for each of the operations.

These four core decisions are concerned particularly with scheduling and controlling the utilization of the available resource capacities. The problem of material planning within the CGM is of lesser importance and has therefore not been included in this study.

The assembly task within the CGM is of lesser importance than the manufacturing of components. For this reason the manufacturing of components is the main topic of research in this study.

It was mentioned in the previous subsection that the scope of this study has been restricted to the physical manufacturing activities. The scope here is, in fact, limited to the production planning and control of the physical manufacturing activities within a single shop. This means that the process of creating assembly orders is not covered by this study and that the decisions with respect to outsourcing are similarly not discussed.

2.7.4 Planning and control decision rules

Three core decisions remain with respect to the production planning and control of the manufacturing of components within a single shop of the CGM:
- due date assignment, assuming that all of the documentation is available and that the assembly order (as part of the customer order) has been accepted;
- work order release;
- operation sequencing.

The planning and control decision rule for sequencing the operations is an Operation Start Date (OSD) rule which is used within the CGM. This means that operations waiting to be performed will be chosen in the order of earliest operation start date. These plan dates are derived from the scheduled due date, the work order release date and the normative waiting times which have been established by the CGM per type of operation. A structured approach to production scheduling is therefore required, including the determination of the relevant parameters. The establishment of a structured approach and the parameters in this respect is closely associated with the definition of the planning and control decision rules for the core decisions. This aspect is discussed in more detail in subsequent chapters of this study.

Four important problems areas have surfaced in connection with the definition of the planning and control decision rules for assigning due dates and releasing the work orders. These problem areas are:

- how to use the typical characteristics of the order structure most effectively.
  All of the components of a single assembly order should be available on the same due date. The geometrical structure of these assembly orders implies that the work orders belonging to a single assembly order will have different throughput times. By accelerating the processing of the large work orders, the realized throughput time of the assembly orders can be improved, provided that all of the work orders belonging to a single assembly order are released simultaneously. This assumes that assigning a longer throughput time to the small work orders will not have any adverse effect upon the throughput time of the related assembly orders. The characteristics of the order structure imply that there is a certain amount of variability and latitude which can be exploited effectively by the production scheduling and control activity. It is unclear how this latitude can be used in a controlled manner for reducing the throughput times of assembly orders;
- how to estimate throughput times reliably.
  The reliability of the due dates within the CGM is poor. The challenge is to find a better way to estimate throughput times, given that a way can also be found to make maximum use of the latitude in the assembly order structures. The question is which factors are significant and should be included in an improved estimation rule;
- whether an assembly order and all of the associated work orders should be released at one time, or the work orders should be released individually.
  The release of entire assembly orders instead of releasing work orders individually is less complicated from an organizational point of view. One of the advantages is having a simple release procedure. A second advantage is that the number of assembly orders to be managed is kept to a minimum in this way. This improves the manageability of the shop activities. It is not clear, however, what the consequences of taking this approach are with respect to the throughput times and due date reliability;
- whether workload control techniques are sensible to use with respect to releasing work

orders?
The use of workload control techniques (see also Chapter 3) appears to be a sensible approach to take in a variety of production planning and control situations ([Bertrand & Wortmann, 1981], [Wiendahl, 1987], [Kingsman et al., 1989]). It is not clear, however, whether workload control is also useful in the type of production scheduling and control situation such as found within the component manufacturing unit of the CGM. Additional study is needed to determine how the workload control technique could be adapted to this type of production planning and control situation and to what extent benefits can be derived from this approach.

At the present time the CGM primarily takes factors such as the total resource capacity requirement of the customer orders (in hours) and the total shop loading percentage into account when assigning due dates. With respect to releasing work orders, the only factor taken into account is whether all of the necessary documentation and materials are available.

2.8 In conclusion

The four problem areas identified in the previous section are considered in more detail and rephrased as research issues in the following two chapters.

The CGM recognizes the fact that manpower as well as machinery can be critical, limited resources with respect to the manufacturing of components. Both of these factors may be responsible for waiting time delays at the operation code level. The critical factor of having sufficient human resources can be alleviated by ensuring that workers are skilled in multiple specialized areas so that they can be employed with a high degree of flexibility. This means that the planning and control decision rules also need to take the multi-skilled human resources into account so that optimal decisions can be made with respect to which capacity group and which type of operation a multi-skilled worker should be assigned. The benefit of using multi-skilled workers is not addressed in this study ([Bertrand et al., 1991], [Ooijen, 1993]). A number of simplifications will be made with respect to this factor in the structure of the model for the theoretical research study. (See Chapter 4).

Much of this study focuses on developing the planning and control decision rules for the core decisions with respect to "assigning due dates" and "releasing work orders". The assignment of due dates is discussed in detail in Chapters 5, 6, 7 and 8. The release of work orders is discussed further in Chapters 7, 8 and 9. A summary of relevant studies published in the literature in presented in Chapter 3. Practical recommendations are provided in Chapter 10.

Chapter

3 REVIEW OF THE LITERATURE

3.1 Introduction

The published studies and available literature on the subject of production planning and control in manufacturing component parts, such as described in Chapter 2, are reviewed in this chapter. The terminology from this study is used in the description of the results of the relevant published studies and literature.

The relevant literature can be grouped into three categories:
- the literature dealing with the production planning and control implications of orders with network structures, typically oriented toward the formulation of due date assignment and sequencing rules;
- the literature dealing with specific subjects related to the planning and control problems in shops which handle orders with network structures;
- the literature dealing with the development of decision rules for releasing work orders based upon the principles of workload control, whereby aspects concerning the network structure of orders are not considered.

Subsequent sections in this chapter present a review of the available literature in each of these three categories.

A formulation of the research objective and the approach which has been chosen in this study are included at the end of this chapter.

3.2 Literature dealing with the implications of orders with network structures

The chosen models for the network structures of assembly orders used in the simulation analyses incorporated in this study are described in Chapter 4. This section covers the models of order structures which have been developed and used by a number of other researchers. The major findings of the published results of their research are described. Specific attention is paid to two subjects which have been addressed by studies in the past.

◆ *Order structures used by other researchers*

Much of the research described in the literature is focused on the subjects of controlling throughput time and due date reliability for customer orders with convergent nodes in functionally organized shops. A customer order with convergent nodes is typically referred to as an "assembly order". Studies in this area have been carried out by, for example: [Maxwell & Mehra, 1968], [Maxwell, 1969], [Goodwin & Goodwin, 1982], [Fry et al., 1989, a, b], [Adam et al., 1987], [Adam et al., 1991], [Weeks, 1979] and [Siegel, 1971].

W.L. Maxwell was one of the earliest researchers to publish the results of simulation studies involving work orders with network structures ([Maxwell, 1969]). Maxwell defined the assembly orders in this study according to a geometrical distribution function with an average of nine operations per work order and a maximum of 39 operations per work order. Each assembly order consisted of either two, five or ten work orders. In addition, each assembly order had one assembly operation with an assembly time of zero. When these assembly orders are represented in the form of a network diagram, then each network structure has one divergent node (the starting point of the order) and at least one convergent node (the assembly operation).

Sculli ([Sculli, 1980]) used order structures similar to those used by Maxwell.

A larger number of divergent nodes were defined in the assembly orders modelled in the study carried out by Adam ([Adam et al., 1987], [Adam et al., 1991]). The number of divergent nodes and the positioning of these nodes in the network structure of the assembly orders was fixed. Adam defined four basic structures in this way with a uniform distribution of the number of work orders per divergent node. Similar to the models used by Maxwell and Sculli, Adam also included one convergent node defined as an assembly operation with a processing time of zero. In addition, Adam utilized a special procedure to approximate a geometric distribution for defining the number of operations per work order. He also set a maximum limit of 39 operations per work order with an average of nine.

Other researchers have typically chosen to use a limited number of fixed order structure definitions in their models. The results of these studies are less relevant to this study because of the static nature of the order structures and the specific focus on multi-level aspects where assembly orders can have multiple convergent nodes.

◆ *Results of published studies*

Maxwell studied the effects of various alternative priority rules. Maxwell ([Maxwell & Mehra, 1968]) used four basic decision rules and various composite rules. They discovered that composite decision rules based upon complex structures provided performance improvements. A study carried out by Maxwell ([Maxwell, 1969]) demonstrated that good results could be obtained by using a number of sequencing rules in conjunction with the basic SPT (Shortest Processing Time first) rule. This was done, firstly, by assigning a priority category to all of the work orders for each separate work station based upon the first decision rule criterion. Then, for each priority category, the SPT rule was applied. Maxwell discovered that the decision rules which used the remaining slack criterion generally provided the best results with respect to the average tardiness. The rules based upon the remaining work effort of the work orders or assembly orders provided the best results in terms of minimizing the average total throughput time. It is interesting to note that the rule based upon the remaining number of operations per work order produced better results in situations where there were a relatively small number of work orders per assembly order (2 and 5). The rule based upon the remaining number of work orders per assembly order (referred to by Maxwell as "NUSEG", the number of remaining segments) demonstrated better results when there were a relatively large number of work orders per assembly order (10).
When compared to the First-Come-First-Served rule, this approach provided a reduction in throughput time as follows:

- 40% when there were two work orders per assembly order;
- 25% when there were five work orders per assembly order;
- 18% when there were ten work orders per assembly order.

The improvement with respect to the average tardiness varied between 68% and 12%.

Sculli confirmed the results published by Maxwell, but added that using the "number of remaining work orders" rule requires an extensive data collection system which would be extremely costly to implement in most instances.

Siegel ([Siegel, 1971]) extended the work of Maxwell and studied a wide variety of decision rules for assigning due dates and sequencing operations. Siegel determined that the sequencing rule based upon the minimum total remaining work effort of assembly orders (Total WorK Remaining, or "TWKR") provided the best results with respect to minimizing the average throughput time. Siegel identified three factors which influenced the throughput time:

- pacing, whereby work orders belonging to a given assembly order are processed more-or-less simultaneously within the shop. If one of the work orders is delayed, then it is no longer critical for the related work orders to be completed according to the originally assigned priorities and production schedule;
- acceleration, whereby assembly orders requiring a relatively small remaining processing effort are given a higher priority;
- structural dependency, whereby the characteristics of the network structure of an order need to be considered.

The acceleration factor has, in essence, been incorporated in the NUSEG rule developed by Maxwell. The other two factors will receive the most attention in the study presented here and in regard to the planning and control decision rules to be developed. The structural dependency factor, in particular, will be investigated in more detail and developed further.

Fry et al. ([Fry et al., 1989, a, b]) studied the performance of a number of variants of the due date assignment rules developed by Maxwell and Siegel. The most important enhancement was the inclusion of workload data in calculating the coefficients of the due date assignment rule. They determined that the performance improved substantially when the workload data was included.

Adam et al. ([Adam et al., 1987]) have extended this study even further by allowing for dynamic adaption of the coefficients, dependent upon the order mix and the workload conditions. The resulting decision rules demonstrated that the completion delay[1] could be reduced. These decision rules were based upon the TWKR rule. Initially, two work orders belonging to a single assembly order are given the same priority based upon the TWKR rule. Adam developed two additional decision rules to take into account the relative remaining work effort associated with the operations incorporated within a single work order in relation to the average of all of the work orders belonging to a given assembly order. Adam was able to show a 5% to 15% reduction in the average

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[1] The completion delay represents the waiting time which can occur in connection with assembly operations where the components produced from multiple work orders must be combined. If the completion of a component work order occurs before the earliest possible start time for the assembly operation due to a delay in one or more of the component work orders, then a completion delay is said to occur. In this way the completion delay for each of the component work orders is defined as the period of time between the arrival of that component part at the assembly station and the time of arrival of the last component part at the assembly station.

throughput time as compared with the TWKR rule. He did not report the outcome of this research with respect to other possible evaluation criteria such as lateness.

Adam et al. ([Adam et al., 1991]) additionally investigated the effects of various due date assignment and priority rules based upon the same order structure models. The results of this study demonstrated that dynamic decision rules are better than static rules. The assignment of a dynamic (i.e., workload dependent) due date which is independent of the order characteristics (i.e., based upon the average for all of the orders) is just as reliable as the alternative decision rules which he evaluated, including dynamic rules, which take the order characteristics into account. Adam recommends using the first rule in view of its relative simplicity. The validity of Adam's conclusion is questioned in this present study, however. The results reported by Adam may have been biased by the static structure characteristics upon which his research was based. The present study has not been restricted to such static characteristics and, as a result, arrives at different conclusions.

Adam et al. ([Adam et al., 1991]) introduced a new decision rule designed to reduce the lateness factor to zero. Adam discovered a reduction in the tardiness in the instances dealing with the multi-level assembly of assembly orders. This improvement was achieved at the expense of an increase in the average assembly order throughput time.

In this study, Adam experimented with two different priority rules: a work order due date rule and an operation due date rule. The first rule provided better results in the case of multi-level assembly of assembly orders.

Philipoom et al. ([Philipoom et al., 1991]) have taken the findings of Adam one step further by introducing the Importance Ratio (IR). The IR provides an indication of the relative positioning of an operation within the total routing. This can be illustrated by assuming, for example, that there are three operations left to be performed in the manufacturing process routing for a component part to complete the customer order. If there are five operations in total, then the IR of the current operation is 3/5. According to Philipoom, the relative simple, composite priority rule based on IR/TWKR provides the best results. In connection with this, however, it was noted that the improvements caused by this operation sequencing rule are dependent upon the characteristics of the order structure as well as the shop.

3.3 Literature dealing with specific subjects

Literature has been published on two subjects which are not directly related to assembly orders but are nevertheless relevant to this study, namely:

- pacing: the pacing effect within assembly orders is optimal when the average lateness and the variance of the lateness of the work orders are minimal. The published research in this area will be reviewed here;
- completion delays: the known techniques for estimating completion delays will be reviewed.

As noted above, pacing has been recognized by Siegel as being an important factor in determining the total throughput time. Useful research with respect to this factor has been carried out particularly in job shop environments based upon orders without network structures.

The second subject deals primarily with the effects of the structural dependence factor, focusing specifically on the structural characteristic concerning the "number of work orders per assembly order".

♦ *Realistic work order due dates*

When the average lateness and variance of the lateness of the work orders are significant, this indicates that a disappointing degree of pacing has occurred. The following research results provide guidance on how to minimize the average lateness and the variance of the lateness.

Eilon and Chowdhury ([Eilon & Chowdhury, 1976]) have published the results of experiments in which Bertrand ([Bertrand, 1983, b]) postulated that the standard deviation of the lateness is minimized when the average lateness approaches zero. This means that incidental occurrences of lateness will be minimized when the estimated completion times are as close as possible to the actual completion times. With respect to scheduling, this implies that the scheduled slack time should generally be equal to the average actual waiting time.
Bertrand has been able to test and confirm these findings with respect to other priority rules and due date assignment rules.

Kanet & Hayya ([Kanet & Hayya, 1982]) have compared a number of priority rules. One of the important conclusions which they were able to make was that the Operation Due Date rule (ODD) produced by far the best results. In addition, the utilization of this rule

had a favourable influence on the quantity of work in progress. The use of ODD gave the smallest variance in the lateness of the work orders. This finding is also consistent with the intuitive expectation according to Kanet & Hayya. The Operation Due Date approach requires the definition of "milestones" to structure the flow of the work orders within a shop.
A somewhat surprising result, contrary to the findings of Conway et al. ([Conway et al., 1967]), was that the Operation Due Date rule also performed better than the Slack per Operation rule.

♦ *Completion delay*

The term "completion delay" is used frequently in connection with network scheduling theory. A network generally consists of activities which must be performed simultaneously in parallel as well as sequentially in series. Such a network has a single starting point and a single end point. The duration of each activity can be modelled based upon the random sampling of a specific distribution function.

A "node" is defined as a point in the network at which multiple parallel activities must all be completed before a new activity can be initiated. A "branch" consisting of a number of activities in series can be used to connect two nodes.[2]

A "completion delay" occurs whenever a completed activity is required to wait for the completion of a parallel branch at a specific node. These completion delays at the various nodes in a network are the factors which make it difficult to estimate the total duration of a whole network.

Much has been published on the subject of estimating the total duration of a network. Early studies were typically based upon a normal distribution of activity times. In this way the duration of branches and of whole networks could be determined using convolution and maximization functions. Clark ([Clark, 1961]) published an article in which he presents a convenient method for determining the maximization function for more than two mutually dependent but dissimilar normal distributions. Numerous useful tables are also included in this article.

In recent years various authors have concluded that the duration of activities is more likely to conform to a beta distribution function than a normal distribution function. Sculli & Wong ([Sculli & Wong, 1985]) present evidence in their article that the summation

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[2] The definitions of a "node" and a "branch" are switched around in some network theories. These alternative definitions are not convenient for use in connection with the structure of sub-orders and, therefore, are not used here.

function (convolution) and the maximization function of mutually independent beta distributions can be approximated by new beta distributions. An article written by Golenko-Ginzburg ([Golenko-Ginzburg, 1989]) appeared in 1989 which also discussed mutually independent beta distributions. He proposed the use of a new distribution function, specially developed by him, to approximate the convolution and maximization functions.

The implications of completion delays are covered in more detail in Chapter 6.

3.4 Literature on the principles of workload control

The published findings with respect to the development of planning and control decision rules for releasing work orders based upon the principles of workload control are reviewed in this section.

Bertrand and Wortmann ([Bertrand & Wortmann, 1981]) have developed a theoretical framework for controlling the throughput time in functionally-oriented manufacturing units in which singular components are produced in batches. Their approach provides for a better control of waiting times and, consequently, the throughput times by maintaining a constant workload in the manufacturing unit. This approach is called the workload control method. Wiendahl ([Wiendahl, 1987]) also developed a method in which the workload is held constant. Wiendahl's approach differs significantly from the workload control method in a number of ways, however. These differences are described in more detail later in this section.

The principles of workload control are reviewed here and the practical implications are described. A summary of the reasons typically given to justify the use of workload control is also presented. Subsequently, a method for establishing different flow rates for work orders in manufacturing units is described.

♦ *The principles of workload control*

Bertrand and Wortmann ([Bertrand et al., 1991]) distinguish two levels of aggregation for production planning and control:

- the plant logistics planning and control level (or materials management level) at which the flow of materials for a whole manufacturing plant is coordinated;
- the manufacturing unit level at which the production planning and control for a single shop or manufacturing unit takes place within the framework of the manufacturing plant's logistics planning and control. Manufacturing units are essentially isolated from

each other and from the business environment through the use of buffer stocks at key points.

Workload control techniques are applied at the manufacturing unit (shop) level.

A shop cannot produce output without having work in progress. Output is defined as the accomplished work contents per time unit, expressed e.g. in processing hours per time unit. Output is generated only after a work order is issued to the shop along with the associated materials and instructions. The output of a shop is also dependent upon the amount of work in progress which is present. The work in progress is defined as the total work contents of the work orders assigned to the shop which have not yet been completed. The utilization percentage is defined as the actual average output divided by the maximum output potential of the net available resource capacity per period. The relationship between work in progress and the shop utilization percentage is presented graphically in Figure 3.1.

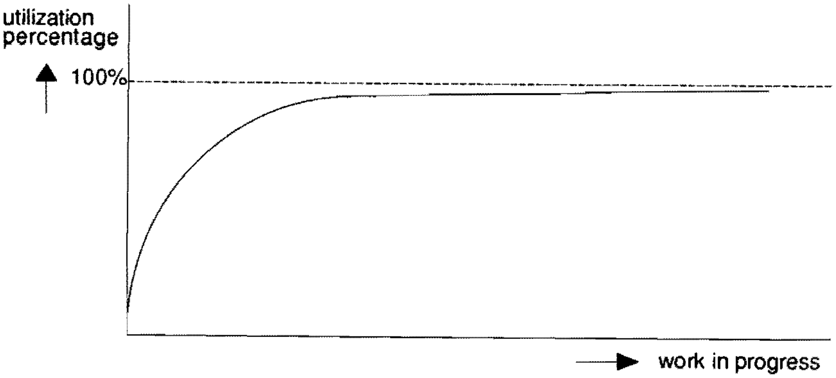


Figure 3.1:
The relationship between work in progress and the shop utilization percentage.

When there is a low utilization percentage, doubling the amount of work in progress will normally result in nearly a doubling of the output. However, if a shop is already producing output based upon full utilization of the maximum available resource capacity, increasing the work in progress will have little effect upon the volume of output.

This relationship is of essential importance in controlling the total order throughput times for a shop. This shop throughput time is defined as the elapsed time between the release of a work order to the shop for processing and the time of completion. The shop throughput time is thus equal to the sum of the operation times, transport times and waiting times. The transport times are not examined further in this study and are, as such, assumed to be negligible. The operation times are generally fixed. The waiting times can fluctuate greatly, however. ([Shelton, 1960])

The utilization percentage typically has a maximum achievable value of less than 100% in practice. Due to maintenance or other disruptions it is rarely possible to achieve a 100% utilization level. Examples of disruptions which could reduce the availability of a resource include organizational disturbances, missing instructions, mechanical failures, etc. The maximum achievable utilization percentage is dependent upon the specific situation.

A certain level of work in progress is necessary to realize the maximum achievable utilization percentage. A lesser amount of work in progress will result in a lower utilization percentage. A greater amount of work in progress will not increase the utilization percentage; in some situations more work in progress may even reduce the utilization level. More work in progress will affect the throughput time, however. Doubling the work in progress will generally double the average throughput time while leaving the output of the shop unchanged. The relationship between the average throughput time and the work in progress is presented in Figure 3.2.

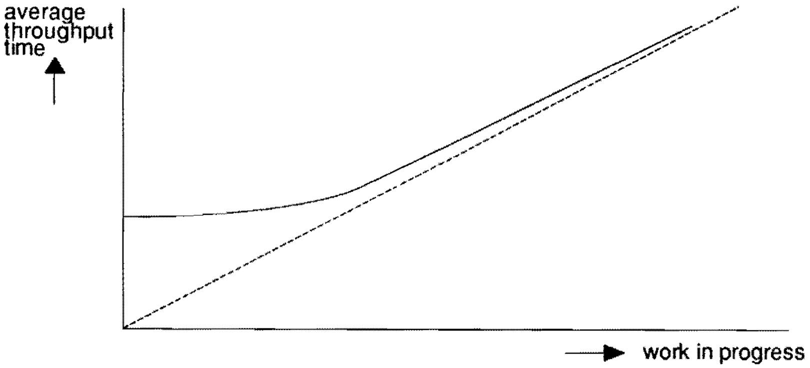


Figure 3.2: The relationship between average throughput time and work in progress.

If the amount of work in progress is held constant in a situation with a constant average arrival rate of new orders, then the average throughput time will also remain constant and a certain average utilization percentage will be realized. The work in progress level for a given shop should therefore be set at a point which provides for the desired average throughput time and an acceptable average utilization percentage (see figure 3.3).

Work in progress contains also work that is already completed. In most situations, a number of the manufacturing operations of a work order will have been completed but the final operations will not yet be completed. The amount of work remaining is the only aspect which is relevant for workload control. For this reason, a new term is needed: the "remaining workload". Using this new term, the principle of workload control can be restated as follows: the remaining workload level should be established based upon the desired average throughput time and utilization percentage for a given shop.

The remaining workload will normally be expressed in terms of hours. In some situations it may be useful to define a related unit for measuring the workload, such as the number of products or the number of orders. The work content of shop orders in tool & die shops (expressed in hours) can vary enormously, depending upon the type of manufacturing process. For this reason, this study will use "hours" as a basic unit for measuring the remaining workload.

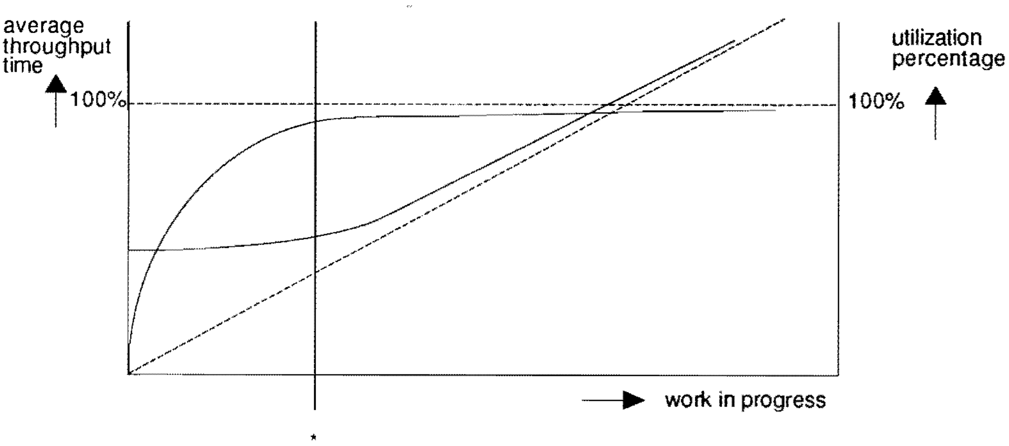


*Figure 3.3: The determination of the work in progress level (denoted with *).*

◆ *Practical implications*

Shops often utilize a variety of limited resources for which workload control is required. Examples of such resources could be:

- single machines or groups of interchangeable machines;
- individual machine operators or groups of machine operators having similar skills;
- combinations of machine operators and machines;
- the total shop capacity.

The use of workload control methods may not be relevant for certain types of limited resources. For example, machines with a relatively low utilization percentage (e.g., 30% or less) will almost never have a significant influence on the total throughput time. Workload control is generally only needed in situations where significant waiting times can occur with respect to specific limited resources. In these situations it is important to provide for the accurate registration and monitoring of the remaining workload for the relevant resources.

The workload control approach is not applicable in every manufacturing environment. It is worthwhile to utilize the principles of workload control only when:

- appropriately controlled waiting times are the primary determinant factor influencing the throughput times;
- the layout of the shop is organized along functional lines or according to the criteria

used in group technology theory (see [Bertrand et al., 1991]). A functional layout is typically used within the clusters which are defined in this way;

- the capacity loading of the limited resources are sufficiently stable over reasonable periods of time. If fluctuations in the capacity loading are too extreme, then the remaining workload levels will need to fluctuate accordingly. This can result in an unacceptable instability within the total system.

A work station is defined as a group of machines an/or machine operators which functions as a single limited resource. In practice, such a group of machines will typically be located in the same general area so that they are also physically identifiable as belonging to a single work station. A carefully designed model of the resource capacity structure and the queuing situations in a shop is necessary in practice for identifying the work stations and other limited resources in an appropriate way.

The usefulness of implementing the workload control approach has been demonstrated in a number of practical situations. Published studies have also shown that applying the principles of workload control has a favorable effect on the spread of lateness times (see [Bertrand, 1983, b].

♦ *Justification for the application of the principles of workload control*

Up until now, there has been no theoretical support to prove that the workload control approach will lead to a reduction in the average total throughput times. The total throughput time is defined here as the period of time from the arrival of the order at the shop until the date of completion. If work orders are not explicitly released in a given shop, then the total throughput time is equivalent to the shop throughput time. When work orders are explicitly released, for example, based upon the principles of workload control, then they can be held back in a sort of buffer stock. The length of time which a work order is held in a buffer in this way is referred to as the *buffer holding time*. In this case the total throughput time is then equivalent to the buffer holding time plus the shop throughput time.

There are numerous practical reasons for using the principles of workload control in a shop to control the shop throughput times. These reasons include:

- limiting the number of work orders being processed in the shop to the minimum necessary quantity. A better supervision of activities can be maintained in this way;
- allowing for the possible reexamination and modification of due date assignment decisions for work orders up until the time that the order is released;
- taking decisions with respect to the expansion of resource capacities (e.g., through overtime or contracting out to third parties) at the proper level in the organization

based upon workload data. Such decisions can, of course, also be taken based upon other information;

- providing for continual on-the-job training in multiple skill areas by limiting the number of work orders on the shop floor to the minimum necessary quantity so that machine operators are given ample opportunity to develop and maintain multiple skills. In this way a high degree of flexibility and a better utilization of resources can be achieved.

In view of these practical aspects, it is advantageous from an organizational point of view to utilize the workload control approach as an effective technique for the control of the average shop throughput time.

Alternatives for the workload control approach followed by Bertrand and Wortmann have been published by other researchers in the meantime. Perhaps the most well-known alternative approach is the "Belastungsorientierte Fertigungssteuerung" proposed by Wiendahl ([Wiendahl, 1987]). A second example of an alternative for the original approach to workload control has been provided by Kingsman ([Kingsman et al., 1989]).

The workload control method uses a single average rate of flow for all of the work orders. When scheduling takes place, the same waiting time per operation is planned for all of the operations and, as a result, identical priorities are assigned. Within limits, the assignment of different rates of flow to different work orders has no significant influence on the effectiveness of the workload control method. In practice, however, there are a multitude of reasons for assigning different priorities to different types of work orders. Providing for a distinction between only "normal" and "rush" orders is not sufficient. A rush order is generally given the highest possible priority which is, in principle, to be used only for the true "emergency" situations. A method for controlling a variety of flow rates is a critical requirement in tool & die shops.

♦ *Different flow rates*

Van Ooijen ([Bertrand & Ooijen, 1991]) researched the effects of using different rates of flow for two different categories of work orders. The average throughput time was controlled using the principles of workload control. The specified slack for the first order category was reduced and the slack for the second order category was increased in such a way that the average slack remained equivalent to the standard waiting time (see also the conservation laws of Kleinrock [Kleinrock, 1976]). Van Ooijen discovered in this situation that a reduction in the slack to a specific percentage resulted in a proportional reduction in the waiting time in relation to the maximum possible reduction in waiting time.(See also [Goldberg, 1977], [Bertrand & Ooijen, 1991], [Ooijen, 1991].) (See Figure

3.4.)

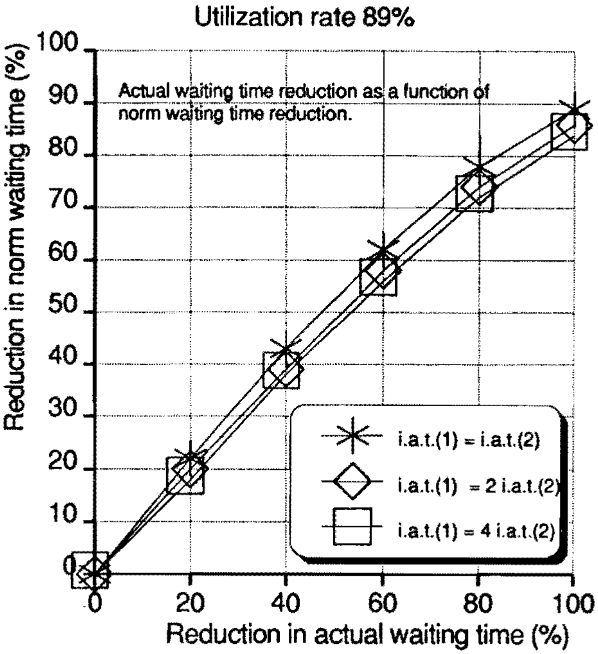


Figure 3.4:
Actual waiting time reduction as a function of norm waiting time reduction; utilization percentage 89%. (From [Bertrand & Ooijen, 1991].)

The size of work orders in tool & die shops can vary anywhere from one operation to dozens of operations. A work order is assigned a specific flow rate depending upon its structure.

The method developed by Van Ooijen is based upon the ODD priority rule and can be used effectively for the assignment of due dates. This method is called "acceleration and retardation" because the first category orders are speeded up, accelerated, and the second category orders are slowed down, retardated.

3.5 Formulation of the research objective

The subject of this study was introduced in Chapter 2. A more precise formulation of the research objective of this study is presented here. The four problem areas posed in Chapter 2 were as follows:

- how to utilize the available latitude in the structure of an assembly order;
- how to forecast the order completion dates;
- deciding whether to release orders at the assembly order level or the work order level;
- determining whether it is worthwhile to release orders using the workload control method.

Finding the solutions to these problem areas will help in formulating planning and control decision rules for assigning due dates and releasing work orders.

Operation sequencing at the CGM was performed based upon the ODD rule. Published studies indicate that this is a sensible priority rule to use with respect to pacing.

This section covers the various solutions described in the literature with respect to the four above-mentioned problem areas. The areas are also identified in which further research is required before useful solutions can be found. This analysis provides the basis for formulating the specific research issues.

♦ *Throughput time reduction*

The research results published by Van Ooijen have shown that it is possible to assign different flow rates to separate categories of work orders within the context of workload control. The flow rates can be regulated by increasing or decreasing the slack associated with the work orders in such a way that the average slack is the same as the standard waiting time. ODD can be used as the priority rule in this case.

The traditional method of estimating the throughput time of an assembly order is to identify the critical path and then to use the throughput time of the critical path as the throughput time for the whole assembly order. As described in Chapter 2, there is generally a certain amount of latitude built into the structure of assembly orders which could be utilized to reduce the throughput time of the assembly orders. Shorter slack times per operation can be assigned to the larger work orders belonging to a given assembly order and longer slack times per operation to the smaller work orders. This can be done so that the average slack time remains unchanged. The magnitude of the increase or decrease in slack time is wholly dependent upon the structure of the assembly order. In this way an unlimited number of work order categories can be created, each with its own flow rate.

Several researchers have developed due date assignment rules in which slack time is implicitly swapped between different work orders. The exchange of slack time in this way is not scheduled in advance, however, such as in the method used by Van Ooijen. A number of the significant drawbacks in using the implicit method of slack time swapping as discussed in the literature will be described in Chapter 7.

An initial question to be answered is whether the method presented by Van Ooijen can be used in a situation where the order structure has network characteristics. Workload control methods are generally not used in this type of situation.

Assuming that the slack can indeed be transferred from one work order to another work order, are there then limits to the amount of slack which can be transferred? How can the transfer of slack be scheduled so that a reliable estimate of the throughput time of each assembly order can be made? To what extent can the throughput time of assembly orders be reduced? What implications does this have with respect to the reliability of the due date?

The first research issue is to determine whether Van Ooijen's method of using acceleration/retardation can lead to shorter throughput times for assembly orders. This research issue has three parts:

- determining how Van Ooijen's approach should be utilized;
- determining the expected reduction in throughput time for assembly orders;
- determining the effects on the performance of assembly orders, given the effects on the performance of the associated work orders.

◆ *Due date reliability*

A prerequisite to being able to assign feasible and reliable due dates is to have accurate estimates of the throughput times. Reliability in this context means that the assigned due date is as close as possible to the actual completion date.

The approach of using different flow rates within assembly orders, as referred to in the first research objective, needs to be reformulated as a due date assignment rule.

Published studies suggest that it is sensible to include dynamic workload data within a due date assignment rule to establish the due date. In addition, there is the problem of how to handle the completion effects of the assembly orders. Completion delays are normally associated with work orders belonging to an assembly order. The completion delay is also an important factor in determining the critical path in network scheduling theory. To what extent is it necessary to incorporate the aspect of completion in a due date assignment rule for assembly orders?

The second research issue is to develop a due date assignment rule to provide a minimum throughput time in conjunction with reliable due dates for assembly orders.

♦ *Order release*

In a network environment, attention is focused primarily on assembly orders. A logical approach would be to release all of the work orders belonging to a given assembly order together at the same time, rather than individually. This approach is implicitly followed in the published studies. There are two conceivable disadvantages to taking this approach, however:

- the specific structure of an assembly order can result in the addition of extra slack caused by differences in the scheduled throughput times of the work orders belonging to a given assembly order. This can lead to a sequencing of operations at the work order level which is different than the sequencing which was intended when the plan dates were scheduled;
- relatively high workload peaks are released each time, potentially causing large fluctuations in the shop workload. These workload peaks result from the fact that the total amount of work per assembly order is greater than the amount of work per work order.

Alternatively, the work orders could be released separately. This causes a dilemma with respect to the sequencing of the released work order, however. If work orders are released according to a FIFO priority rule, then the smaller work orders will generally be completed too soon. This approach implies also that all of the work orders of a prior assembly order must first be released before the first (largest) work order of a subsequent assembly order can be released. A problem occurs when the large work orders of new assembly orders have such long throughput times that they need to be released much earlier than the smaller work orders of previously released assembly orders. By following this approach, the smaller work orders can inappropriately monopolize the resource capacity needed by the large work orders belonging to new assembly orders.

The third research issue is to determine in which situations orders should be released at the work order level versus the assembly order level and how the release of work orders should be sequenced.

◆ *Workload control*

The principles of workload control have proven to be useful for controlling the average throughput time of a manufacturing shop in real-life situations. For this reason it is logical to apply these same principles to a component manufacturing unit of a tool & die shop for controlling the average throughput times.

Manufacturing environments which handle assembly orders can generally be characterized as being extremely versatile. Three typical characteristics of component manufacturing units within tool & die shops are:

- work stations with a large spread in the operation times, primarily due to the large diversity of component parts produced. Small, simple component parts typically have a short processing time which can be expressed in seconds or minutes. Large, labor-intensive components may have a processing time lasting several hours or days;
- a large number of routing possibilities, particularly when component parts are made-to-order. All component parts have their own specific operations structure and associated routing. Components having identical routings are uncommon. The CGM case described in Chapter 2 can be seen as a typical example;
- an irregular workload, especially when both the engineering design and manufacturing activities are specific to each customer order. The total shop workload in this situation is dependent upon the incidental quantity, size and composition of the customer orders. This results in an irregular workload for the component manufacturing unit of such a tool & die shop.

A relevant question is whether the principles of workload control should be applied at the assembly order level or rather at the work order level. In the last case, the problem of sequencing at the time of order release must be resolved. In this situation the work orders belonging to different assembly orders will be competing with each other for the limited resource capacities.

The fourth research issue is to determine to what extent the principles of workload control are applicable and can improve the performance in a component manufacturing unit environment in which assembly order structures are used.

3.6 Developing the research design approach

A summary of the published research findings which are relevant to this study has been presented in this chapter. It is apparent that use of the ODD priority rule (see [Stommels, 1979]) can be recommended to improve the due date reliability of work orders. Use of the ODD rule ensures the best due date reliability for work orders, whereby reliability is defined as the degree to which the actual completion dates correspond to the scheduled due dates.

The use of the ODD rule has been seen as a crucial decision with respect to the research design approach for this study. The use of ODD requires a detailed scheduling of the due dates (including ODD's) and release dates for the assembly orders, work orders and operations. The scheduling of assembly orders (including the work orders and operations belonging to these assembly orders) is needed as an initial reference point for planning and control purposes and to be able to guarantee the reliability of the due dates of assembly orders. The specified conditions required to control the ODD's are used in this connection.

Two factors are significant in (structuring) this study:

- pacing, with the objective of reducing the average lateness to zero and minimizing the variance of the lateness; and
- structural dependency, whereby the characteristic differences between assembly orders and work orders need to be recognized.

The pacing factor is implicitly included by basing this study on the use of ODD. The ODD's are used as the basis for ensuring a high degree of due date reliability.

The research method and approach are described in more detail in Chapter 4.

Chapter
4 RESEARCH METHOD AND APPROACH

4.1 Introduction

The research approach chosen for this study is described in this chapter. The remaining chapters are subsequently organized along the lines of this research approach. The reason for this is clarified in this chapter.

A brief description of the research method and techniques used in this study is also presented in this chapter.

4.2 Research approach

The research issues which are presented in chapter 3, are deducted from practice. The practice is described by means of the case study of the central tool and die shop CGM in chapter 2. The four research issues are:

- the first research issue is to determine whether Van Ooijen's method of using different flow rates can lead to shorter throughput times for assembly orders. This research objective has three parts:
  . determining how Van Ooijen's method should be utilized,
  . determining the expected reduction in throughput time for assembly orders,
  . determining the effects on the performance of assembly orders, given the effects on the performance of the associated work orders;
- the second research issue is to develop a due date assignment rule to provide a minimum throughput time in conjunction with reliable due dates for assembly orders;
- the third research issue is to determine in which situations orders should be released at the work order level versus the assembly order level and how the release of work

orders should be sequenced;
- the fourth research issue is to determine to what extent the principles of workload control are applicable and can improve the performance in a component manufacturing unit environment in which assembly order structures are used.

These research issues can be mainly solved by means of an investigation of the effects of using four different production planning and control methods with respect to due date improvements in terms of reliability as well as throughput time. The following methods (see also chapter 3) are evaluated:
- acceleration and retardation (see also Chapter 5);
- releasing whole assembly orders (a method which is implicitly used in a number of published studies, including the research work carried out by Maxwell and Adam ([Maxwell & Mehra, 1968], [Maxwell, 1969], [Adam et al., 1987], [Adam et al., 1991]); refer also to Chapter 7);
- dynamic due date assignment (as described by Bertrand in [Bertrand & Wortmann, 1981] and [Bertrand, 1983, b]; refer also to Chapter 8);
- workload control (see also Chapter 9).

There is a logical sequence in the adaptation of the four methods. This sequence is firstly determined by the principle of extending the planning and control complexity step by step and is secondly determined by the degree of loosening the relationship between the scheduled slack per operation and the average waiting time. The effects of using various methods are evaluated based upon systematic simulation studies. An initial state is defined and used as the starting situation for the subsequent simulation experiments to evaluate each of the alternative methods. The following research steps are observed:

- Step 0: Definition of the initial state.

  The initial state was defined as a set of scheduled operations grouped in work orders, whereby a fixed slack time was assigned to each operation. Slack is a dynamic factor, however. As time passes, the amount of slack time available for a work order becomes less. For this reason, the amount of slack which is available at the time of scheduling is referred to as the *allowance*. From the published studies (refer to Chapter 3) it is clear that pacing at the work order level can be controlled by allocating an allowance to each operation which is approximately equivalent to the average waiting time associated with the respective operation. Since the average waiting time is not yet known at the time of scheduling, it is necessary to use an estimate of this waiting time. Since the planning and control activity uses this estimate as an objective in the subsequent steps, the estimate is referred to as the *normative waiting time*.

  The fixed allowance in the planning of the initial state is set to be equal to the normative waiting time. In practice it is normal to release work orders as late as possible (refer also to Chapter 2). The planned release dates (PRD's) for the work orders are typically determined by counting backwards from the scheduled due date. An example is given in figure 4.1. The technique of acceleration/retardation can only be used when the ODD priority rule is followed. This priority rule is therefore used to define the initial state in this study. The performance which results when none of the four above-mentioned methods for production planning and control are utilized is used as a benchmark for the evaluation in the remainder of this study.

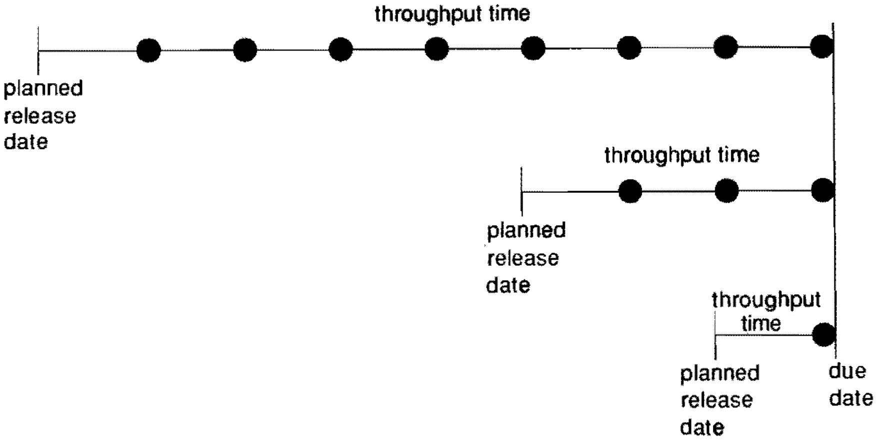


Figure 4.1:
All work orders of an assembly order scheduled to be completed at one given point in time, which is the assembly order due dated.

- Step 1: The "acceleration/retardation" method.

The acceleration/retardation method is evaluated first. This approach focuses on maintaining an average allowance for all of the operations at a level which is equivalent to the normative waiting time. The allowance per operation is variable. It can be expected that the use of this method will lead to an improvement in the throughput time of assembly orders by accelerating the time-critical work orders at the expense of the non-critical work orders.

- Step 2: The "releasing whole assembly orders" method.

  The method of releasing whole assembly orders is evaluated next. This is the traditional approach used in published studies in the past. The use of this method also leads to an improvement in the throughput time of assembly orders, but without keeping the average allowance at a level which is equal to the normative waiting time.

- Step 3: The "dynamic due date assignment" method.

  This method uses an approach whereby the allowance is dependent upon the amount of work in progress in the unit. Published studies indicate that this approach has a favorable effect on the due date reliability.

- Step 4: The "workload control" method.

  The last method evaluated in this study is workload control. The effects of using workload control with respect to throughput time and due date reliability are investigated in this study.

The research steps have been carried out in this order to ensure that the results of this study can be compared with the results of previously published experiments. Maxwell ([Maxwell, 1969]) and Adam (Adam et al., 1987]) evaluated their decision rules in a situation without workload control and without a dynamic due date assignment rule; their assembly orders were released as a whole at the time that the due dates were assigned.

By completing the research steps in this order, it is easier to compare the four methods with each other. The first two methods both focus on improving the assembly order throughput times. The second method follows the first to enable comparisons to be made, particularly with respect to the rule of keeping the average allowance equal to the normative waiting time (which is omitted in the second method). The last two methods both focus on improving the due date reliability. In connection with this, the existence of a dynamic due date assignment rule is a required condition for the useful application of workload control. The dynamic due date assignment approach takes the amount of work in a shop into account. The amount of work in this respect is dependent to some extent upon the throughput time. A shorter throughput time means that the amount of work in a shop will be less.

These research steps are illustrated in Figure 4.2. The relationships with the research issues are also indicated in Figure 4.2.

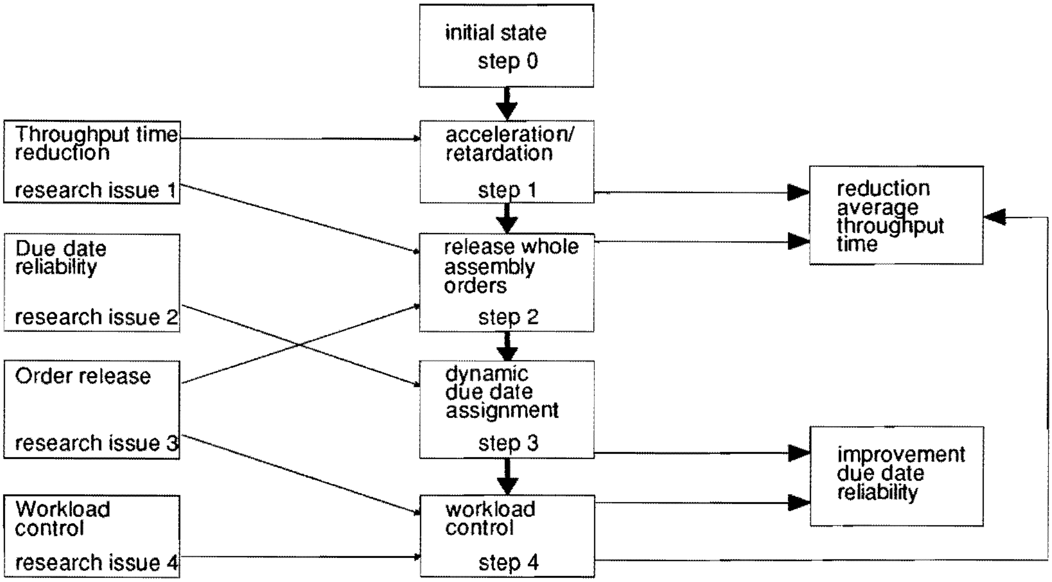


Figure 4.2: The research steps.

◆ *The impact of the category large assembly orders*

Three of the four investigated methods are developed for situations where mono products are manufactured and not multi products as in tool & die shops. Specific in multi product situations is the assembly order structure. This structure can be described with two geometric distributions, one for the number of operations per work order and one for the number of work orders per assembly order (see also section 2.6 and section 3.2). The geometric distribution for the number of work orders per assembly order indicates that there are different categories of assembly orders, whereby each category contains assembly orders with a certain given number of work orders per assembly order. The performance per category is often differently weighted in practice. A good performance of a large assembly order, in number of work orders, is in most cases more important than the performance of a mono assembly order (an assembly order containing one work order) because of the financial impact for both the customer as the supplier. Therefore is the performance of the category of assembly orders with the largest number of work orders apart investigated in this study.

In the next section we discuss the consequences of the assembly order structure characteristics for the throughput time modelling. Thereafter is the organization of the remaining chapters presented. The utilized tools and techniques for the systematic simulation studies are described in the last sections.

4.3 Components of the throughput time

The work orders belonging to a single assembly order usually differ in size (which is primarily a function of the number of operations) and therefore also differ with respect to the planned work order throughput time based upon a fixed allowance per operation. Two extreme variants exist for scheduling the release of the work orders belonging to a single assembly order, namely:

- all of the work orders are scheduled to be released simultaneously (refer to Figure 4.3);
- all of the work orders are scheduled to be completed at one given point in time, which is the assembly order due date, and are released at different times (refer to Figure 4.1).

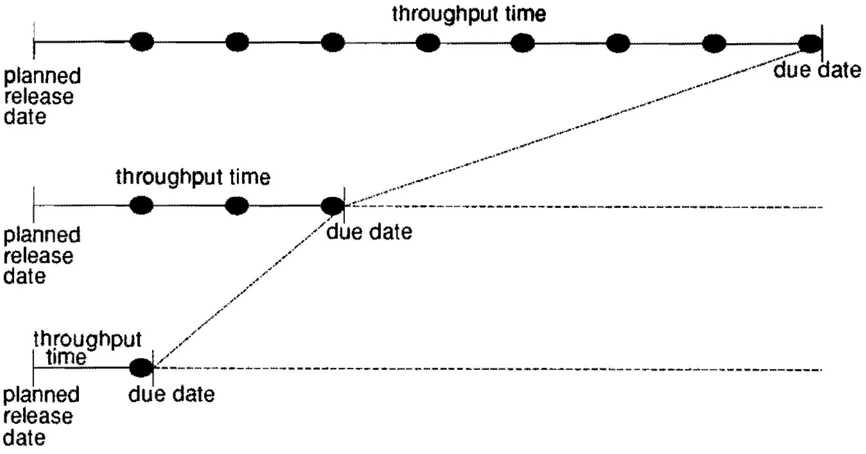


Figure 4.3:
All work orders of an assembly order scheduled to be released simultaneously.

A shortcoming of the first variant is that the smaller work orders are more likely to occupy the resource capacity while they are not time-critical, prohibiting the timely processing of larger work orders which may indeed be on the critical path. A non-critical work order can in this way block the capacity for a critical work order which arrives later in the system but nevertheless has a higher priority than the non-critical work order which has already been released. In such a situation, the higher priority work order may not be released due to the workload situation. This assumption will be tested in more detail in Chapters 7 and 9. The second variant does not have this shortcoming and provides a better solution in practice. In the second situation the documentation and resources for the time-critical work orders are first prepared within a product engineering unit and a process planning unit so that they can be made available for release at the earliest possible date. The remaining work orders which are not time-critical are then prepared and made available for release at a later date. This second variant is used for the study here.

The following events can be registered with respect to each work order:
- arrival in the system;
- release to the shop;
- completion;
- removal (upon completion of the assembly order).

Based upon these four events, the following measurements can be made:
- the buffer time for the work order, defined as the length of time between the arrival event and the release event. The buffer is the waiting queue in which orders have to wait for their release to the shop after their arrival;
- the shop throughput time for the work order, defined as the length of time between the release event and the completion event;
- the completion delay time for the work order, defined as the length of time between the completion event and the removal event.

An assembly order is defined as being released when at least one of the associated work orders is released. An assembly order is defined as being completed only when all of the associated work orders have been completed. As a result, the following events can be registered with respect to each assembly order:
- arrival in the system;
- release to the shop;
- removal (which is also the time of completion).

Based upon these three events, the following measurements can be made:
- the buffer time for the assembly order, defined as the length of time between the arrival event and the release event;
- the shop throughput time for the assembly order, defined as the length of time between the release event and the completion event.

♦ *Consequences of the structure characteristics*

The planned throughput times of the work orders belonging to a single assembly order will all be the same when the available latitude in the structure of the assembly order is utilized to the maximum extent to improve the throughput time of the assembly order. If this is the case, then an interesting question arises regarding whether the planned throughput time of the work orders (belonging to a single assembly order) can be equal to the planned throughput time of the assembly order. The answer to this question is "no", for the reason described hereunder.

If the work orders belonging to a single assembly order are scheduled with the same throughput time, then they will also have the same scheduled due date. Throughput times are stochastic variables. The realized throughput times will generally not be exactly the same as the planned throughput times, resulting in a variance in the lateness of work orders. When the average actual completion date of all of the work orders belonging to a given assembly order is equal to the originally scheduled due date of the work orders, then it can be said that the production plan for the assembly order has been realized to a high degree. Nevertheless, the completion date of the assembly order (which is defined as the completion date of the last work order) is always later than the average realized completion date of the work orders belonging to this assembly order due to the variance in the lateness of the work orders. This interval of time is referred to as the structure throughput time or, simply, *structure time*. The scheduled structure time is called the *structure allowance*.

For scheduling purposes, a distinction needs to be made between the expected throughput time of an assembly order and the expected throughput time of the associated critical path work order. These two throughput times have a different duration. Similarly, a distinction between an assembly order's expected completion date and the due date of the associated work orders is also required.

Three components of the planned throughput time of an assembly order can be identified:

1. The planned buffer time: the average time planned for an assembly order to wait before it can be released. This is referred to as the *buffer allowance*;

2. The planned shop throughput time: the planned throughput time of an assembly order which is derived from the planned shop throughput times of the associated work orders;

3. The structure allowance: the estimated period of time between the due date of the work orders of an assembly order and the expected actual completion date of that assembly order. Structure time is caused by the fact that the work orders belonging to a given assembly order are almost never completed at the same point in time; one of the work orders is generally finished last. A further explanation of how structure time is defined and estimated is included in Chapter 6.

The three components of the planned throughput time of an assembly order are illustrated in Figure 4.4.

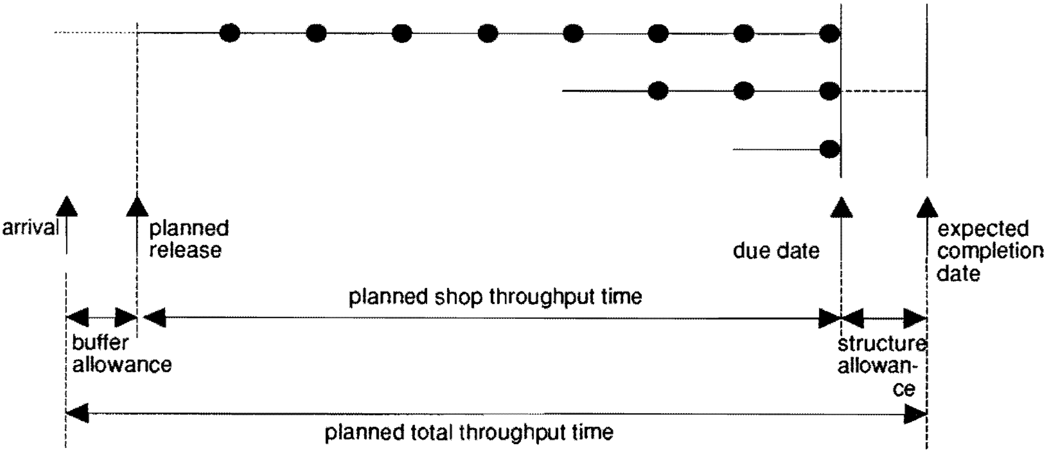


Figure 4.4:
The three components of the planned total throughput time of an assembly order.

4.4 Organization of the remaining chapters

This study is organized along two basic dimensions. One dimension is the research into the three components of the throughput time of assembly orders. In particular, the third component ("structure time") is unique for the manufacturing situations investigated here. The second dimension is concerned with research into the effects of using the four methods and techniques mentioned previously.

In Chapter 5, "Reducing Assembly order Throughput Time", the initial state for the simulation experiments is defined. In addition, the acceleration/retardation method is adapted to fit the specific manufacturing situations with assembly order structures which are studied here. The work orders belonging to a given assembly order are released as late as possible and are all scheduled for completion on the same due date in order to avoid differences in structure time effects. The structure time effects are negligible if the work orders belonging to a single assembly order are, for example, planned with a fixed allowance, released on the same date and scheduled with different due dates. When the acceleration/retardation approach is used, the throughput times of the work orders in an extreme situation will all be the same and all of the work orders will have the same scheduled due date. In this case the effect of the structure time is noticeable. To simplify matters, the scheduled due date of the assembly order is set to be the same as the scheduled due dates of the associated work orders for the situation studied in Chapter 5; the method for determining the structure allowance is not handled until Chapter 6 "Estimating the Assembly order Completion Date".

By using the acceleration/retardation approach, an attempt is made to keep all of the throughput times of work orders belonging to a single assembly order the same. In connection with this it is necessary to recognize the structure time factor. Structure time is discussed in more detail in Chapter 6. The other three methods for production planning and control are subsequently discussed in Chapter 7 ("Releasing Work Orders Belonging to a Single Assembly order"), Chapter 8 ("Dynamic Due Date Assignment and Work Order Release") and Chapter 9 ("Releasing Work Orders Using Workload Control") in a logical sequence as explained in Section 4.2. In chapter 10 "Translating Theory to Practice" are the results of the theoretic part of the study translated to practice. The conclusions are summarized in chapter 11 "Conclusions".

4.5 Utilized tools and techniques

During the development of the theoretical framework for this study it was determined that the standard computer programs available for carrying out simulation studies would not be able to meet all of the needs of this study. Special computer programs were therefore developed during the course of this study.

The specially-developed computer program to support this study is called "JAWS", an abbreviation for Job shop with Assembly and Workload Simulation. JAWS was initially developed as a thesis project by Rooijmans ([Rooijmans, 1988]). Subsequent modifications were made by Huibers and by this author.

A job shop is defined as being a dynamic, stochastic, discrete system. This means, in other words, that the situation within a job shop can be modelled as a function of time, that there are certain degrees of uncertainty with respect to the output results, and that the situation changes as the result of specific events.

JAWS requires the specification of variables. Values must be assigned to the variables to specify a given initial state (representing the situation e.g. of an autonomous group within the CGM). The setting of those variables is called the simulation model. This simulation model is defined in more detail in the following paragraphs. The purpose of this simulation model is not only to support the research of typical situations which occur in connection with manufacturing components in tool & die shops (such as the CGM), but also to provide a basis for drawing general conclusions.

Statistical distributions of data will be used whenever possible in view of the typical characteristics of such distributions which provide a reliable basis for estimating and interpreting results.

The following four basic aspects of the simulation model are described here:
- the shop structure;
- the order structures;
- the decision rules;
- control parameters.

♦ *The shop structure*

The shop structure of JAWS is presented in Figure 4.5.

The intermediate arrival times of the assembly orders are represented as random occurrences based upon a specified probability distribution function.

The shop modelled in JAWS has a single work order release point. There is a single input queue of work orders and assembly orders preceding this order release point. Individually released work orders are processed in the shop. The shop consists of a number of work stations; each work station has one or more machines. The processing time characteristics can be specified separately for each work station. Each work station has one input queue.

The probabilities of all movements between work stations are stored in the route matrix.

Finally, the shop modelled in JAWS has a single assembly point with a separate buffer. This enables the completion delay times of the work orders to be measured at the assembly point.

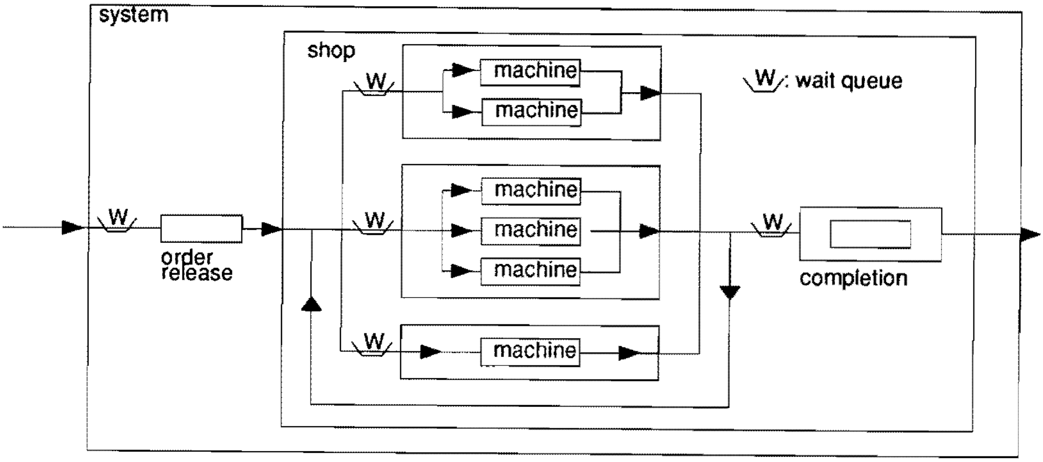


Figure 4.5: The shop structure in JAWS.

The primary factor for determining the size of simulation experiments is the total number of work stations. If the number of work stations is too small, then there is a significant risk that work orders belonging to the same assembly order will interfere with each other. If this occurs then the flow of one work order can block the flow of another work order from the same assembly order, in spite of the fact that the intention was to coordinate the flow rates between the work orders. Research into this type of interference has not been included in this study. A job shop consisting of five machines is typically used as a model in traditional simulation studies. Adam used six machines in the model of his job shop and Maxwell used nine machines in his model. Fifteen machines have been used in the study presented here. With this number of machines it is anticipated that there will be no significant interference problems between work orders belonging to a given assembly order.

No allowance has been made for modelling machine failures. No distinction is made in the model between the planned processing times based upon a probability distribution at the time of scheduling and the realized processing times upon completion.

An important assumption is that there are no dependencies between the size of a work order and the type of routing. Similarly, it is assumed that there are no dependencies between the composition of an assembly order and the type of routing. The case study presented in Chapter 2 supports the validity of these assumptions. The model incorporates a random routing structure whereby the probability of work flowing from any given work station to any other work station is always the same. The number of operations included in a work order essentially determines when the work order will be completed.

◆ *The order structures*

JAWS recognizes assembly orders and work orders. An assembly order is basically a set of work orders. The number of work orders per assembly order is determined randomly in each case based upon a probability distribution function. A work order consists of a series of operations which are performed sequentially. The number of operations per work order is also determined randomly based upon a probability distribution function. The processing times are determined in the same way. This order structure is illustrated in the form of an entity model in Figure 4.6 (a description of the notation conventions is given in appendix B).

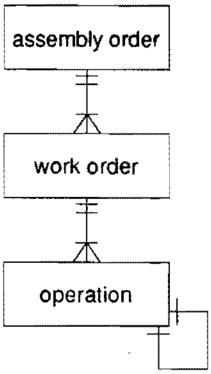


Figure 4.6: The order structure in JAWS.

All of the assembly orders have one node which represents an assembly operation. The assembly times for this simulation study have been set to zero in each case. One due date is assigned to each assembly order. This due date is thus also the scheduled completion date for all of the associated work orders.

A structure is defined for an assembly order upon its arrival in the buffer. This means that values are assigned to the appropriate variables which define (in the following sequence):
- the number of work orders;
- the number of operations per work order;
- the routing for each work order;
- the processing times.

The number of work orders per assembly order is determined randomly based upon a geometric distribution function. The reason for this choice is explained in the analysis of the case study. The average value of the geometric distribution function has been set at three. The truncation percentage for this function has been set at 98.5% to ensure that the maximum number of work orders per assembly order does not exceed ten.

The number of operations per work order is also geometrically distributed. The motivation for this choice has similarly been discussed in the analysis of the case study. The average value has been set at five. Similar to the experiments carried out by Maxwell and Adam, the truncation percentage has been set at approximately 99.7% to ensure that there are no more than 39 operations per work order.

The processing times are determined randomly based upon a negative exponential distribution function with an average value of 1 and a truncation percentage set at 90%. This results in a processing time limit of approximately 2.303. The use of a negative exponential distribution function for modelling the processing times is similarly based upon the case study situation. The interpretation of the simulation results is simplified by maintaining an average processing time of 1.

♦ *The decision rules*

Due date assignment rules

A due date is assigned to each assembly order when it arrives in the buffer. This due date can be determined based upon any one of a number of due date assignment rules.

One possibility is to assign fixed throughput times. In this case the due date of an assembly order is calculated by adding the fixed throughput time to the time at which the assembly order arrived in the buffer.

A second possibility is to assign the assembly order due date based upon the estimated throughput time of the largest work order. The size of a work order is defined by the number of operations in JAWS. The throughput time of a work order can be affected greatly by the waiting times which occur in job shop situations where there is a relatively high resource utilization percentage, however. The total waiting time of a work order is also largely dependent upon the number of operations. In view of this, using the total number of operations is preferred as the criterion for determining which work order is the largest (refer also to [Maxwell, 1969]).

When this second method of estimating completion dates is used, the allowance per operation is also determined. The work orders belonging to a given assembly order can swap allowances with each other. The extent to which this is permitted is governed by a number of restrictions dictated by the acceleration/retardation method. This is covered in more detail in Chapter 5.

A third alternative for assigning due dates is a variant of the second method. This third approach makes allowance for including an estimate of the buffer time, dependent upon the workload, in the calculation of the due date. Once the due date of an assembly order has been assigned, then the order can be completely scheduled. This means that the release date and due date for each work order can be scheduled. The start date for each of the operations can also be scheduled. There are two variants to this rule: one for reverse planning and one for forward planning. In both of these instances the due date assignment can be done dynamically.

Order release

Work orders are released primarily based upon the planned release date. In addition, work orders can be released based upon the principles of workload control. This essentially means that a new work order can be released as soon as the level of the remaining workload in the shop falls below a specified norm for the remaining workload. This event can occur whenever an operation is completed. If a number of (work) orders with the same planned release date are waiting but it is not possible to release all of these waiting (work) orders at the same time due to the workload control restrictions, then release priorities need to be established for these work orders.

The possible priority rules for controlling the release sequence of orders are based upon:
- the planned release date;
- the smallest total work order processing time;
- the smallest number of operations;
- the percentage of the work orders belonging to the related assembly order which have already been released.

The reasons for using these priority rules are explained in Chapter 9.

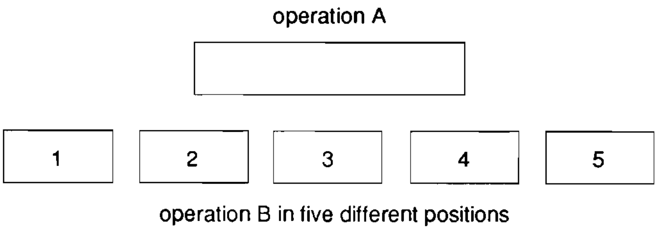
Another alternative for releasing work orders is to release all of the work orders associated with a given assembly order on the release date planned for the largest work order.

Priority rules

Four priority rule alternatives are available within JAWS:
- the planned operation start date (POSD) rule;
- the planned operation due date (PODD) rule;
- the shortest processing time first (SPT) rule;
- the first-in, first-out (FIFO) or first-come, first-served (FCFS) rule;

The justifications for using these rules are thoroughly described in the literature. The first two alternatives are used in the ODD approach. There is no real difference between the POSD rule and the PODD rule when the processing times are fairly constant. There is a difference in the performance of these two rules when the processing times fluctuate widely and when the SPT-rule is used as a tie-breaker, however. This can occur, for example, when a negative exponential probability distribution is used.

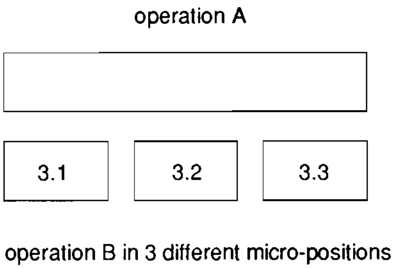
An example with two operations A and B is illustrated with Figure 4.7 and Figure 4.8 and is discussed hereunder. The processing time of operation B is much smaller than of A. In Figure 4.7 five different positions of operation B are given in relation to operation A.



B in position:	POSD	PODD
1	B	B
2	B	B
3	A	B
4	A	A
5	A	A

Figure 4.7:
An example with five different positions of operation B in relation to operation A.

The priorities of both rules are set different only in position number 3. This position is worked out in Figure 4.8. The processing time of operation B is set at one time unit and of operation A at three time units.



ODD/SPT:

micro-positions:	PODD of A	PODD of B	lateness of A	lateness of B	average lateness	variance lateness
3.1	3	1	1	0	0.5	0.25
3.2	3	2	1	-1	0	1
3.3	3	3	1	-2	-0.5	2.25
					0	3.5

OSD/SPT:

micro-positions:	POSD of A	POSD of B	lateness of A	lateness of B	average lateness	variance lateness
3.1	0	0	1	0	0.5	0.25
3.2	0	1	0	2	1	1
3.3	0	2	0	1	0.5	0.25
					2	1.5

Figure 4.8:
An example with three different micro positions of operation B in relation to operation A.

For this deterministic example are the mean lateness and the variance of the lateness for the three different micro positions of operation B in relation to operation A calculated, whereby SPT is used as a tie-breaker. The planned due date of operation A is set at three and the planned due date of operation B is set at respectively: one, two and three. In Figure 4.8 is the mean variance of the lateness calculated for both rules: PODD/SPT and POSD/SPT. POSD/SPT performs better with respect to the mean variance of the lateness of operations. A larger spread in the distribution of the lateness values of work orders has a negative effect on the completion delay times. For this reason, preference is given to the use of the POSD/SPT rule in this study (shortly referred to as OSD).

◆ *Control parameters*

There are three initial parameters which must be specified before carrying out the simulation experiment:

- the time interval between the arrival of assembly orders;
- the norm level for the remaining workload;
- the normative waiting time.

The first two parameters can directly influence the resource capacity utilization level. When the event generator is used to simulate the arrival of assembly orders, then the selected arrival process will result in a specific utilization percentage. The utilization level can generally be increased by reducing the average time interval between the arrival of assembly orders.

The utilization level can also be regulated at the order release point. A lower norm level specification for the remaining workload (RWLN) will normally result in a lower utilization percentage.

When order release based upon workload control is used in conjunction with the assembly order arrival event generator, it is necessary to specify a norm for the remaining workload which corresponds to a higher utilization level than the utilization level associated with the standard time interval specified for the arrival of assembly orders (see Figure 4.9). The arrival process will dominate the control of the utilization level in this case. If the control is not defined correctly in this way, then the buffer queue for the release of orders will be overloaded.

The time interval between the arrival of assembly orders is determined randomly based upon a negative exponential distribution function of the probabilities with a truncation level at 90%. The average value for the distribution needs to be estimated based upon the specific situation in each case.

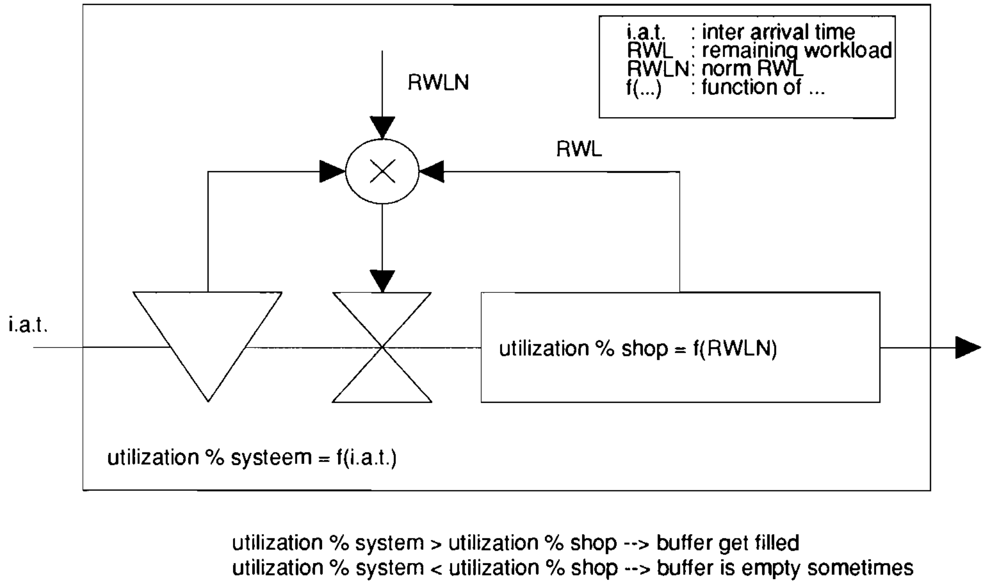


Figure 4.9: The utilization percentage in the shop and in the total system.

An estimate of the throughput time with respect to the buffer delay and other factors is required before the due date can be assigned. This implies that an estimate of the average buffer delay (the order release queue time) must be specified as well as an estimate of the average workload remaining in the buffer (norm for the remaining workload in the buffer).

The third parameter is the normative waiting time for the work stations. This parameter is used for the assignment of due dates and is particularly important in determining the degree of due date reliability.

4.6 Final note

The research issues are covered in more detail in the following chapters. The next chapter concentrates primarily on how the throughput time of assembly orders can be reduced by using the acceleration/retardation method.

Chapter

5 REDUCING ASSEMBLY ORDER THROUGHPUT TIME

A method for reducing the average throughput of assembly orders is developed in this chapter. The approach developed here is based upon the acceleration/retardation method (refer also to Chapter 3).

Use has been made of the simulation program and model described in the previous chapter.

5.1 Introduction

The main production planning and control objectives in tool & die shops are to reduce throughput times and to improve the degree of due date reliability. The throughput times of assembly orders can be reduced by taking advantage of the available latitude in the structure of the assembly orders. By reducing the throughput time in this way, however, the extent to which due dates are realized may become worse.

A due date assignment rule is developed in this chapter which is designed to maximize the reduction of the average throughput time of assembly orders while minimizing the degeneration of due date reliability. Simulation experiments are then used to verify to what extent the envisaged effects have actually been achieved. In connection with this the extent to which the reduction in throughput time can be estimated is also examined.
To start with, the reference situation is defined for use as a reference point for the simulation experiments.

5.2 Establishing a reference situation

5.2.1 Geometric assembly order structure

It is apparent from the case study in Chapter 2 that an assembly order structure can be defined, for the most, in terms of the number of work orders and the number of operations per work order. A geometric distribution function (see also Chapter 4) is used to define these variables in the study presented here.

The number of work orders per assembly order and the number of operations per work order thus determined randomly based upon geometric distribution functions. The average number of operations per work order has been set at five and the distribution is truncated to ensure a maximum of 39 operations per work order. The average number of work orders per assembly order has been set at three, whereby the distribution is truncated at the 98.5% level to provide a limit of ten work orders.

The forms of these two distribution curves result in assembly orders which typically have a structure as illustrated in Figures 5.1 and 5.2.

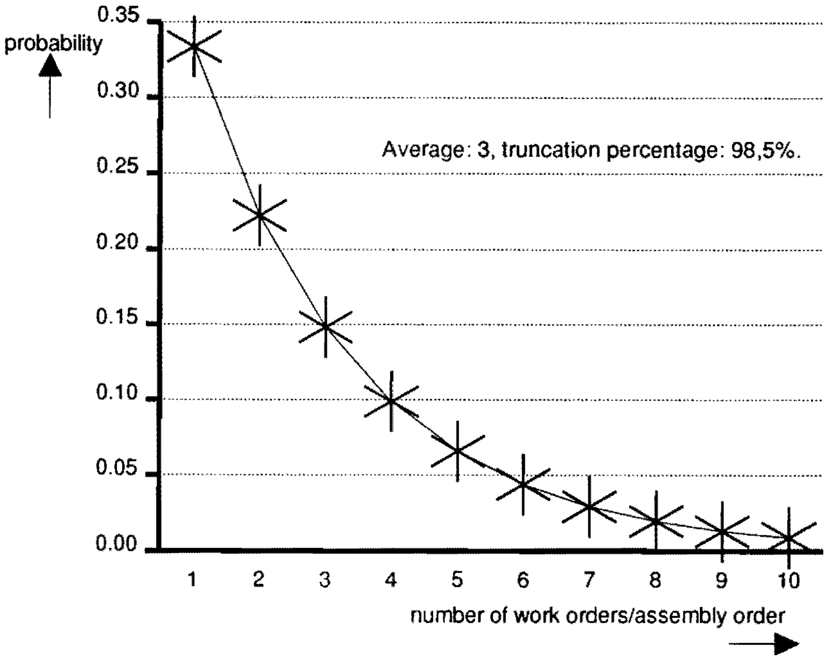


Figure 5.1: The distribution curve of the number of work orders per assembly order.

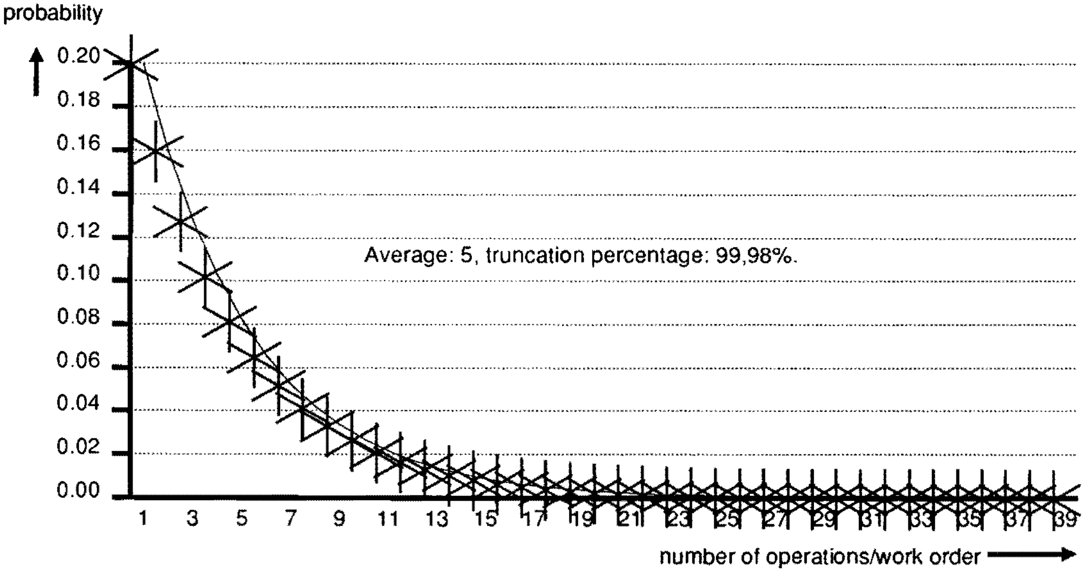


Figure 5.2: The distribution curve of the number of operations per work order.

This means that an assembly order consists of several large work orders (i.e., work orders with a large number of operations) and a number of relatively small work orders. An assembly order with a relatively large number of work orders is more likely to include an abnormally large work order (with a large number of operations). Similarly, a relatively large work order is also more likely to include an operation with an abnormally long processing time. As a result, a relatively large assembly order is generally large in three respects: the number of work orders, the number of operations and the processing time.

5.2.2 Control rules

The allowance per operation is set to be equal to the normative waiting time in the reference situation. As mentioned in Chapter 3, Eilon & Chowdhury ([Eilon & Chowdhury, 1976]) have shown that this approach results in a minimal spread in the distribution of the lateness.

It is normal in practice to delay the release of subsequent work orders as much as possible in order to ensure that the first work order of an assembly order does not need to wait for the completion of the engineering and process planning activities associated with subsequent work orders. This means that, in real-life situations, engineering and process planning activities for certain work orders are carried out in parallel with the manufacturing operations for other work orders belonging to the same assembly order. This approach has been incorporated in the definition of the reference situation for the study presented here (see also Figure 4.2). The due date for an assembly order is determined by the largest work order in this way. In most instances the largest work order is the work order with the greatest number of operations.

The control rules which are applicable in the reference situation have been defined as described hereunder.

The *due date assignment rule* for assembly orders specifies that the due date be calculated taking the total processing time of the largest work order belonging to the assembly order plus the allowance (equal to the normative waiting time) multiplied by the number of operations in the largest work order and adding this to the time of arrival in the shop. This rule is defined in the following formula (1).

D_k : due date of assembly order k and all associated work orders

n : total number of assembly orders

$o_{k,j}$: total number of operations in work order j of assembly order k

$p_{k,j,i}$: processing time of operation i in work order j of assembly order k

A : allowance

m_k : number of work orders in assembly order k

M_k : number of operations in the largest work order (as indicated by J) of assembly order k

$$M_k = \max_{j=1}^{m_k} o_{k,j}$$

$$D_k = \text{time} + M_k \cdot A + \sum_{i=1}^{M_k} p_{k,J,i} \qquad (1)$$

The *order release rule* specifies that a work order is to be released on the planned release date (PRD). The PRD of a work order is determined based upon reverse planning, scheduling backwards from the due date of the assembly order. The planned throughput time of a work order is in this case equal to the sum of the processing time of the work order plus the allowance multiplied by the number of operations in the work order.

As indicated in Chapter 4, the OSD rule is used as the *priority rule*.

5.2.3 Simulation results

The simulation experiments carried out in connection with the definition of the reference situation did not make use of the various alternative planning and control methods, namely:

- acceleration/retardation;
- workload control;
- simultaneous release;
- dynamic due date assignment.

The most important simulation results for a range of various utilization percentages are presented in Table 5.1.

The importance of keeping track of the performance for the large assembly order category (i.e., assembly orders with ten work orders) is covered in detail in Chapter 7. Nevertheless, the performance results for this category is also presented here in connection with the initial phase of the study in order to provide a complete picture.

Table 5.1:
Simulation results of the reference situation based upon a utilization percentage of 80%, 90% and 95%. (Left: results for all of the assembly orders. Right: results for the category of assembly orders with 10 work orders).

	80 %		90 %		95%	
average throughput time assembly orders	36	67	67	122	135	246
variance throughput time assembly orders	727	611	2540	2335	9626	9610
average planned throughput time assembly orders	33	57	62	106	126	222
average lateness assembly orders	3	10	5	16	9	25
variance lateness	119	150	442	514	965	947
average tardiness assembly orders	5	10	10	17	17	27
variance tardiness assembly orders	81	142	304	465	533	761
average completion delay	5	6	8	13	15	24
variance completion delay	42	50	129	169	332	384
average throughput time work orders	21	-	40	-	80	-
average waiting time delay	3.3	-	7	-	15.1	-

♦ *Other initial seed values*

Identical simulation runs of the reference situation were also performed using different initial seed values for the random number generators. The most important results for the situation with a utilization percentage of 90% are presented in Table 5.2.

Table 5.2:
Simulation results of the reference situation using different initial seed values based upon a utilization percentage of 90%. (Left: results for all of the sub-orders. Right: results for the category of assembly orders with 10 work orders).

run:	1		2		3		4		5	
average throughput time assembly orders	67	122	65	116	69	128	69	126	69	131
variance throughput time assembly orders	2540	2334	2375	1693	2451	2327	2490	2280	2659	2758
average planned throughput time assembly orders	62	106	61	104	62	110	62	107	61	109
average lateness assembly orders	5	16	4	13	8	18	7	20	8	23
variance lateness assembly orders	442	514	294	264	328	320	348	422	523	675
average tardiness assembly orders	10	17	8	14	11	18	11	20	12	23
variance tardiness assembly orders	304	465	169	220	219	293	220	386	380	635
average completion time delay	8	13	8	14	9	15	9	16	10	16
variance completion time delay	129	169	118	137	133	155	145	229	193	251
average throughput time work orders	40	-	38	-	41	-	41	-	42	-
average waiting time delay	7	-	6.7	-	7.3	-	7.3	-	7.4	-

Such a set of five different simulation runs where only the initial seed values differ, is called a simulation experiment in this study.

5.3 Choosing a method for work order acceleration/retardation

5.3.1 Basic principle

As explained in Chapter 2, the acceleration/retardation method is based upon a two-stream model in which different categories of identical work orders can be assigned different flow rates. In this way, different throughput times can be assigned to identical work orders in such a way that they can be estimated accurately.

The most important conclusions from the research carried out by Van Ooijen ([Bertrand & Ooijen, 1991], [Ooijen, 1991]) are that:

- there is a linear relationship between a reduction of the allowance and a reduction in the waiting time, provided that the allowance reduction does not exceed 60% of the normative waiting time (whereby the normative waiting time is equal to the average waiting time) and provided that the total amount of the allowance reduction is equal to the total amount of increase in allowance (based upon the balanced equation in which the average allowance must be kept equal to the normative waiting time);
- the waiting time reduction should be expressed in terms of the minimum required waiting time (i.e., as a relative waiting time reduction) in such a way that a necessary differentiation is made between the scheduled due date (for internal use) and the expected completion date (for external purposes);
- an implicit corollary of the linear relationship indicated above is that this is only valid provided that an increase in the allowance does not exceed 160%;
- the variance in the lateness of work orders increases.

The application of this method, based upon the identification of certain groups of work orders belonging to multiple assembly orders, can lead to a reduction in the throughput times of the time-critical work orders. The throughput times of the associated assembly orders can thus be reduced in this way.

A significant factor in this respect is the ratio of the number of operations which can be accelerated versus the number of operations which can be retarded. If there are a relatively small number of operations which can be accelerated or if the amount of the delay which can be imposed upon the operations to be retarded is minimal (without causing an increase in the throughput time of the assembly order), then this method will not be able to provide a significant improvement. This ratio between the number of operations to be accelerated versus the number to be retarded is an inherent characteristic of the assembly order structure.

The assembly order structure and the implications which a particular assembly order structure may have with respect to the applicability of the acceleration/retardation method are described in the following section.

5.3.2 Reducing assembly order throughput time

The acceleration/retardation method can be used to systematically reduce the throughput time of a group of work orders, provided that the allowance can be swapped from the operations in the group of work orders for which the throughput time is to be reduced, to the other groups of work orders. This swapping of allowance is subject to a number of restrictions, however.

The throughput time of assembly orders can be reduced if a relatively small allowance per operation is allocated to the time-critical work orders and a relatively large allowance per operation to the other work orders. Many groups of work orders need to be defined within the assembly order structure due to a wide variation in the possible number of operations per work order.

Van Ooijen limited his research to only two groups of work orders per assembly order. He used the same maximum allowance reduction or allowance increase within each group in his experiments. The degree of reduction or increase can vary, however, when a large number of groups of work orders are defined. The question thus arises of whether the observed upper and lower limits for swapping allowance are valid in the study presented here. It is even possible that no limits are necessary in this situation.

♦ *Lower limit restriction*

If the allowance in the largest work order of an assembly order is reduced, then this "saved" allowance can be distributed over a large number of smaller work orders which are not time-critical.
The ideal situation is when the average throughput time of an assembly order is equal to the average throughput time of the work orders. This can be achieved by swapping the allowances between work orders in such a way that the planned throughput times for all of the work orders become the same. The calculated allowance for a work order is then based upon the average throughput time of the work orders and the number of operations in the work order. In this way the various groups of work orders are defined based upon the number of operations in the work orders in each group. To illustrate this, an example of the calculation of allowance is presented here in which all of the groups of work orders have a single constant average throughput time. The average number of operations per work order is distributed geometrically, as stated in Subsection 5.2.1.

The results presented in Table 5.3 are based upon a normative waiting time of 5 and an average processing time of 1. The 39 groups are listed in the first column of Table 5.3. The probabilities of an occurrence based upon the geometric distribution function are indicated in the second column. The cumulative probabilities are listed in column 3. The distribution is truncated beyond 39 operations. The probabilities listed in columns 4 and 5 are adjusted upward to make the total cumulative probability equal to 1. The average number of operations is calculated in column 6: 4.994 operations rounded off to the nearest whole number gives 5 operations. The normative allowance per operation of a work order is called "fraction". "Fraction" is defined as the quotient of the allowance per operation of a work order and the normative waiting time. The calculated fractions are listed in column 7. These fractions have been calculated as follows.

o := number of operations in a work order, $1 \leq o \leq 39$
$\underline{p}$:= average processing time per operation
$\underline{o}$:= average number of operations per work order
$\underline{h}$:= average throughput time for work orders
$h(o)$:= throughput time of a work order with o operations
$\underline{A}$:= average allowance per operation
W_n := normative waiting time
$p(o)$:= probability of the occurrence of o operations within a work order
$A(o)$:= allowance per operation in a work order with o operations after acceleration/retardation
$f(o)$:= fraction, the quotient of $A(o)$ and W_N, per operation in a work order with o operations

$$f(o) = \frac{A(o)}{W_n}$$

Assumption:
the average allowance $\underline{A}$ per operation before the acceleration/retardation adjustment is applied is equal to the average allowance $\underline{A}$ per operation after the acceleration/retardation (the balancing equation).

Before the acceleration/retardation adjustment is applied, the average allowance is:

$$\underline{A} = \frac{\sum_{o=1}^{39} o \cdot p(o) \cdot W_n}{\sum_{o=1}^{39} o \cdot p(o)} = W_n$$

After the acceleration/retardation adjustment is applied, the throughput time of a work order is:

$$h(o) = A(o) \cdot o + \underline{p} \cdot o = f(o) \cdot \underline{A} \cdot o + \underline{p} \cdot o$$

The average throughput time for work orders is:

$$\underline{h} = \underline{o} \cdot (\underline{A} + \underline{p})$$

If the planned throughput time of all of the work orders after application of the acceleration/retardation adjustment is equal to the average throughput time ($h(o) = \underline{h}$), then the o fractions ($f(o)$'s) can be calculated as follows:

$$f(o) = \frac{\underline{h} - \underline{p} \cdot o}{\underline{A} \cdot o} \quad \text{and} \quad A(o) = f(o) \cdot \underline{A}$$

From Table 5.3 it is apparent that the calculated fractions are negative, representing impractical OSD's, for the work orders with, for example, 39 operations. The throughput time of a work order is always greater than the sum of the individual processing times.

The allowance should therefore never be negative. A minimum waiting time per operation needs to be observed, even when the associated work order is assigned the highest priority. It is assumed that a previous operation will always need to be completed before a given machine is available for starting a new operation.

Table 5.3:
Allowance calculation in a situation with a fixed work order throughput time.

column 1	column 2	column 3	column 4	column 5	column 6	column 7
1	0.2000	0.2000	0.2000	0.2000	0.2000	5.792
2	0.1600	0.3600	0.1600	0.3601	0.3201	2.796
3	0.1280	0.4880	0.1280	0.4881	0.3841	1.797
4	0.1024	0.5904	0.1024	0.5905	0.4097	1.298
5	0.08192	0.6723	0.08193	0.6724	0.4097	0.9984
6	0.06554	0.7379	0.06555	0.7380	0.3933	0.7987
7	0.05243	0.7903	0.05244	0.7904	0.3671	0.6560
8	0.04194	0.8322	0.04195	0.8324	0.3356	0.5490
9	0.03355	0.8658	0.03356	0.8659	0.3020	0.4658
10	0.02684	0.8926	0.02685	0.8928	0.2685	0.3992
11	0.02147	0.9141	0.02148	0.9143	0.2363	0.3447
12	0.01718	0.9313	0.01718	0.9314	0.2062	0.2994
13	0.01374	0.9450	0.01375	0.9452	0.1787	0.2609
14	0.01100	0.9560	0.01100	0.9562	0.1540	0.2280
15	0.00880	0.9648	0.00880	0.9650	0.1320	0.1995
16	0.00704	0.9719	0.00704	0.9720	0.1126	0.1745
17	0.00563	0.9775	0.00563	0.9776	0.0957	0.1525
18	0.00450	0.9820	0.00450	0.9821	0.0811	0.1329
19	0.00360	0.9856	0.00360	0.9858	0.0685	0.1154
20	0.00288	0.9885	0.00288	0.9886	0.0577	0.0996
21	0.00231	0.9908	0.00231	0.9909	0.0484	0.0853
22	0.00185	0.9926	0.00185	0.9928	0.0406	0.0724
23	0.00148	0.9941	0.00148	0.9943	0.0340	0.0605
24	0.00118	0.9953	0.00118	0.9954	0.0283	0.0497
25	0.00094	0.9962	0.00094	0.9964	0.0236	0.0397
26	0.00076	0.9970	0.00076	0.9971	0.0197	0.0305

Table 5.3:
Allowance calculation in a situation with a fixed work order throughput time.

27	0.00060	0.9976	0.00060	0.9977	0.0163	0.0219
28	0.00048	0.9981	0.00048	0.9982	0.0135	0.0140
29	0.00039	0.9985	0.00039	0.9986	0.0112	0.0066
30	0.00031	0.9988	0.00031	0.9989	0.0093	-0.0003
31	0.00025	0.9990	0.00025	0.9992	0.0077	-0.0067
32	0.00020	0.9992	0.00020	0.9994	0.0063	-0.0127
33	0.00016	0.9994	0.00016	0.9995	0.0052	-0.0184
34	0.00013	0.9995	0.00013	0.9997	0.0043	-0.0238
35	0.00010	0.9996	0.00010	0.9998	0.0036	-0.0288
36	0.00008	0.9997	0.00008	0.9998	0.0029	-0.0336
37	0.00006	0.9997	0.00006	0.9999	0.0024	-0.0381
38	0.00005	0.9998	0.00005	1.0000	0.0020	-0.0423
39	0.00004	0.9998	0.00004	1.0000	0.0016	-0.0464
average:					4.994	4.994

A lower limit with a value greater or equal to zero must be specified since it is apparent that using the formula for calculating fractions can otherwise result in an infeasible, negative value. This is described further in Section 5.4.3.

Allowance reduction is also referred to as process acceleration. Conversely, increasing the allowance is also referred to as process retardation.

- *Upper limit restriction*

The number of operations per work order within an assembly order may be distributed disproportionately in a given situation as a result of the geometric characteristics of the assembly order structure. It is possible to imagine a situation in which, for example, allowance is swapped between two work orders belonging to a given assembly order whereby one work order consists of only one operation and the other work order contains 39 operations. In this situation it may be desirable to multiply the smaller work order's allowance by a factor of, say, 20 (thus making the processing times negligible) in order to make the planned throughput time for both of the work orders the same. Expanding the allowance to this extent is probably not effective, however. In addition, the effects of imposing an upper limit on allowance adjustments will be examined in further detail.

5.3.3 Relating the geometric structure to production planning and control

There are four aspects of using a geometric order structure for production planning and control purposes which need further attention:

1. A geometric order structure essentially provides an extensive range of potential groups of work orders between which different amounts of allowance can be swapped. It has been shown that the acceleration/retardation method is useful for swapping allowance in situations in which there are two groups of work orders with the same route length or, in other words, the same number of operations. It is not clear to what extent the acceleration/retardation method is similarly useful in situations where the route length may vary within an extensive range of values.

2. The geometric structure provides a large potential variation with respect to the composition of assembly orders. It is not clear to what extent the individual structure characteristics of an assembly order should be considered when a due date is assigned. For example, such individual characteristics are ignored when the same, fixed flow time is assigned to all of the assembly orders.

3. It is not clear between which groups of work orders the allowance can or should be swapped. The three possible variants are described in the following section.

4. Use of a geometric structure implies that there will be a relatively large number of small assembly orders in the sense of a small number of work orders per assembly order, a small number of operations per work order and short processing time durations. A relatively small reduction in the throughput times of a large number of small assembly orders and, at the same time, a large increase in the throughput times of a limited number of large assembly orders could easily lead to a significant reduction in the average assembly order throughput time. This solution is unacceptable in practice, however, in view of the tendency to place much more importance on the throughput and due date reliability performance of the larger assembly orders (refer also to Chapter 4). It is not clear which performance criteria should be used to evaluate all of the consequences of applying a given control rule.

5.4 Developing a due date assignment rule

A due date assignment rule for assembly orders is developed in this section. The objective of this decision rule is to provide a minimum average throughput time for assembly orders while ensuring good results with respect to lateness.

To start with, the design requirements with respect to this decision rule are described and the selection criteria for choosing a rule are outlined. Several alternative solutions are then presented. Each of these alternatives is evaluated and a choice is made. A detailed specification of the chosen due date assignment rule is provided at the end of this section.

5.4.1 Design requirements and evaluation criteria

◆ *Design requirements*

The following requirements have been established:
- the decision rule must provide an estimate of the shop throughput time for an assembly order;
- it must be possible to use the decision rule in combination with the acceleration/retardation method;
- the decision rule must take the route length of the work orders into account such that, for example, a work order with 39 operations will have a longer throughput time than a work order with only one operation.

◆ *Evaluation criteria*

Different criteria are important with respect to evaluating the various alternatives for a due date assignment rule. The rule must:
- provide evidence of the feasibility of the planned reduction in throughput time. This means that using the acceleration/retardation method must not only result in a reduction of the throughput time but it must also be possible to calculate the amount of the reduction in advance;
- provide improvements in the throughput time of large assembly orders. In real-life situations it is important to reduce the throughput time particularly in the case of relatively large assembly orders. Smaller assembly orders are often used as fill-work to utilize resource capacity which would otherwise be wasted. This type of work is typically not time-critical. This situation also implies that separate performance measurements are required for each type of assembly order;

- be usable and applicable in practical situations for assigning due dates;
- provide a consistent, minimal lateness and tardiness whereby the spreads in the distribution of lateness and tardiness are also minimal;
- provide a maximum improvement in the throughput time of assembly orders with respect to the reference situation.

5.4.2 Alternative decision rules

The acceleration/retardation method can only be used to improve the shop throughput times of assembly orders. To start with, attention is focused on this aspect of the due date assignment rule.

The associated reduction and increase in throughput times involves swapping allowances between the various groups of work orders. In general, the assembly order structure permits allowance swapping to occur in three different ways:

1. swapping between all of the work orders. In this case the work orders with the most operations are reduced (accelerated) the most and work orders with relatively few operations are expanded (retarded) the most. Depending upon the specific order structure, a single shop throughput time for all of the work orders could theoretically result which is independent of the number of operations of any specific work order. If swapping occurs to this extent, then the planned shop throughput time for the work orders will be equal to the planned shop throughput time for the assembly orders. (See Figure 5.3 a).
2. swapping only between work orders belonging to the same assembly order (see Figure 5.3 b);
3. swapping between different assembly orders, but not between work orders belonging to the same assembly order. The intention in this case is to swap allowance between the larger work orders of the larger assembly orders and the smaller work orders of the smaller assembly orders. In this way it should be possible to achieve the practical objective of minimizing the throughput time of the largest assembly orders, in particular (see Figure 5.3 c). Allowance swapping between the larger work orders of the smaller assembly orders and the smaller work orders of the larger assembly orders does not contribute to a reduction of the throughput time of the larger assembly orders and is therefore not desirable.

Each of these alternatives is described in more detail here. Following this, an evaluation and choice is made.

◆ *Swapping allowance between all of the work orders*

With this alternative, the allowance associated with the operations belonging to the largest work orders of the assembly orders is calculated in the same way as in the example presented in Table 5.3 in Subsection 5.3.2. The allowance in this case is defined as a specific fraction of the average normative waiting time. This fraction is defined as a function of the number of operations in the work order. The calculation of the fractions needs to be adjusted whenever upper and lower limits are imposed. In this last case it is apparent that the shop throughput times for some different work orders will differ because at least a lower limit of zero has to be imposed.

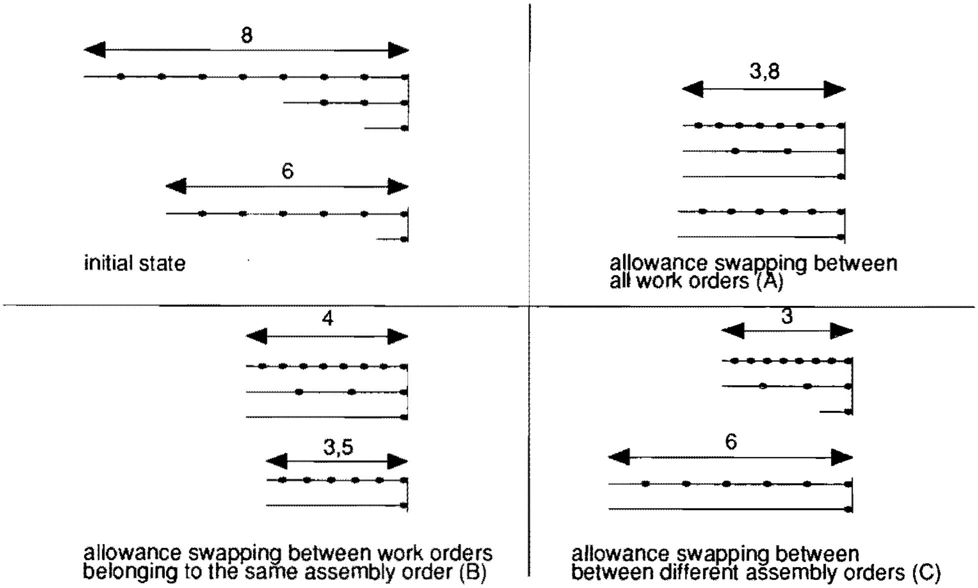


Figure 5.3: Three alternatives of allowance swapping.

The planned shop throughput time for an assembly order will be equal to the planned shop throughput time for the largest work order. Some of the assembly orders will still have work orders with different planned throughput times. This means that whenever the smaller work orders belonging to the assembly orders with varying work order throughput times can be delayed, some of the other assembly orders can then be accelerated. How this delay and acceleration can be calculated is not covered here. This calculation is, however, included in the explanation of a different topic in a subsequent section (see subsection 5.6.1).

An important implication is that the allowance will be swapped between large and small assembly orders. An assembly order which includes a larger work order with relatively few operations may be delayed, regardless of the number of work orders included in the assembly order. The throughput times of the large assembly orders with relatively large work orders comprised of many operations will always be reduced. The total average throughput time of assembly orders will be shorter or longer, depending upon the extent to which throughput times are reduced/expanded and the ratio of small to large assembly orders. It should also be noted that an improvement in the throughput times of the larger orders, at the expense of an increase in the throughput times of the smaller assembly orders, is a highly desirable phenomenon in real-life situations.

An excessive amount of allowance may be swapped by following this approach, however. Allowance will be swapped e.g. between assembly orders with one work order but with different numbers of operations per work order. This means that allowance may be swapped in certain cases where no improvement in the throughput time of the assembly orders results. Furthermore, such swaps could lead to a degeneration of the due date reliability as a result of the relative character of reducing or expanding waiting time (see Subsection 5.3.1).

This first approach of acceleration/retardation has two advantages and three shortcomings which are described here.
The advantages are:

- the due date for an assembly order can be determined quickly based upon the total number of operations included in the largest work order, provided that the fraction is known in the form of a function of the number of operations;
- the spread in the distribution of work order and assembly order throughput times is minimal. This essentially means that a maximum degree of levelling has been achieved.

The shortcomings are:

- it is not easy to determine the fractions. This can be a problem in real-life situations;
- only the structure of the largest work order of an assembly order is taken into account in assigning the due date. This means that no consideration is given to other parts of the assembly order structure and factors such as the total number of work orders and the number of operations included in the other work orders;
- a larger variance in the lateness of the work orders can occur as the result of an excessive amount of allowance swapping. The swapping is excessive when a work

order is the sole work order of an assembly order and the acceleration or delay in the processing of this work order does not improve the average throughput time of the assembly orders or of the larger assembly orders. (This is also related to the previous point, above).

◆ *Swapping allowance only between work orders belonging to the same assembly order*

In the second approach, allowance is swapped only between work orders belonging to the same assembly order. An allowance which is smaller than the normative waiting time is allocated to the largest work orders while an allowance larger than the normative waiting time is assigned to the smaller work orders. In this way the average allowance for all of the operations associated with a given assembly order is still equal to the normative waiting time. The amount of allowance deducted from the larger work orders is the same as the amount of allowance added to the smaller work orders. The total amount of allowance assigned to the assembly order thus remains unchanged.

The advantages are:

- the amount of allowance to be swapped is primarily dependent upon the number of work orders in the assembly order and the number of operations associated with these work orders;
- the throughput times of the separate assembly orders never become longer.

A shortcoming is:

- any available capacity for the further delay of non-critical work orders, which could potentially be used to improve the throughput time of other assembly orders, is not utilized in this approach. This capacity is the potential for increasing the work order throughput times, after the allowances have been swapped within the various assembly orders, without adversely affecting the assembly order throughput time.

◆ *Swapping allowance between different assembly orders*

A further approach can be envisaged whereby allowance is swapped between different assembly orders, but not between work orders belonging to the same assembly order.

A large assembly order normally contains many work orders, including a few work orders with a relatively large number of operations. The small work orders belonging to such assembly orders will normally have significantly fewer operations. A small assembly order will, on the other hand, generally have a limited number of work orders and the number of operations per work order will not vary as widely as in the case of the large

assembly orders. Nevertheless, most of the assembly orders are small.
The purpose of swapping allowance is to improve the throughput times of primarily the large assembly orders. It is therefore often desirable to swap allowance particularly between the large work orders of the large assembly orders and the small work orders of the small assembly orders.

The balanced distribution of the number of operations per work order which is characteristic of the small assembly orders means that the relatively large number of small work orders can each accept a small amount of additional allowance without causing an increase in the average assembly order throughput time. The large work orders belonging to the large assembly orders will be accelerated only marginally so that the unbalanced distribution of the number of operations per work order within the large assembly orders will remain more or less unchanged. The maximum potential improvement in the throughput time will not be realized with this approach since the remaining capacity for swapping allowance between the small and large work orders within the large assembly orders is not utilized. As a result, it can be concluded that it is not advantageous to swap allowance between assembly orders without also swapping allowance between the work orders belonging to each individual assembly order to achieve a maximum improvement in the average throughput time of assembly orders.

This approach to swapping allowance is really only feasible when used as an extension to the previously described approach. When the available capacity for swapping allowance within assembly orders has been fully utilized based upon the previous approach, then any remaining "free slack" for delaying work orders within an assembly order can subsequently be swapped with other assembly orders which can still be accelerated. In practice, sufficient data regarding the remaining "free slack" in the work in progress associated with the assembly orders in the shop will need to be provided.

- *Evaluating the alternatives*

The first alternative approach is not suitable for use in practice due to the undesirable negative effects with respect to due date reliability. The third alternative approach is not acceptable because it does not provide for sufficient improvements in throughput time.

Subsequent attention is therefore focused on the second alternative.

5.4.3 Detail specification of the algorithm

The amount of allowance which can be transferred from the large work orders to the small work orders is calculated per assembly order. In connection with this, upper and lower limits need to be established to control the extent to which acceleration and retardation can be applied. The algorithm for calculating the amount of allowance to be swapped can be described as follows:

A acceleration/retardation fraction $f_{k,j}$ is calculated for each work order j belonging to assembly order k. (j is in this case no longer equal to the number of operations associated with the work order). The fraction $f_{k,j}$ is calculated first by dividing the average number of operations per work order for assembly order k [$\underline{o}_k$] by the number of operations associated with work order j [$o_{k,j}$]. The value of $\underline{o}_k$ is equal to the total number of operations [o_k] divided by the total number of work orders [m_k]. This can be expressed by the following formulae:

$$\underline{o}_k = o_k / m_k$$

$$f_{k,j} = \underline{o}_k / o_{k,j}$$

The fractions need to be adjusted for the upper and lower limit restrictions (U and L):

$L \leq f_{k,j} \leq U$, for each work order j of assembly order k.

At the same time, the total quantity of allowance allocated to each assembly order must be kept constant. This can be formulated as follows:

$$\sum_{j=1}^{m_k} (f_{k,j} \cdot o_{k,j}) = \underline{o}_k \cdot m_k$$

The fractions of the most accelerated or most delayed work orders are adjusted as necessary to comply with these stipulations. If the amount of acceleration has been excessive ($f_{k,j} < L$), then the fractions of the work order(s) with the longest throughput time are increased and the fractions of the work orders with the shortest throughput time (and not all of the other work orders) are reduced. The result of this change is that the fractions which are the most difficult to realize (i.e., those which have been increased the most) are adjusted in such a way as to have a positive effect on the due date reliability.

If too much delay has been introduced ($f_{k,j} > U$), then the fractions of the work orders with the shortest throughput time will need to be reduced. The fractions of all of the other work orders will then need to be increased. As a result, the throughput times of all of the other work orders are increased by the same absolute amount. The surplus allowance is maximally distributed in this way. By following this approach, the increase in throughput time is kept to a minimum.

As soon as the allowance adjustments have been made, the operation start dates are calculated and scheduled. The sequencing of operations is based upon these start dates (see figure 5.4.). In addition, a release date for each work order is determined and scheduled.

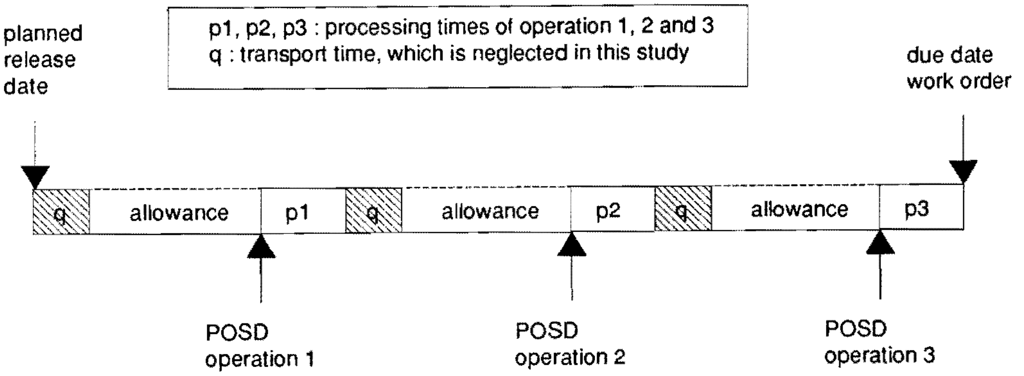


Figure 5.4: The calculation of POSD's.

5.4.4 Design of the simulation experiments

The simulation studies have been divided into two steps as follows:

- Step 1: Estimating the upper and lower limits.
  The upper and lower limits for swapping allowance are to be determined using simulation experiments in this first step. This is described further in Section 5.5.
- Step 2: Evaluating the performance of the due date assignment rule.
  A method for estimating the expected improvement in throughput time is presented in Section 5.6. The results of simulation experiments are then used to validate the accuracy of this estimating method and an evaluation is carried out to determine the extent to which this method is applicable.

5.5 Determining the parameter values for swapping allowance

Recognition of the fact that an excessive reduction in the average assembly order throughput time can cause extremely large variances in the lateness (see Subsection 5.3.1) is important in determining the lower and upper limits. In fact, a trade-off needs to be made between both changes in performance when applying the acceleration/retardation technique. The main focus in this study is to achieve a maximum reduction in the throughput time for all of the orders. A secondary objective is to improve the degree of due date reliability for all of the orders.

The study of the effectiveness of the acceleration/retardation technique shows that when the allowance is reduced to approximately 60% of the normative waiting time, there is a linear relationship between the allowance reduction and the relative waiting time reduction. (See also Section 3.4). This finding can also be applied to assembly order structures. In this case the maximum percentage reduction in the allowance can be expressed as a function of the normative waiting time: the lower limit factor (L). The lower limit factor is 0.4 when the allowance is reduced by 60%. Furthermore, it can be expected that if the lower limit factor for the lower limit is too small, then there will no longer be a linear relationship between the allowance reduction and the relative waiting time reduction.

The mix of categories and orders used in the study of acceleration/retardation was chosen in such a way to ensure that a 60% reduction in the allowance corresponds with an allowance increase of 160%. The maximum percentage for increasing the allowance can be expressed as a function of the normative waiting time and is referred to here as the upper limit factor (U). A 160% increase in the allowance is equivalent to a upper limit factor of 1.6. Furthermore, it can be expected that if the upper limit factor for the upper limit is too large, then there will no longer be a linear relationship between the increase in allowance and the relative increase in waiting time. There are significantly fewer operations to be delayed within a single assembly order than the number of operations to be accelerated when a geometric order structure is used. As a result, it can be expected that setting an upper limit for increasing the allowance will have more effect than setting a lower limit for allowance reduction.

The first experiment deals with the effects of increasing the allowance excessively.

The simulation program used includes a facility for keeping track of various categories of work orders. Work order categories can be defined based upon the fraction value. In this way a total of 15 work order categories have been defined with an upper limit of 3. Subsequently, the due date reliability performance was measured for each work order category. Based upon the a priori assumptions, it is expected that the average lateness of the work orders in the categories with excessively increased allowances will be extremely negative. For the purpose of illustration, the results of the simulation run per work order category using an upper limit of 3 are presented in Table 5.4 (90% utilization, one run with the first setting of seed values).

The results of this simulation experiment shows that the average lateness doubles (from -2 to -4) when the allowance is increased by more than two. This implies that the allowance should not be increased by more than two. Other performance indicators do not provide evidence to suggest that an upper limit is required for increasing the allowance.

Table 5.4:
The due date reliability performance of 15 categories of work orders with a maximum delay factor of 3.

cate-gory	fraction interval	fraction		lateness work orders		tardiness work orders		number of operation	
		avera	var	averag	var	average	var	aver	var
1	0.0 - 0.2	-	-	-	-	-	-	-	-
2	0.2 - 0.4	0.36	.000	9.39	443	12.46	336	13.7	38.0
3	0.4 - 0.6	0.52	.003	7.04	473	11.26	331	10.7	27.9
4	0.6 - 0.8	0.70	.003	3.85	442	9.25	275	8.1	20.0
5	0.8 - 1.0	0.96	.004	2.20	409	8.13	240	5.5	18
6	1.0 - 1.2	1.11	.003	1.69	448	8.43	245	5.1	5.1
7	1.2 - 1.4	1.30	.003	0.14	433	7.67	218	3.8	3.7
8	1.4 - 1.6	1.50	.003	-0.73	454	7.29	230	3.2	2.7
9	1.6 - 1.8	1.70	.003	-1.25	447	7.14	213	2.9	1.7
10	1.8 - 2.0	1.94	.005	-1.98	424	6.67	197	2.4	1.4
11	2.0 - 2.2	2.13	.002	-4.00	489	6.67	193	2.5	1.0
12	2.2 - 2.4	2.31	.003	-4.91	410	5.62	151	2.1	1
13	2.4 - 2.6	2.51	.002	-3.29	490	6.75	208	1.9	0.8
14	2.6 - 2.8	2.71	.003	-5.36	494	5.96	196	1.8	0.7
15	2.8 - 3.0	2.99	.001	-4.45	406	5.83	175	1.3	0.3
total:	0.0 - 3.0	1.44	.701	0.76	446	7.95	238	5.0	19.9

The next problem is to establish a lower limit for allowance reductions. The results of a simulation run per work order category using an upper limit of 2 for increasing the allowance are presented in Table 5.5. Twenty work order categories have been defined in this case.

These results show that it is useless to reduce the allowances by more than 70%. From the data in the table it is clear that it was possible to reduce the allowances by more than 70% only in a very few instances. The average lateness increases from 6.5 (at the 60% level) to 8.5 (at the 70% level), which is not particularly spectacular. The lower limit has therefore been set at 0.3.

Table 5.5:
The due date reliability performance of 20 categories of work orders with a maximum delay factor of 2.

cate-gory	fraction interval	fraction		lateness work orders		tardiness work orders		number of operation	
		avera	var	averag	var	average	var	acer	var
1	0.0 - 0.1	-	-	-	-	-	-	-	-
2	0.1 - 0.2	-	-	-	-	-	-	-	-
3	0.2 - 0.3	0.29	.000	-7.12	-	0.0	-	6.0	-
4	0.3 - 0.4	0.38	.001	8.53	513	11.7	410	12.1	46.1
5	0.4 - 0.5	0.47	.001	6.54	442	10.9	303	12.4	34.1
6	0.5 - 0.6	0.56	.001	6.13	487	10.9	328	11.1	27.6
7	0.6 - 0.7	0.66	.001	3.84	469	9.4	295	9.2	26.3
8	0.7 - 0.8	0.76	.001	2.85	461	8.8	279	8.3	22.2
9	0.8 - 0.9	0.85	.001	1.19	409	7.8	220	7.6	19.1
10	0.9 - 1.0	0.99	.001	1.35	403	7.6	233	5.3	19.7
11	1.0 - 1.1	1.06	.001	1.08	427	8	225	5.7	5.9
12	1.1 - 1.2	1.15	.001	0.86	474	8.1	260	4.8	4.8
13	1.2 - 1.3	1.25	.001	-0.29	455	7.6	230	4.4	5
14	1.3 - 1.4	1.35	.001	-0.63	422	7.2	202	3.7	3.8
15	1.4 - 1.5	1.47	.001	-1.81	429	6.5	211	3.2	3.2
16	1.5 - 1.6	1.57	.001	-0.65	484	7.8	234	3.6	2.5
17	1.6 - 1.7	1.66	.001	-1.16	449	7.1	218	2.9	1.9
18	1.7 - 1.8	1.75	.001	-2.62	445	6.6	201	2.9	1.6
19	1.8 - 1.9	1.86	.001	-2.05	499	7.2	239	2.8	1.2
20	1.9 - 2.0	2	.000	-2.00	342	5.9	176	1.6	0.8
totals	0.0 - 2.0	1.29	.26	0.52	418	7.5	229	5.0	19.8

The data in both of these tables shows that the average lateness increases as the work orders are accelerated. This means that accelerated work orders are generally completed ahead of schedule when the total schedule is accelerated. The converse is also true; a delayed work order is increasingly likely to be completed after the scheduled due date.

The most significant results from two additional simulation runs are presented in Table 5.6. One of these runs was carried out with no restrictions on the swapping of allowance while the swapping of allowance was restricted in the other run. The results of the reference simulation run are also included in this table for the purpose of making comparisons.

Table 5.6:
Simulation results based upon an utilization of 90%:
The reference situation (ti590001), unlimited allowance swapping (ti590093)and limited allowance swapping (ti590056). (The results for all of the assembly orders are presented on the left. The results for assembly orders with 10 work orders are presented on the right.)

	ti590001		ti590093		ti590056	
average throughput time assembly orders	67	122	51	69	55	80
variance throughput time assembly orders	2540	2335	1284	834	1695	1213
average geplande throughput time assembly orders	62	106	42	48	49	63
average throughput time work orders	40		40		40	
variance throughput time work orders	1582		955		1159	
average waiting time delay	7		7.2		7.1	
variance waiting time delay	107		136		114	
average lateness assembly orders	5.4	15.5	8.5	20.6	6.7	17.8
variance lateness assembly orders	442	514	489	606	462	576
average lateness work orders	0.1		0.9		0.6	
variance lateness work orders	404		510		423	
average tardiness assembly orders	9.9	16.8	12.3	21.8	10.9	19.3
variance tardiness assembly orders	304	465	346	546	319	506
average tardiness work orders	7.0		8.5		7.5	
variance tardiness work orders	218		252		229	

The average throughput time increases by approximately 8% (or 16% for large assembly orders) when limits for the swapping of allowance are imposed compared with unlimited allowance swapping. At the same time, the due date reliability of assembly orders does not improve significantly. These results support the conclusion that it is generally not useful to set limits for swapping allowance. It is important to note, however, that with a geometric order structure the allowance cannot be swapped in approximately thirty percent of the work orders because they belong to single-work-order assembly orders. This category of work orders has a stabilizing effect with respect to the whole situation. With a geometric structure, more operations are accelerated than delayed when the acceleration/retardation technique is applied (refer also to Subsection 5.6.1). When the allowances associated with a large number of operations are unaffected, then the accelerated operations have a greater probability of actually being processed in the envisaged sequence at the respective work stations.

An analysis of the lateness for the various categories of work orders indicates that it is nevertheless useful in practice to impose limitations for swapping allowance when assembly orders have an extremely unbalanced distribution with respect to the number of operations per work order. Limits therefore need to be set for such assembly orders with an extremely unbalanced distribution. It is expected that this will have only a negligible influence on the total performance.

The degree of due date reliability generally does not become significantly worse when allowance is swapped. The average lateness for all of the assembly orders increases from 5.4 in the reference situation to 8.5 when an unlimited amount of allowance swapping is permitted. This represents an increase of approximately 6% when related to the resulting throughput time (51).

5.6 Evaluating the throughput time performance of the decision rule

The results of applying the acceleration/retardation technique in situations with different resource capacity utilization levels are presented in the following three tables.

Table 5.7:
Simulation results based upon a utilization of 80%: The reference situation, unlimited allowance swapping and limited allowance swapping.

run	1	2	3	4	5	average
The reference situation, simulation experiment ti580001.						
average throughput time assembly orders	35.7	35.1	35.6	35.3	35.1	35.4
average planned throughput time assembly orders	32.8	32.7	32.8	32.9	32.7	32.8
average waiting time	3.3	3.2	3.2	3.2	3.2	3.2
average throughput time work orders	21	20.4	20.6	20.6	20.3	20.6
average throughput time large assembly orders	66.9	65.3	68.2	67.3	63.9	66.3
average planned throughput time large assembly orders	57.1	55.9	58.2	58.5	55.6	57.1
Unlimited swapping, simulation experiment ti580093.						
average throughput time assembly orders	28.4	28.2	28.4	28.1	27.9	28.2
average planned throughput time assembly orders	23.6	23.6	23.6	23.7	23.6	23.6
average waiting time	3.4	3.3	3.4	3.3	3.3	3.3
average throughput time work orders	21.5	21.1	21.2	21.1	20.7	21.1
average throughput time large assembly orders	41.4	40.7	41.8	41.4	40.1	40.1
average planned throughput time large assembly orders	29.1	28.6	28.9	29.8	28.6	29.0
Limited swapping, simulation experiment ti580056.						
average throughput time assembly orders	29.6	29.3	29.7	29.3	29.3	29.4
average planned throughput time assembly orders	26.0	25.9	26.0	26.0	26	26.0
average waiting time	3.4	3.3	3.3	3.3	3.3	3.3
average throughput time work orders	21.3	20.9	21.0	20.9	20.7	21.0
average throughput time large assembly orders	44.4	43.3	45	44.1	43.2	44.0
average planned throughput time large assembly orders	33.6	33	33.7	34.2	33.1	33.5

With a utilization level of 80%, the throughput time for all of the assembly orders is reduced by 20% when the swapping of allowance is unlimited. The throughput time is reduced by 17% when limitations are imposed. The throughput time improvements are 40% and 34%, respectively, for the large assembly orders.

Table 5.8:
Simulation results based upon a utilization of 90%: The reference situation, unlimited allowance swapping and limited allowance swapping.

run	1	2	3	4	5	average
The reference situation, simulation experiment ti590001.						
average throughput time assembly orders	67.0	65.2	69.1	69.4	69.3	68.0
average planned throughput time assembly orders	61.6	61.4	61.5	61.9	61.2	61.5
average waiting time	7	6.7	7.3	7.3	7.4	7.1
average throughput time work orders	39.5	38.1	41.2	41.2	41.6	40.3
average throughput time large assembly orders	122.0	116.3	127.8	126.4	131.0	124.7
average planned throughput time large assembly orders	106.5	103.7	110.0	106.7	108.5	107.1
Unlimited swapping, simulation experiment ti590093.						
average throughput time assembly orders	50.7	49.9	53.3	52.6	53.9	52.1
average planned throughput time assembly orders	42.2	42.1	42.1	42.2	42.0	42.1
average waiting time	7.2	7.0	7.6	7.5	7.7	7.4
average throughput time work orders	40.4	39.6	42.3	42.0	42.8	41.4
average throughput time large assembly orders	68.8	65.2	70.7	71	76.4	70.4
average planned throughput time large assembly orders	48.6	46.9	48.3	47.9	48.9	48.1
Limited swapping, simulation experiment ti590056.						
average throughput time assembly orders	55.1	54.4	57.9	57	58.1	56.5
average planned throughput time assembly orders	48.8	48.7	48.7	49	48.5	48.7
average waiting time	7.1	7	7.5	7.4	7.6	7.3
average throughput time work orders	39.8	39.2	41.9	41.2	42.3	40.9
average throughput time large assembly orders	80.0	75.1	84.2	83.2	87.7	82.0
average planned throughput time large assembly orders	62.7	59.6	64.4	62.9	63.1	62.5

With a utilization level of 90%, the throughput time for all of the assembly orders is reduced by 23% when the swapping of allowance is unlimited. The throughput time is reduced by 17% when limitations are imposed. The throughput time improvements are 44% and 34%, respectively, for the large assembly orders.

Table 5.9:
Simulation results based upon a utilization of 95%: The reference situation, unlimited allowance swapping and limited allowance swapping.

run	1	2	3	4	5	average
The reference situation, simulation experiment ti595001.						
average throughput time assembly orders	135.4	135.2	145.7	139.4	148.4	140.8
average planned throughput time assembly orders	126.2	126	126.2	126.8	125.5	126.1
average waiting time	15.1	15.1	16.9	15.5	17.3	16.0
average throughput time work orders	80.4	80.5	89.0	82.8	91.0	84.7
average throughput time large assembly orders	246.5	233.8	262.1	246.9	272.8	252.4
average planned throughput time large assembly orders	221.9	208.6	222.7	217.4	224.5	219.0
Unlimited swapping, simulation experiment ti595093.						
average throughput time assembly orders	97.2	99.3	110	104.7	111.9	104.6
average planned throughput time assembly orders	83.7	83.6	83.7	83.8	83.5	83.7
average waiting time	15.5	15.9	17.5	16.5	17.8	16.6
average throughput time work orders	81.7	83.4	91.4	87.1	92.8	87.3
average throughput time large assembly orders	121.7	120.7	136.3	129.3	145.7	130.7
average planned throughput time large assembly orders	91.2	86.7	90.4	89.1	91.7	89.8
Limited swapping, simulation experiment ti595056.						
average throughput time assembly orders	106.3	107.9	117.2	111.3	119.2	112.4
average planned throughput time assembly orders	94.9	94.7	94.7	95.1	94.4	94.8
average waiting time	15.4	15.8	17.3	16.1	17.5	16.4
average throughput time work orders	81.5	83.0	90.3	85.1	91.3	86.2
average throughput time large assembly orders	140.4	135.4	154.5	144.9	162.6	147.6
average planned throughput time large assembly orders	112.8	104.8	112.8	110.3	112.5	110.6

With a utilization level of 95%, the throughput time for all of the assembly orders is reduced by 26% when the swapping of allowance is unlimited. The throughput time is reduced by 20% when limitations are imposed. The throughput time improvements are 48% and 42%, respectively, for the large assembly orders.

It is relatively easy to calculate the improvement in the average throughput time for an assembly order. A method for calculating the reduction in throughput time and the validation of this method based upon simulation results are presented in the following two sections.

5.6.1 Calculating the reduction in throughput time

It is possible to calculate the expected reduction in the throughput time which can be derived from applying the acceleration/retardation technique. In the example used in Subsection 5.2.1, ten categories of assembly orders were defined in which each category consisted of assembly orders with a specific number of work orders. An average number of operations per work order can be determined for each category of assembly orders. Based upon the definition of an average assembly order per category in this way, the swapping of allowance can be carried out. Specification for the upper and lower limits are also taken into account. The results of the calculations, including the calculation of the fractions, are presented in Table 5.10. The fractions associated with the largest work orders provide an indication of how much improvement is possible with respect to the throughput time of the average assembly order in each category.

The average reduction in the allowance for the largest work orders of the assembly orders is equivalent to the sum of all of the fractions of the largest work order in each category multiplied by the respective probability of the occurrence of the assembly order in each category. When the acceleration/retardation limitations are imposed, this sum is equal to: 0.231 (= 0 * 0.3389 + 0.17 * 0.2261 + 0.37 * 0.1508 + 0.45 * 0.1006 + ...).

Rounded off, the reduction in the allowance for the largest work orders of the assembly orders is 23%. With a 90% utilization level, the operation processing time represents an average of 12.5% of the shop throughput time. This means that the planned reduction in the throughput time of the assembly orders is 20.1% when the utilization level is 90%.

Table 5.10: Calculated reductions in throughput time based upon the use of acceleration/retardation with limits within assembly orders.

assembly order category	o	p(o)	o_k	$f_{k,j}$	$L \le f_{k,j} \le U$	assembly order occurance	reduction
1	3	0.5	3	1	1	0.3389	0
2	1	0.25	7	3.5	2		
	6	0.75		0.58	0.83	0.2261	0.17
3	1	0.17	12	4	2		
	3	0.5		1.33	1.67		
	8	0.83		0.5	0.63	0.1508	0.37
4	1	0.12	17	4.25	2		
	2	0.37		2.13	2		
	4	0.62		0.22	1.38		
	10	0.87		0.43	0.55	0.1006	0.45
5	1	0.1	20	4	2		
	1	0.3		4	2		
	3	0.5		1.33	1.78		
	5	0.7		0.8	1.07		
	10	0.9		0.4	0.53	0.06708	0.47
6	1	0.083	28	4.67	2		
	1	0.253		4.67	2		
	3	0.423		1.56	2		
	4	0.593		1.17	1.5		
	7	0.763		0.67	0.86		
	12	0.933		0.39	0.5	0.04474	0.5
7	1	0.071	30	4.3	2		
	1	0.211		4.3	2		
	2	0.351		2.15	2		
	3	0.491		1.43	1.83		
	5	0.631		0.86	1.1		
	7	0.771		0.61	0.79		
	11	0.911		0.39	0.5	0.02984	0.5
8	1	0.0625	36	4.5	2		
	1	0.1875		4.5	2		
	2	0.3125		2.3	2		
	3	0.4375		1.5	1.87		
	4	0.5625		1.13	1.4		
	5	0.6875		0.9	1.12		
	8	0.8125		0.56	0.7		
	12	0.9375		0.38	0.47	0.0199	0.53
9	1	0.056	40	4.44	2		
	1	0.167		4.44	2		
	2	0.2775		2.22	2		
	2	0.3885		2.22	2		
	3	0.4995		1.48	1.87		
	4	0.61106		1.11	1.4		
	6	0.7222		0.74	0.93		
	8	0.83325		0.56	0.7		
	13	0.94435		0.34	0.43	0.01328	0.57
10	1	0.05	45	4.5	2		
	1	0.15		4.5	2		
	1	0.25		4.5	2		
	2	0.35		2.25	2		
	3	0.45		1.5	1.94		
	4	0.55		1.13	1.46		
	5	0.65		0.9	1.17		
	6	0.75		0.75	0.97		
	9	0.85		0.5	0.65		
	13	0.95		0.35	0.45	0.008855	0.55

A reduction in the allowance can be expressed as a certain reduction in the waiting time as compared to the maximum possible waiting time reduction. To determine this, the minimum waiting time must first be calculated based upon processing the operations with the highest priority ([Ooijen, 1991]). A simplified version of the calculation proposed by Conway ([Conway et al., 1967]) for determining the minimum waiting time is as follows:

utilization percentage: r
utilization percentage for a category of accelerated operations: $r(a)$
expected waiting time: $E(w)$
expected minimum waiting time: $E(v)$

With several simplifications, the calculation can be performed as follows:

$$E(v) = E(w) \cdot \frac{(1 - r)}{(1-r(a))}$$

Approximately 56% (see also table 5.10) of the operations are accelerated. This means that:

$$r(a) = 0.56 \cdot r$$

$E(v) = 0.2 \cdot E(w)$, in the case of a 90% utilization level.

This shows that 80% of the average waiting time can eventually be reduced by 20.1%. This will result in a 16.1% reduction in the total average throughput time when the allowance is swapped and the utilization level is 90%.

Similar calculations can be carried out for a situation in which no limitations are imposed on the swapping of allowance. In this case the result is a 23.8% reduction in the throughput time when the utilization level is 90%. Similar calculations can also be made for other levels of utilization.

5.6.2 Validating the calculations using experimental results

The expected reduction in the throughput time calculated in the previous subsection will be negated to some extent by an increase in the average throughput time of the work orders. This increase in the average throughput time of work orders is caused by the normally to be expected increase in the average waiting time which results from swapping the allowance.

The average throughput time of work orders will increase as a result of applying acceleration/retardation (see Column 3 of Table 5.11). The direct cause of this increase in the average throughput time is an increase in the average waiting time. Intuitively, this is a logical relationship because the large operations in the large work orders are generally given a higher priority than the smaller operations in the small work orders. This results in an LPT effect (LPT: Longest Processing Time, see [Conway et al., 1967]) at the level of operation processing.

The calculated reductions and the reductions observed in the simulation runs are presented in Table 5.11.

Table 5.11:
The calculated and observed reductions in throughput time.
(The percentages listed in rows 2, 3, 4 and 5 have been calculated based upon the associated assembly order throughput times for the reference simulation situations.)

	limits imposed			no limits imposed		
1. utilization percentage	80%	90%	95%	80%	90%	95%
2. percentage waiting time of throughput time	77.3	87.5	93.9	77.3	87.5	93.9
3. increase of the average throughput time of work orders	1.9	1.5	1.8	2.4	2.7	3.1
4. calculated expected reduction	11.4	16.1	19.4	16.8	23.8	28.7
5. actual throughput time reduction of assembly orders	16.9	16.9	20.2	20.3	23.4	25.7

No allowance has been made for an increase in the average work order throughput time in the calculations. The data presented in Table 5.11 shows that there is a fair degree of conformance between the expected reductions which have been calculated ("estimated actual" in row 4) and the results of the simulations ("actual" in row 5) except only for the 80% situation with limited allowance swapping.

5.7 Conclusions

1. By using the acceleration/retardation technique within assembly orders, the average throughput time of assembly orders can be reduced by approximately 23% (based upon a utilization level of 90%). The following remarks need to be made, however:
   - Allowance is swapped between the work orders belonging to the same assembly order.
   - The average lateness increases by approximately 6% of the average throughput time in the reference situation. (This aspect is discussed in more detail in Chapter 6).
   - No limitations are imposed upon the swapping of allowance.
   - One disadvantage of applying the acceleration/retardation technique is that the average work order throughput time is increased by between 1.5 and 3 percent, depending upon the utilization level.
   - An accurate prediction of the reduction in the average throughput time of the assembly orders can be made in advance.

2. Using the acceleration/retardation technique in a situation with a 90% utilization level provides a 23% reduction in the average shop throughput time for assembly orders. A reduction of 44% can be realized with respect to large assembly orders. In practice, the performance of the large assembly orders is typically more important than the average performance for all of the assembly orders. A significantly greater reduction in the average throughput time of the large assembly orders as compared with the reduction in the average throughput time for all of the assembly orders can be realized by using the acceleration/retardation technique within assembly orders. (The importance of the throughput time reduction of the large assembly orders is covered in detail in Chapter 7.)

Chapter

6 ESTIMATING THE ASSEMBLY ORDER COMPLETION DATE

A variety of situations may arise in which all of the work orders belonging to a given assembly order are scheduled with the same due date. If, for example, all of the work orders have the same planned throughput time as a result of applying the acceleration/retardation technique, then they will all be scheduled for release on the same date and all have the same due date. Even without using the acceleration/retardation technique, the work orders could still be scheduled in such a way that they will all be completed on the same date. This could be done by calculating backwards from the due date to schedule the appropriate release dates. This approach is used in the reference situation presented in Chapter 5. When all of the work orders belonging to a given assembly order have the same due date, then completion disturbance can be expected to occur, resulting in a structure delay time for the assembly order. (A description of structure time and structure allowance is given in section 4.3.) The concepts associated with completion disturbance are presented in this chapter. These concepts lead to an explicit definition for assembly order structure delay time. Subsequently, a method for estimating the structure delay time is presented and validated using simulation experiments. The effects of applying the acceleration/retardation technique with respect to the structure delay time are then investigated. Conclusions are presented at the end of this chapter.

6.1 Introduction

A due date assignment rule (see Equation 1) was developed in the previous chapter. This decision rule has been designed to determine the due dates for assembly orders.

The probability of all of the work orders belonging to a given assembly order being completed at the exact same point in time is extremely small. The last work order to be completed will determine the completion date for the whole assembly order. A completion delay will be experienced by all of the other work orders. This delay is the amount of time that a completed work order must wait until the whole assembly order can be considered to be completed. The completion delay consists of two parts: a planned component and a random component (refer also to section 4.3). The due date assignment rule and the work order release rule introduced in Chapter 5 have both been designed to reduce the value of the planned component to zero. This is accomplished by scheduling all of the work orders for completion on the same due date, but scheduling the work orders for release at different times. The realized work order throughput times and actual completion dates will generally show a variance with respect to the planned times and dates. An example is presented in Figure 6.1.

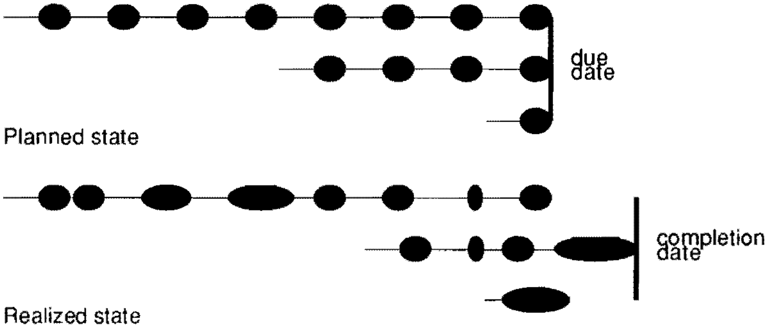


Figure 6.1: Planned versus realized times and dates of an assembly order example.

The average lateness for the work orders belonging to a given assembly order is zero when the average completion date of the work orders is equal to the scheduled due date. It is the stochastic nature of this lateness within an assembly order which causes the completion delay at the work order level and the structure delay time at the assembly order level. A method for estimating the structure delay time is presented in this chapter.

6.2 Structure delay time and structure allowance

The simplest form of structure delay time occurs when all of the work orders belonging to a given assembly order are scheduled with the same due date and the completion dates of the work orders show a random fluctuation about the due date. Both of the conditions are satisfied in the reference situation defined in Chapter 5. A method for estimating the structure delay time for this situation is presented here. The effects of applying the acceleration/retardation technique with respect to the structure delay time are analyzed in Section 6.5.

◆ *Defining the concepts*

The due date assignment rule introduced in Chapter 5 (Equation 1) is based upon releasing the first work order (i.e., the largest work order in terms of number of operations) immediately upon the arrival of the assembly order in the shop.

k : index indicating assembly order (k)
j : index indicating work order (j) of the assembly order
i : index indicating operation (i) of the work order

D_k : due date of assembly order k

n : total number of assembly orders
m_k : total number of work orders in assembly order k
$o_{k,j}$: total number of operations in work order j of assembly order k
$p_{k,j,i}$: processing time for operation i in work order j of assembly order k
A : allowance
M_k : number of operations in the largest work order (designated as J) in assembly order k
W_n : normative waiting time

$$A = W_n$$

$$M_k = \max_{j=1}^{m_k} o_{k,j}$$

$$D_k = \text{time} + M_k \cdot A + \sum_{i=1}^{M_k} p_{k,J,i} \qquad (1)$$

(from Chapter 5)

The remaining work orders are released on the scheduled release dates. The waiting time between arrival and release was defined as the "buffer time" in Chapter 4. The shop throughput time for a work order is equivalent to the period of time between the release and the completion of the work order. The total throughput time for a work order is defined as the sum of the buffer time and the shop throughput time. The throughput time of an assembly order is equivalent to the throughput time of the associated work order with the longest throughput time.

H_k : actual throughput time for assembly order k

$h_{k,j}$: actual throughput time for work order j of assembly order k

$$H_k = \max_{j=1}^{m_k} (h_{k,j}) \qquad (2)$$

The completion date of the assembly order is the completion date of the latest associated work order (see Equation 3).

C_k : completion date of assembly order k

$c_{k,j}$: completion date of work order j of assembly order k

$$C_k = \max_{j=1}^{m_k} (c_{k,j}) \qquad (3)$$

The completion date of a work order is related to its due date. This relationship can be described with a stochastic variable as is written down with Equation 4.

$d_{k,j}$: due date of work order j of assembly order k

$\underline{\Phi}_{k,j}$: random disturbance between completion and due date of work order j of assembly order k

$\underline{\Phi}_{k,j} \sim N(\mu,\sigma^2)$ ($\underline{\Phi}_{k,j}$ is normal distributed with mean μ and standard deviation σ^2)

$$c_{k,j} = d_{k,j} + \underline{\Phi}_{k,j} \qquad (4)$$

Because of the stochastic disturbances between the due dates and the completion dates of the work orders, we have to expect that the expected value of the completion date of the assembly order will always be greater than the mean completion date of the associated work orders when the assembly order contains more than one work order. Therefore we define a variable "structure delay time" (see equation 5a) of an assembly order as the difference between the completion date of the assembly order itself and the average completion dates of its work orders. The estimate of the structure delay time of an assembly order is the so-called "structure allowance". Structure allowance of an assembly order is defined as the difference between the due date of the assembly order and the due date of the associated work orders if these are the same for all work orders (see equation 5b). Now, we have to determine an adequate value for the structure allowance of an assembly order. This is worked out in Equation 5.

s_k : structure delay time of assembly order k

S_k : structure allowance of assembly order k

d_k : due date of all work orders of assembly order k when the due dates of the work orders from k are equal to each other (notice: d_k is not equal to D_k)

$$s_k = C_k - \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k} \qquad (5a)$$

$$S_k = D_k - \frac{\sum_{j=1}^{m_k} d_{k,j}}{m_k} \qquad (5b)$$

Equation 4 substituted in Equation 3 gives:

$$C_k = d_k + \max_{j=1}^{m_k} \underline{\Phi}_{k,j} \qquad \text{if } d_{k,j} = d_k \text{ for all j from k} \qquad (5c)$$

(5c) substituted in (5b) gives:

$$S_k = D_k - d_k = D_k - C_k + \max_{j=1}^{m_k} \underline{\Phi}_{k,j} \qquad (5d)$$

after rewriting (5a):

$$C_k = s_k + \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k}$$ we substitute S_k (5b and 4) for s_k:

$$C_k = \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k} + D_k - \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k} + \frac{\sum_{j=1}^{m_k} \underline{\Phi}_{k,j}}{m_k}$$

$$C_k - D_k = \frac{\sum_{j=1}^{m_k} \underline{\Phi}_{k,j}}{m_k}$$ which we substitute in (5d):

$$S_k = \max_{j=1}^{m_k} \underline{\Phi}_{k,j} - \frac{\sum_{j=1}^{m_k} \underline{\Phi}_{k,j}}{m_k} \qquad (5)$$

The variable $\underline{\Phi}_{k,j}$ is also called the work order lateness. This variable $\underline{\Phi}_{k,j}$ can be considered as being compounded out of two different other stochastic variables, which is worked out in Equation 6. The work order lateness consists of an assembly order dependent part which is equal for all the work orders of the same assembly order and an assembly order independent part which is not the same. The dependent part is due to the workload level in the shop at the time that the assembly order is present in the shop. Only the independent part contributes to the structure delay.

$\underline{\alpha}_{k,j}$ and $\underline{\beta}_{k,j}$ are two stochastic variables, whereby:

$\underline{\Phi}_{k,j} = \underline{\alpha}_{k,j} + \underline{\beta}_{k,j}$ in such a way that:

for all work orders j and j' from k,
  and j and j' are not the same work order:

$\underline{\alpha}_{k,j} = \underline{\alpha}_{k,j'} = \underline{\alpha}_k$ and $\underline{\beta}_{k,j}$ is not equal to $\underline{\beta}_{k,j'}$

Per definition is the average $\underline{\beta}_{k,j} = 0$ (6)

The stochastic variable ($\underline{\alpha}_k$) should be eliminated when we want to determine the structure allowance. This variable ($\underline{\alpha}_k$) is zero when the allowance per operation of a work order of an assembly order is equal to the waiting time of the same operation at any moment in time. The waiting time allowances have to be perfectly dynamically controlled and estimated when we want to be able to eliminate ($\underline{\alpha}_k$). Workload control and dynamic due date assignment contributes to such a dynamic control of waiting time allowances (refer also to Chapter 8 and 9). This results in an average work order lateness of zero.

Equation 5 can now be rewrite in Equation 7, as follows:

$$s_k = \max_{j=1}^{m_k} \underline{\beta}_{k,j} - \frac{\sum_{j=1}^{m_k} \underline{\beta}_{k,j}}{m_k}$$

the average $\underline{\beta}_{k,j} = 0$, so we approximate s_k by:

$$s_k = \max_{j=1}^{m_k} \underline{\beta}_{k,j} \qquad (7)$$

We call the variable $(\underline{\beta}_{k,j})$ the "independent disturbance", and the variable $(\underline{\alpha}_k)$ the "dependent disturbance". The words independent and dependent are chosen from the point of view of an assembly order.

The structure allowance is therefore equal to the maximum value from a set of stochastic variables. In this way the problem of estimating the structure delay time can be formulated in terms of a classic problem in the field of network planning theory. This is described further in the next section.

To be able to estimate the structure allowance both the average and the standard deviation of the work order lateness, under the stipulation of dynamical controlled and estimated waiting time allowances, should be known. The average work order lateness is equal to zero, when the stipulation valid is (see also equation 6). The standard deviation is in one way or an other related to the standard deviation of the completion delay. This is explained and investigated hereunder.

Interesting to notice is the fact that the standard deviation of the completion delay is not influenced by the standard deviation of the variable $(\underline{\alpha}_k)$. This is worked out in Equation 8.

$k_{k,j}$: completion delay of work order j in assembly order k

$$k_{k,j} = (\max_{j=1}^{m_k} c_{k,j}) - c_{k,j}$$

$$k_{k,j} = \max_{j=1}^{m_k} (d_{k,j} + \underline{\alpha}_k + \underline{\beta}_{k,j}) - (d_{k,j} + \underline{\alpha}_k + \underline{\beta}_{k,j})$$

because, for all j and j' from k; and j and j' are not the same,:

$\underline{\alpha}_{k,j} = \underline{\alpha}_{k,j'} = \underline{\alpha}_k$ we can write:

$$k_{k,j} = \max_{j=1}^{m_k} (d_{k,j} + \underline{\beta}_{k,j}) - (d_{k,j} + \underline{\beta}_{k,j})$$

$$k_{k,j} = \max_{j=1}^{m_k} (\underline{\beta}_{k,j}) - (\underline{\beta}_{k,j}) \quad (8)$$

In the Appendix to this chapter a plausible reasoning is worked out which results in the assumption that the standard deviation of the Independent Disturbance approximately equal is to the standard deviation of the completion delay. (See the Appendix to this Chapter.)

It is important to notice that when the waiting time allowances are not dynamical controlled and estimated, the standard deviation of $(\beta_{k,j})$ still can be determined by measuring the standard deviation of the completion delay. For the rest, this is only true under the condition that work orders of one assembly order have the same due date and the same expected average completion date. In Equation 9 is worked out that the structure time of an assembly order is equal to the average completion delay of the associated work orders.

L : index associated with the last work order of an assembly order

x_k : average completion date of the work orders belonging to assembly order k

$$x_k = \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k}$$

$$s_k = \max_{j=1}^{m_k} (c_{k,j} - x_k) =$$

$$= c_{k,L} - x_k = c_{k,L} - \frac{\sum_{j=1}^{m_k} c_{k,j}}{m_k} =$$

$$= \frac{m_k \cdot c_{k,L} - \sum_{j=1}^{m_k} c_{k,j}}{m_k} =$$

$$= \frac{\sum_{j=1}^{m_k} (c_{k,L} - c_{k,j})}{m_k} = \frac{\sum_{j=1}^{m_k} (k_{k,j})}{m_k} \qquad (9)$$

The structure delay time of an assembly order can therefore be described as the average completion delay of the associated work orders. This means that the structure delay time can be measured.

The actual throughput time for an assembly order can now be defined as the sum of the average actual buffer time of the work orders, the average actual shop throughput time of the work orders and the average completion delay of the associated work orders. This is presented below as Equation (10).

$b_{k,j}$: buffer time of work order j in assembly order k

$g_{k,j}$: shop throughput time for work order j in assembly order k

$\underline{H}$: average throughput time of assembly orders

$$h_{k,j} = b_{k,j} + g_{k,j} + k_{k,j}$$

$$H_k = \frac{\sum_{j=1}^{m_k} h_{k,j}}{m_k} = \frac{\sum_{j=1}^{m_k} b_{k,j}}{m_k} + \frac{\sum_{j=1}^{m_k} g_{k,j}}{m_k} + \frac{\sum_{j=1}^{m_k} k_{k,j}}{m_k}$$

$$\underline{H} = \frac{\sum_{k=1}^{n} H_k}{n} \qquad (10)$$

It is clear from Equation (10) that the average throughput time for a given assembly order is not the same as the average throughput time for all of its work orders. This is also apparent from the fact that the assembly order throughput time is equal to the maximum throughput time from a subset of work orders.

The assembly order due date is a so-called "expected completion date" of the assembly order because of the estimation of the structure delay time.

Various suggestions for distinguishing so-called external due dates for entities such as work orders or assembly orders have been published in the literature. (See [Bertrand & Wortmann, 1981]). This type of external due date for assembly orders is not the same as an expected completion date, however. The external due date is defined as the latest date on which the actual completion will occur or will have occurred with a specified percentage of reliability (for example 95%). For purposes here, the external due date will be defined in relation to the expected completion date. The further issues which arise in dealing with external due dates will not be covered here.

The model of throughput times of assembly orders developed in this section differs from the customary models found in the literature to date. A typical model as found in the literature (see Chapter 3) is presented in Figure 6.2. The model developed here is illustrated in Figure 6.3.

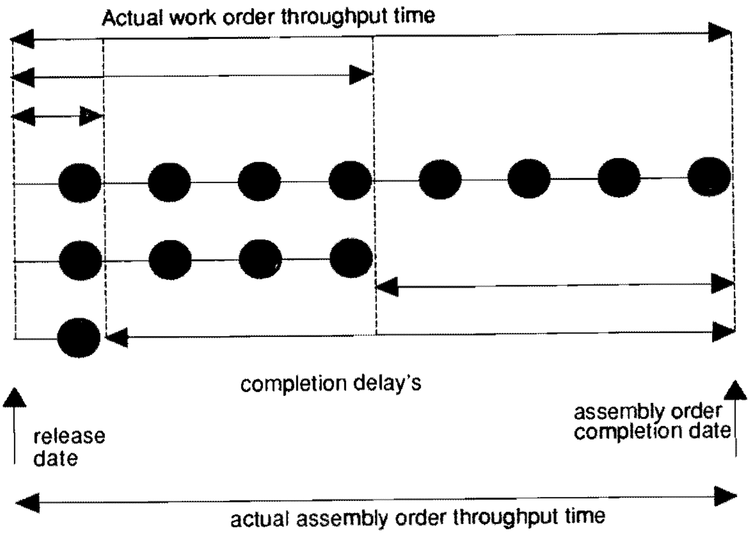


Figure 6.2: Throughput time model used in literature.

It has been explained in this section how the structure delay time can been viewed as the maximum value from a set of stochastic variables. A method for determining the expected structure delay time, the so-called structure allowance, is developed in the next section. This leads to a research hypothesis which will be tested using simulation experiments described in a subsequent section.

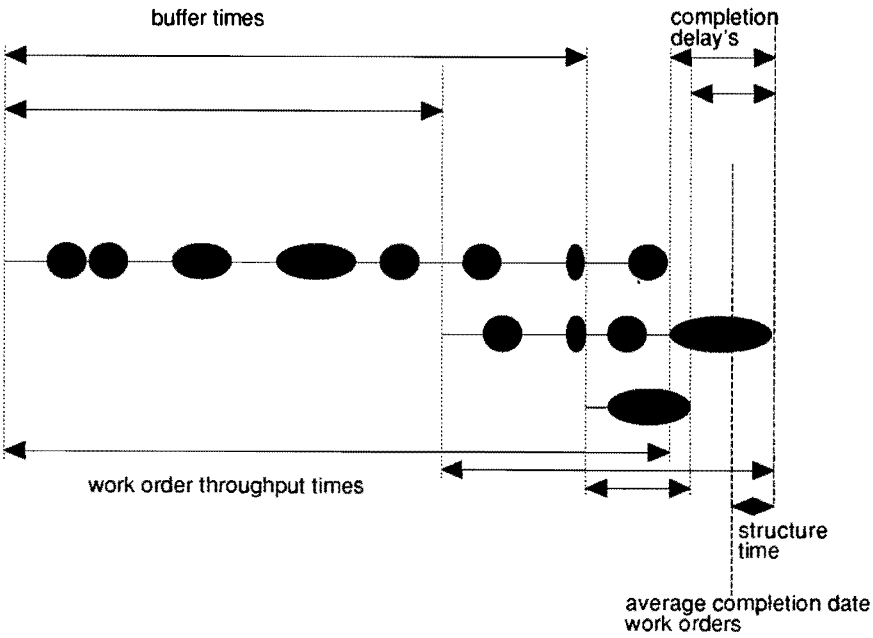


Figure 6.3: Throughput time model used in this study.

6.3 Estimating the structure delay time

Clark ([Clark, 1961]) has described a method for determining the maximum value from a set of normally distributed values which may be mutually dependent. His publication on this topic represented an important milestone in the development of network planning theory. The only aspect which has been seriously criticized in subsequent publications is his assumption with respect to a normal distribution of the lengths of times associated with the paths through a network. It is now more common to assume that these lengths of times will correspond to a beta distribution. Golenko-Ginzburg ([Golenko-Ginzburg, 1989]) presented a method for determining both the sum and the maximum value from a set of beta-distributed stochastic values. The stipulation of a normal distributed Independent Disturbance fits for the purposes of this study. As a result, it has been decided to start with the method used by Clark.

Clark presents a table with average values and the standard deviations of the maximum value of m independent, normally distributed, normalized stochastic variables (see

Table 6.1).

Table 6.1:
The Maximum Value of m Independent, Normally Distributed Variables, from [Clark, 1961].

m	average	standard deviation
2	0.5642	0.8256
3	0.8463	0.7480
4	1.0294	0.7012
5	1.1630	0.6690
6	1.2672	0.6449
7	1.3522	0.6260
8	1.4236	0.6107
9	1.4850	0.5978
10	1.5388	0.5868

If it is assumed that the Independent Disturbances ($\beta_{k,i}$'s) of work orders belonging to a given assembly order are mutually independent and normally distributed, then the structure allowance can be determined simply using the data in Table 6.1. In this case the structure allowance for an assembly order with m work orders is equal to the value listed in Table 1 multiplied by the standard deviation of the Independent Disturbance, which is equal to the standard deviation of the completion delay time. If the standard deviation is equal to, for example, 11.34, then the structure allowance for an assembly order comprised of seven work orders is equal to: $1.3522 * 11.34 \approx 15.33$.

This method is presented here as a hypothesis for estimating the structure delay time. This hypothesis will be tested using the results of simulation experiments presented in the next section.

6.4 Evaluating the results of simulation experiments

Simulation runs were carried out using utilization percentages of 80%, 90% and 95%. Five runs, each using a different initial seed value for the random number generator, were performed per utilization percentage. The same decision rules and parameter settings were used as in the reference situation described in Chapter 5. In order to be able to measure the effect of the structure allowance on due date reliability, the structure allowance was set to zero for an initial group of simulation runs and set according to the method described in the previous section for a second group of simulations. The standard deviation of the completion delay of the first run per utilization percentage is used to determine the structure allowance.

The results with respect to the structure delay time and the throughput time are presented in Table 6.2. The results in terms of due date reliability are presented in Table 6.3.

Table 6.2:
Simulation Results with respect to the Structure Delay Time and Throughput Time.

runs:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
th580001	0.798	3.200	14.318	3.918	4.846	41.948	35.711	727.120
th580101	0.789	3.292	15.920	3.865	5.105	46.339	35.091	718.447
th580201	0.793	3.410	16.303	3.891	5.199	46.297	35.607	701.122
th580301	0.795	3.188	13.769	3.913	4.867	39.593	35.317	695.982
th580401	0.796	3.163	14.708	3.875	4.858	41.693	35.113	685.910
average:	0.794	3.251	15.004	3.892	4.975	43.174	35.368	705.716
th590001	0.902	5.557	45.259	6.793	8.428	128.557	67.010	2540.174
th590101	0.898	5.424	42.807	6.731	8.322	118.477	65.203	2375.046
th590201	0.904	5.930	49.259	6.769	9.085	133.477	69.067	2451.269
th590301	0.901	6.060	52.090	6.785	9.277	144.726	69.370	2490.025
th590401	0.902	6.335	72.079	6.734	9.675	193.315	69.325	2658.544
average:	0.901	5.861	52.299	6.762	8.957	143.710	67.995	2503.012
th595001	0.959	9.805	121.290	10.932	14.979	332.291	135.442	9626.712
th595101	0.955	9.967	125.007	10.845	15.250	353.758	135.157	9804.079
th595201	0.959	11.391	170.194	10.915	17.463	461.316	145.679	10122.580
th595301	0.956	11.274	181.156	10.912	17.321	489.654	139.418	9994.361
th595401	0.957	12.957	255.561	10.837	19.887	680.817	148.356	10967.810
average:	0.957	11.079	170.642	10.888	16.980	463.567	140.810	10103.108

[Utilization percentage (1), average structure delay time (2), variance of structure delay time (3), average structure allowance (4), average completion delay time (5), variance of completion delay time (6), average actual assembly order throughput time (7), variance of actual assembly order throughput time (8)]

Table 6.3:
Results with respect to Due Date Reliability.

	with structure allowance:				without structure allowance:				both:
runs:	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
th580001	- 1.059	110.771	3.320	58.678	2.860	119.115	5.142	80.720	114.069
th580101	- 1.460	92.833	3.035	43.061	2.404	102.020	4.758	64.595	94.953
th580201	- 1.041	92.568	3.278	42.082	2.850	102.016	5.128	64.388	93.409
th580301	- 1.494	79.245	2.836	33.110	2.419	87.944	4.641	53.179	83.417
th580401	- 1.475	79.668	2.755	35.436	2.400	87.476	4.546	54.493	81.021
average:	- 1.306	91.017	3.045	42.473	2.587	99.714	4.843	63.475	93.374
th590001	- 1.376	421.251	6.744	231.686	5.417	441.772	9.852	304.232	404.842
th590101	- 2.977	271.814	5.203	107.970	3.753	293.637	8.296	168.727	265.991
th590201	0.790	303.529	7.254	147.976	7.558	328.414	10.969	218.791	292.403
th590301	0.701	320.635	7.424	147.069	7.485	348.257	11.197	219.889	321.162
th590401	1.397	491.558	8.643	291.548	8.131	523.404	12.118	380.311	432.295
average:	- 0.293	361.757	7.054	185.250	6.469	387.097	10.486	258.390	343.339
th595001	- 1.724	900.242	11.442	347.777	9.209	965.447	17.143	532.910	935.708
th595101	- 1.650	1096.934	12.677	424.864	9.197	1173.133	18.306	624.783	1148.311
th595201	8.511	1179.702	17.227	718.430	19.427	1274.533	24.424	934.379	1144.794
th595301	1.701	1088.267	14.248	465.466	12.614	1180.030	20.381	689.422	1059.510
th595401	12.022	1854.462	23.146	1095.935	22.860	1975.747	29.719	1407.742	1679.449
average:	3.772	1223.921	15.748	610.494	14.661	1313.778	21.995	837.847	1193.554

[average assembly order lateness (1) & (5), variance of assembly order lateness (2) & (6), average assembly order tardiness (3) & (7), variance of assembly order tardiness (4)& (8), variance of work order lateness (9)]

The structure delay time is represented as a function of the number of work orders in the following three figures (showing 80%, 90% and 95% utilization percentages).

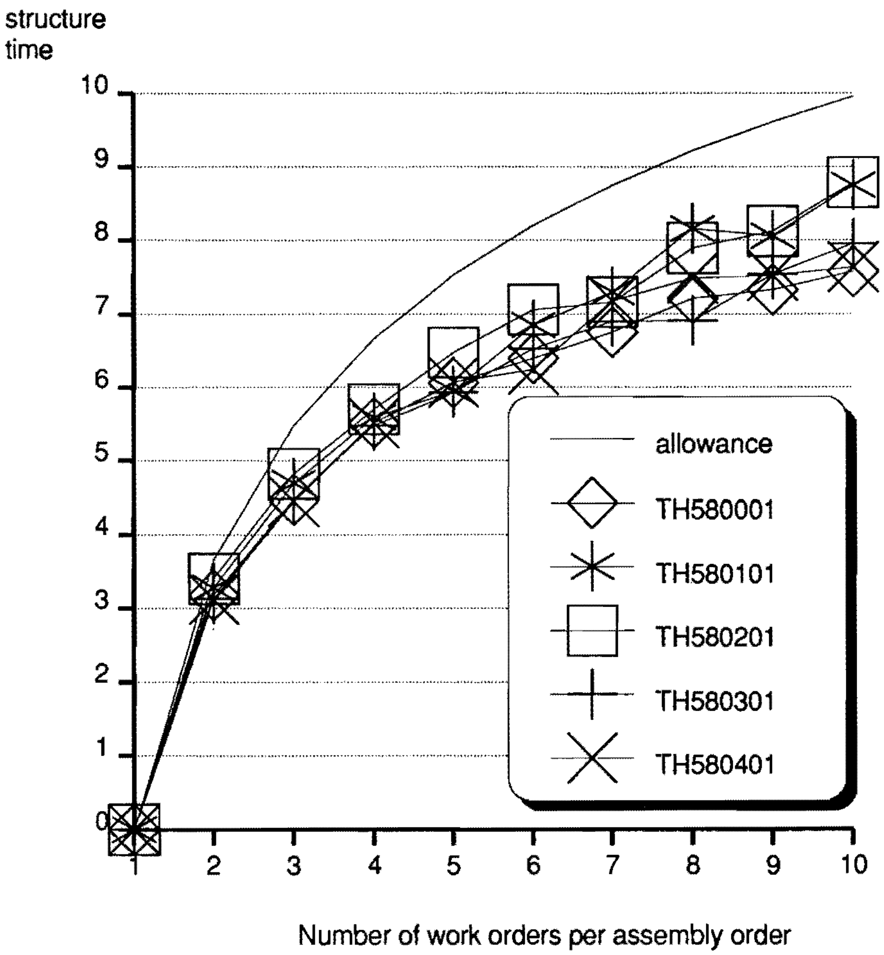


Figure 6.4: Structure delay time, utilization percentage 80%.

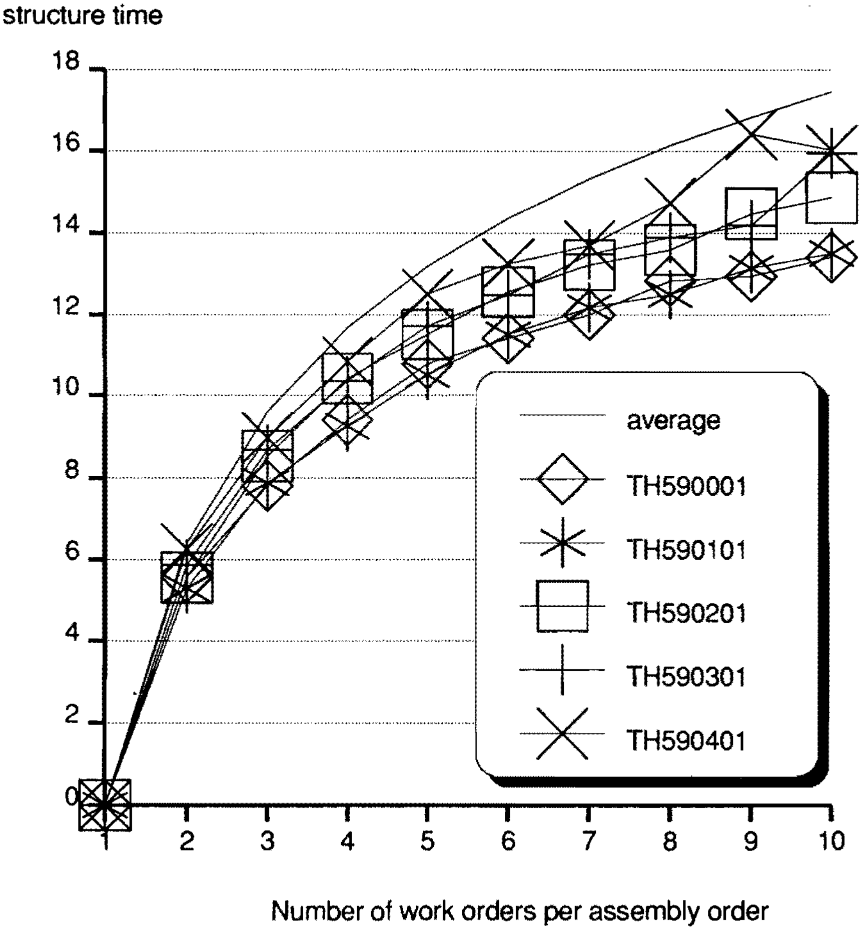


Figure 6.5: Structure delay time, utilization percentage 90%.

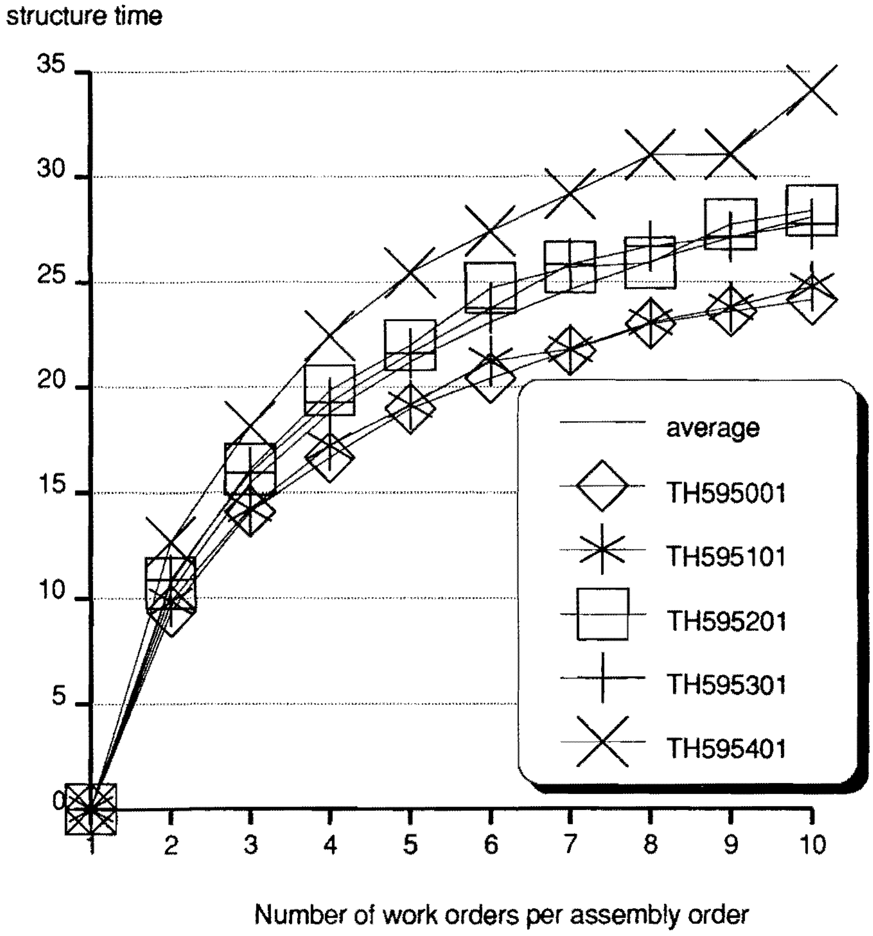


Figure 6.6: Structure delay time, utilization percentage 95%.

The structure delay time as a percentage of the total throughput time is presented in Table 6.4. This has been calculated for all of the assembly orders (in the first column) and separately for only the large assembly orders (in the second column).

Table 6.4:
Structure Delay Time as a Percentage of the Total Throughput Time.

	all assembly orders	large assembly orders
th580001	8.96	11.34
th580101	9.38	13.41
th580201	9.58	12.89
th580301	9.03	11.82
th580401	9.01	11.94
80%	9.19	12.28
th590001	8.29	11
th590101	8.32	11.62
th590201	8.59	11.64
th590301	8.74	12.63
th590401	9.14	12.23
90%	8.62	11.82
th595001	7.24	9.8
th595101	7.37	10.59
th595201	7.82	10.82
th595301	8.09	11.23
th595401	8.73	12.50
95%	7.85	10.99
total	8.55	11.7

◆ *Evaluation of the results*

On the average, the structure delay time consumes nine percent of the total assembly order throughput time. For the large assembly orders this figure is twelve percent.

The structure allowances provide a good indication of the actual structure delay times (columns 2 and 4 from Table 6.2).

The due date reliability improves when the structure delay time approach is used. In particular, the performance with respect to tardiness is significantly better. The standard deviation is improved by 15% on the average. The average is reduced by 28 to 40 percent.

One method of reducing the structure delay time even further is to schedule a buffer time between the scheduled due dates of subsequent work orders and the scheduled due date of the first work order. In this way the subsequent work orders can be completed sooner. This is explained in more detail in Chapter 7 and 9.

6.5 Structure delay time and the acceleration/retardation of work orders

The method for determining the structure allowance described in the preceding section is based on the assumption that all of the work orders belonging to a given assembly order are scheduled with the same due date. An additional assumption is that the actual work order completion dates show a random fluctuation about the scheduled due date. This second assumption is no longer completely valid when the work orders are accelerated/retarded. The consequences of this for determining the structure allowance are explained in more detail in this section.

As explained in Chapter 5, there is a structural difference between the degree of allowance reduction (as opposed to expansion) and the resulting degree of waiting time reduction (as opposed to expansion). The reason for this is that the work orders with the highest absolute priority always have a minimum waiting time while the work orders with the lowest absolute priority have a maximum waiting time (see [Conway, 1967]). This means that an independent work order due date can be scheduled, and an expected work order completion date can be estimated. The expected completion date will be later than the internal due date when a work order is accelerated. The opposite is true when a work order is delayed. This leads to a larger variance in the work order lateness with respect to the internal due date.

It is more difficult to explain the resulting effects on the variance of the Independent Disturbance. The variance of the Independent Disturbance will not increase significantly as long as the differences between the internal due date and the expected work order completion dates fall within the margins of the Independent Disturbances. This can be illustrated using an example of a single assembly order as presented in Figure 6.7.

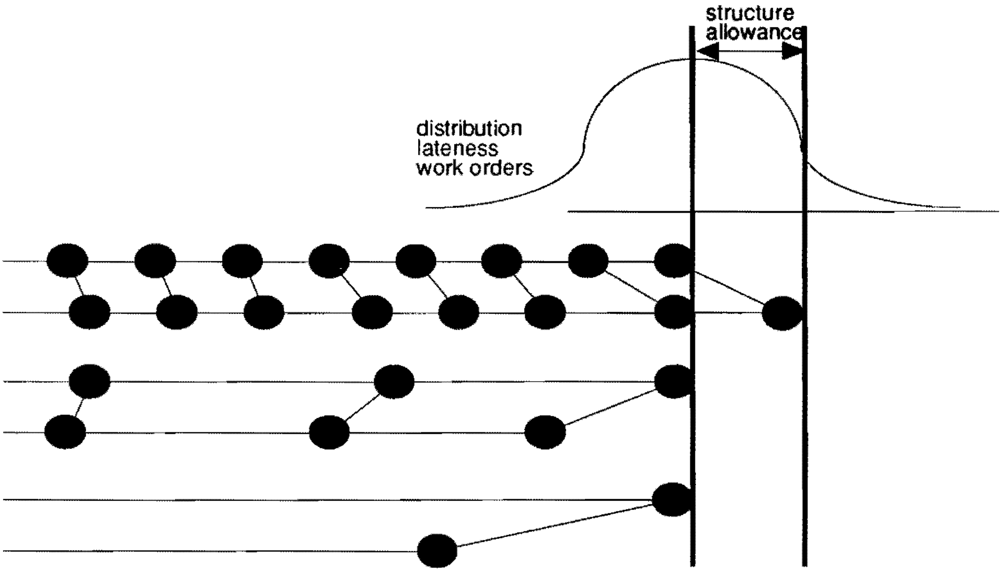


Figure 6.7:
Illustration of the resulting effects of acceleration/retardation on the Independent Disturbance.

The disadvantage of using the acceleration/retardation technique is that accelerated work orders often run behind schedule. It can be expected that these work orders will be completed later than the originally scheduled due date. Provided that the differences between the expected completion dates and the scheduled due date remain smaller than the structure allowance, this problem with respect to the accelerated work orders is insignificant in comparison with the completion delay time. The effects of this problem are therefore negligible. The variance of the Independent Disturbance is nevertheless of more importance. The acceleration/retardation technique used here is based on the premise that there will be equal amounts of acceleration and retardation within an assembly order. It is therefore plausible that the positive and negative effects of accelerating/retarding will cancel out with respect to the average completion delay times of the work orders per assembly order. Therefore, it is expected that the estimated structure delay times described in the previous sections will also prove to be reliable estimates of the structure delay times in situations when the acceleration/retardation technique is used. This hypothesis has been tested using simulation experiments. The results are presented in Tables 6.5 and 6.6.

Table 6.5:
Simulation Results with respect to the Structure Delay Time and Throughput Time with the use of Acceleration/Retardation.

runs:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
th590001	5.557	45.259	6.793	8.428	128.557	67.010	122.013	13.421
th590101	5.424	42.807	6.731	8.322	118.477	65.203	116.265	13.506
th590201	5.930	49.259	6.769	9.085	133.477	69.067	127.803	14.874
th590301	6.060	52.090	6.785	9.277	144.726	69.370	126.352	15.952
th590401	6.335	72.079	6.734	9.675	193.315	69.325	131.044	16.029
average:	5.861	52.299	6.762	8.957	143.710	67.995	124.695	14.756
th590093	7.235	80.064	6.792	10.890	236.697	50.683	68.759	17.403
th190093	7.356	77.559	6.730	11.156	232.598	49.858	65.177	17.420
th290093	7.979	89.267	6.770	12.081	269.919	53.341	70.683	19.850
th390093	7.767	82.671	6.784	11.603	250.863	52.624	70.964	18.477
th490093	8.338	122.382	6.734	12.649	349.358	53.925	76.392	20.062
average:	7.735	90.389	6.762	11.676	267.887	52.086	70.395	18.642
th590056	5.846	53.017	6.792	8.985	149.402	55.072	80.030	14.833
th190056	5.974	54.543	6.730	9.207	150.826	54.351	75.134	15.455
th290056	6.657	64.295	6.771	10.228	178.640	57.910	84.168	17.181
th390056	6.342	56.990	6.785	9.768	161.064	56.965	83.189	16.856
th490056	6.886	88.092	6.733	10.567	239.278	58.086	87.716	17.607
average:	6.341	63.387	6.762	9.751	175.842	56.477	82.047	16.387

[Average structure delay time (1), variance of structure delay time (2),average structure allowance (3), average completion delay time (4), variance of completion delay time (5), average actual assembly order throughput time (6), average actual throughout time large assembly orders (7), average structure delay time large assembly orders (8). The results of the first experiment, th590?01, have been copied from Table 6.2 and do not incorporate the use of acceleration/retardation. The unlimited use of acceleration/retardation was applied in the second experiment, th?90093. Acceleration/retardation with a lower limit of 0.3 and an upper limit of 2 was applied in the third experiment, th?90056.]

The measured average structure delay time (column 1), also when acceleration/retardation is used, is more or less equal to the average structure allowance (column 3).

Table 6.6:
Results with respect to Due Date Reliability with the use of Acceleration/Retardation.

	with structure allowance:				without structure allowance:				both:
runs:	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
th590001	- 1.376	421.251	6.744	231.686	5.417	441.772	9.852	304.232	404.842
th590101	- 2.977	271.814	5.203	107.970	3.753	293.637	8.296	168.727	265.991
th590201	0.790	303.529	7.254	147.976	7.558	328.414	10.969	218.791	292.403
th590301	0.701	320.635	7.424	147.069	7.485	348.257	11.197	219.889	321.162
th590401	1.397	491.558	8.643	291.548	8.131	523.404	12.118	380.311	432.295
average:	- 0.293	361.757	7.054	185.250	6.469	387.097	10.486	258.390	343.339
th590093	1.717	465.181	8.412	269.688	8.509	489.250	12.289	346.372	509.593
th190093	0.980	301.071	7.141	141.927	7.710	328.626	11.142	209.342	374.521
th290093	4.477	355.853	9.681	197.665	11.247	388.183	14.030	278.378	434.095
th390093	3.597	325.920	8.969	158.437	10.380	357.268	13.487	231.993	410.279
th490093	5.156	555.916	10.944	358.849	11.890	595.557	15.129	455.805	563.901
average:	3.185	400.788	9.029	225.313	9.947	431.777	13.215	304.378	458.478
th590056	- 0.492	444.822	7.262	245.499	6.700	462.216	10.898	319.448	420.855
th190056	- 1.046	302.746	6.232	132.758	5.752	323.618	9.817	195.593	295.726
th290056	2.480	346.700	8.573	177.951	9.236	366.193	12.493	249.797	345.353
th390056	1.220	305.404	7.488	134.781	8.056	330.405	11.599	204.203	312.757
th490056	2.870	520.369	9.600	312.866	9.748	559.406	13.549	410.546	461.541
average:	1.006	384.008	7.831	200.771	7.898	408.368	11.671	275.917	367.246

[Average assembly order lateness (1) & (5), variance of assembly order lateness (2) & (6), average assembly order tardiness (3) & (7), variance of assembly order tardiness (4) & (8), variance of work order lateness (9).
The results of the first experiment, th590?01, have been copied from Table 6.3 and do not incorporate the use of accele ration/retardation. The unlimited use of acceleration/retardation was applied in the second experiment, th?90093. Acceleration/-retardation with a lower limit of 0.3 and an upper limit of 2 was applied in the third experiment, th?90056.]

The improvement in due date reliability when acceleration/retardation is used and when the structure delay time is isolated and estimated separately, is comparable to the improvement when acceleration/retardation is not used. On the average, structure delay time consumes fifteen percent of the total assembly order throughput time when unlimited allowance swapping is applied. For the large assembly orders is this 26 percent. These higher percentages are due to the shorter average total throughput times.

The approach described in this chapter whereby the structure delay times are isolated and estimated separately, provides good results regardless of whether the acceleration/retardation technique is used. There is no reason to assume that there might be any other significant completion effects which may result from the use or suppression of the acceleration/retardation technique. Consequently, there is no reason to consider the use of any other method for determining the structure allowance for the acceleration/retardation of work orders.

6.6 Conclusions

- If work orders belonging to a given assembly order are released as late as possible with the same scheduled due date, then completion effects occur which cause an assembly order structure delay time.

- A method has been developed in this chapter for estimating the expected structure delay time. The estimated structure delay time is referred to as the structure allowance. The difference between the work order completion date and the average completion date for all of the work orders belonging to an assembly order is called the "independent disturbance". The structure allowance can be determined based upon the number of work orders, the variance of the Independent Disturbance and Clark's table for determining the maximum value from a set of independent, normally distributed values.

- When the acceleration/retardation technique is used, the structure delay time does not change appreciably. The same method for determining the structure allowance can also be used when the acceleration/retardation technique has been applied.

- The structure delay time represents approximately nine percent of the total throughput time of assembly orders when acceleration/retardation is not used. For large assembly orders, this figure is 12 percent on the average. When acceleration/retardation is used, structure delay time takes 15 percent of the total throughput time of all assembly orders and 26 percent of the total throughput time of the large assembly orders. These higher percentages are due to the shorter average total throughput times.

- By defining an expected completion date for assembly orders, the due date reliability of assembly orders can be significantly improved. The expected completion date for assembly orders is found by adding the structure allowance to the scheduled due date of the work orders associated with the assembly order.

- The structure delay time can be reduced further by scheduling subsequent work orders for completion at an earlier date. In other words, processing of the components which do not have a critical throughput time should be completed ahead of the time-critical components so that this last category does not have to wait for subsequent completion. The effects of this are analyzed further in Chapter 7, Section 7.4.

Appendix:

The approximation of the standard deviation of the Independent Disturbance

The maximum-variable (max $\beta_{k,j}$) and the independent disturbance variable ($\beta_{k,j}$) are slightly positively correlated to each other. These variables are positively correlated because of the maximum-function.

To get a better understanding of the relationship between the standard deviations of the Independent Disturbance and the completion delay we firstly discuss the situation when the maximum-variable and the Independent Disturbance variable are assumed to be independent. Two extremes are now thinkable:

1. There exists just one assembly order which contains all work orders. (The number of work-orders per assembly order: $m_k = \infty$)

   ρ : correlation coefficient max $\beta_{k,j}$ and $\beta_{k,j}$

   var(..) : variance of ..

   σ(..) : standard deviation of ..

   Then is: $\sigma(k_{k,j}) = \sigma(\beta_{k,j})$;

2. Each assembly order contains one work order. (The number of work-orders per assembly order: $m_k = 1$). Then is:

$$\mathrm{var}(k_{k,j}) = \mathrm{var}(\max_{j=1}^{m_k} \beta_{k,j}) + \mathrm{var}(\beta_{k,j})$$

So, when m_k increases the contribution of $\sigma(\beta_{k,j})$ to $\sigma(k_{k,j})$ decreases.

But, both variables max $\beta_{k,j}$ and $\beta_{k,j}$ are not independent. Suppose we have categories of assembly orders whereby each assembly order of a category has the same m_k.

When for example $m_k = 1$ for a category, then is:

max $\beta_{k,j} = \beta_{k,j}$; so: $\rho = 1$ and therefore: $\sigma(k_{k,j}) = 0$ for this category.

When m_k increases then decreases ρ. When for example $m_k = 2$ for a category, than one of each two Internal Disturbance variables has a linear relationship to the maximum-variable and the other not (that one is only smaller). The number of not linear related Internal Disturbance variables increases when m_k increases. So, the correlation coefficient is dependent from the number of work orders per assembly order and decreases with an increasing m_k.

Because of these reasons we assume that the correlation coefficients have values between 0 and 0.5 for the assembly order categories with more than one work order per assembly order. Given these correlation coefficient values we are able to determine the standard deviation of the completion delay as follows.

A method to determine the maximum value and the standard deviation of m independent, normally distributed variables is given in section 6.3. The average number of work orders per assembly order is 3. When the maximum-variable is equal to the maximum of three independent disturbance variables then the standard deviation can be approximated with (0.748 * standard deviation of $\underline{\beta}_{k,j}$) (see also table 6.1). Now we are able to calculate the standard deviation of the completion delay for $m_k = 3$ (see equation I).

$\rho(m_k)$: correlation coefficient for the assembly order category with m_k work orders per assembly order

$$\mathrm{var}(k_{k,j}) = \mathrm{var}(\max_{j=1}^{m_k} \underline{\beta}_{k,j}) + \mathrm{var}(\underline{\beta}_{k,j}) + 2 \cdot (-1) \cdot \rho(m_k) \cdot \sigma(\max_{j=1}^{m_k} \underline{\beta}_{k,j}) \cdot \sigma(\underline{\beta}_{k,j})$$

when: $\sigma(\max_{j=1}^{m_k} \underline{\beta}_{k,j}) \approx 0.748 \cdot \sigma(\underline{\beta}_{k,j})$

then is: $\mathrm{var}(k_{k,j}) = (1 + (0.748 - 2 \cdot \rho(m_k=3)) \cdot 0.748) \cdot \mathrm{var}(\underline{\beta}_{k,j})$

if: $\rho = 0.748 / 2 \approx 0.37$ then is: $\sigma(k_{k,j}) \approx \sigma(\underline{\beta}_{k,j})$

0.748 was based upon 3 work orders per assembly order. When the number of work orders per assembly order varies between 2 and 10 the corresponding calculations can be made for all assembly order categories whereby the values from table 6.1 has to be used for the estimates of the standard deviations of the maximum-variable.

So, when $0.2 \le \rho \le 0.4$ then is: $\sigma(k_{k,j}) \approx \sigma(\underline{\beta}_{k,j})$ (I)

We assumed a correlation coefficient with a value between 0 and 0.5. So, it is reasonable to take the standard deviation of the completion delay as an estimate for the standard deviation of the independent disturbance ($\underline{\beta}_{k,j}$). In Chapter 9, table 9.1 are results presented from simulation experiments where the waiting time allowances are dynamical controlled and estimated. The standard deviations of the work order lateness and of the completion delay of those experiments are presented in table 6.7.

Table 6.7:
Standard deviations of work order lateness and completion delay of experiments with dynamical controlled and estimated waiting time allowances.

Run:	standard deviation lateness	standard deviation completion delay	difference	average per run
th59c12c	14.6	14.7	0.1	
th19c12c	16	15.2	-0.8	
th29c12c	16.1	15.8	-0.3	
th39c12c	16.1	15.5	-0.6	
th49c12c	17.4	14.9	1.5	
subtotal			-0.1	-0.02
th59c14c	15.4	15.8	0.4	
th19c14c	15.9	16.3	0.4	
th29c14c	16.3	16.9	0.6	
th39c14c	16.5	16.9	0.4	
th49c14c	16.1	16.3	0.2	
subtotal			2.0	0.4
th59dc09	14.2	14.3	0.1	
th19dc09	14.8	15	0.2	
th29dc09	15.0	15.4	0.4	
th39dc09	14.9	15.2	0.3	
th49dc09	15.0	15.1	0.1	
subtotal			1.1	0.22

The results of the experiments (see table 6.7) show that there is a neglectable difference between the standard deviation of the work order lateness under dynamic control and estimation of waiting time allowances and the standard deviation of the completion delay.

So far, it was not possible to proof this approximated relationship between the standard deviations of the completion delay and the Independent Disturbance. This is an issue for further research. In this study we approximate the standard deviation of the Independent Disturbance with the measured value of the standard deviation of the completion delay.

Chapter

7 RELEASING WORK ORDERS BELONGING TO A SINGLE ASSEMBLY ORDER

7.1 Introduction

A method was developed in Chapter 5 to shorten the shop throughput times for assembly orders as much as possible. This was achieved using the technique of acceleration/retardation within assembly orders. An assumption in this respect was that all of the work orders belonging to a given assembly order are scheduled with the same due date. As described in Chapter 6, the completion disturbance is not affected by using the acceleration/retardation technique. The approach used here assumes that the work orders belonging to a given assembly order are released at different points in time when the acceleration/retardation technique is not used. This approach is, in fact, often followed in practice. The approach taken in this study is described in more detail in Chapter 5 in connection with the definition of the reference situation.

Nevertheless, there is no obvious reason for releasing work orders individually. This is demonstrated by the fact that a decision rule for releasing work orders is generally not even a topic for consideration in the literature. Most of the authors indicate that they immediately release all of the work orders belonging to a given assembly order as soon as each assembly order is ready for processing in their simulation studies. This means that when a new assembly order arrives, all of the work orders belonging to this assembly order are released at the time of arrival. The assembly order is released as a whole in this way. The consequences of releasing whole assembly orders in this way with respect to the assembly order throughput time and the assembly order due date reliability are investigated in this chapter.

To start with, the consequences of releasing at the assembly order level are analyzed in a situation in which acceleration/retardation has not been used. It will become clear that releasing at the assembly order level has several significant disadvantages when compared to planned allowance swapping as explained in Chapter 5. Subsequently, the results of the analyses are validated using simulation experiments in which the acceleration/retardation technique (Chapter 5) is applied and the method of estimating structure delay time (Chapter 6) is used. When the acceleration/retardation technique is not used and all of the work orders belonging to a given assembly order are scheduled with the same release date, then different scheduled due dates are assigned to these work orders. The discrepancies between these scheduled due dates for the work orders can be seen, collectively, as a quantity of slack which could otherwise be utilized. The issues associated with utilizing this slack are investigated in a separate section. The findings and conclusions presented in this chapter are summarized in the final section.

7.2 Analyzing the consequences of releasing at the assembly order level

As mentioned earlier, the OSD priority rule has been selected for use in the study. This rule is used to determine which operation in a queue has the oldest scheduled start date or has the earliest scheduled start date in the future. The operations are selected and initiated in this way, whereby the most significant determinant is the allowance which is assigned to each operation.

Whenever extra allowance is assigned to the operations associated with a given work order, the sequencing of operations at the work station may change. Changing the sequencing of operations in this way can lead to different throughput times, particularly for the assembly orders.

"Priority" is a relative concept. When an operation belonging to one work order is assigned a higher priority than an operation belonging to a different work order, then the operation with the highest priority is started first when both work orders are waiting for processing at a work station. If, for example, the operation which originally had the highest priority is assigned the lowest priority, then the operation which originally had the lowest priority will automatically become the highest priority operation. By assigning extra allowance, the relative priorities of work orders can be changed in this way. Actually, the relative priorities of the operations belonging to the different work orders are changed. Priorities can be swapped between the operations belonging to a single assembly order as well as between the operations associated with different assembly orders. Swapping priorities by assigning extra allowance can affect the shop throughput time of assembly orders. These effects will be analyzed based upon a number of examples. In the remainder of this section it is assumed that the extra allowance is distributed evenly across all of the operations of a given work order.

♦ *Swapping priorities within assembly orders*

An example of an assembly order with two work orders, A and B, is presented in Figure 7.1.

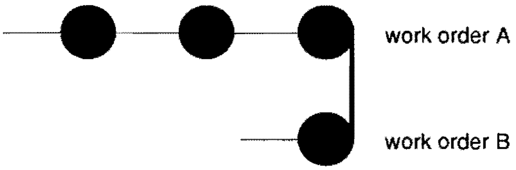


Figure 7.1: Example of an assembly order with two work orders (A and B)

This example assumes a stream of assembly orders, each assembly order having the same structure as indicated in Figure 7.1. This can be also viewed as two streams of work orders when the average inter-arrival times are stationary. One stream consists of Type A work orders and the other stream consists of Type B work orders.

Each of the Type A work orders have three operations while the Type B work orders each have one operation. The work orders are initially scheduled with an allowance per operation which is equal to the normative waiting time. If a Type B work order belonging to a given assembly order is released at the same time as a Type A work order belonging to the same assembly order and the work order due dates are the same, then the Type B work order is assigned an allowance per operation which is three times larger. The average allowance per operation for this assembly order then can be calculated as follows:

$$\frac{1 * 3 + 3 * 1}{4} = \frac{6}{4} = \frac{3}{2} = 1.5 \text{ times the normative waiting time}$$

For purposes here it is convenient to assume that the average waiting time will remain constant. Only the sequence in which the operations are processed may be changed. This means that the sequencing will change because the relative priority of the Type A work orders has become greater than the Type B work orders. The Type B work orders are assigned a lower priority because the allowance has been increased.[1]

When the allowances are adjusted to keep the average allowance per operation equal to the normative waiting time, then the new allowances become:

Type A work orders:

$$\frac{1}{1.5} = \frac{2}{3}$$

Type B work orders:

$$\frac{3}{1.5} = 2$$

Total:

$$\frac{2/3 * 3 + 2}{4} = \frac{4}{4} = 1$$

In this way the average scheduled assembly order throughput time is reduced by (almost) 1/3 because the throughput time for the Type A work orders is reduced by (almost) 1/3. (In reality, the actual waiting time reduction is always somewhat less than the reduction in allowance, see e.g. Chapter 5.)

When assembly orders have different structures, then the (relative) priorities may change as a result of releasing all of the work orders at the same time. This may lead to an exchange of priorities between assembly orders. Different examples of this are illustrated hereunder.

♦ *Swapping priorities between assembly orders*

Two types of assembly orders are presented in Figure 7.2. For the sake of convenience it can be assumed that the same allowance has been assigned to all of the operations.

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[1] Kleinrock ([Kleinrock, 1976]) showed: "so long as the queuing discipline selects work orders in a way that is independent of their processing time then the distribution of the average waiting time will be invariant to the order of processing". Based upon this insight formulated Kleinrock his conservation laws.

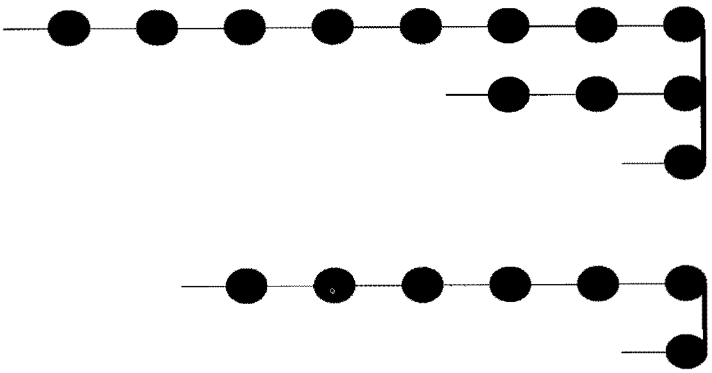


Figure 7.2: Two assembly orders with different structures

If all of the operations keep the same amount of allowance, which implies that the work orders are released exactly on the scheduled release date, then it can be expected that each of the operations will have the same priority at the time of its arrival in a queue. An assumption here is that, on the average, all of the queuing situations are comparable. If one of the operations is given a larger allowance, then the priority of this operation will be lower than the priority of the other operations at the time of its arrival in a queue. This is apparent from the relative amount of allowance assigned to this operation. An operation with more allowance has a lower priority at the time that it arrives in a queue.

If an assembly order is released as a whole, then the (operations of the) subsequent work orders are given extra allowance. In this situation, two aspects need to be recognized:

- the priorities of all of the operations change, resulting in an exchange of priorities between the large and small work orders within assembly orders and between assembly orders;
- structural differences appear between the scheduled and actual average assembly order throughput times.

Several examples are calculated below to illustrate these aspects.

The first example is based upon the assumption that the number of operations per work order is distributed geometrically. This example shows what happens in the case of assembly orders with two work orders as well as assembly orders with three work orders. Similarly, the second example is based upon a geometrical distribution of the number of work orders per assembly order. As described in Chapter 4, the number of operations per work order is determined using a random selection from a geometrical distribution function with an average of 5 and an upper limit of 39.

An example
The example presented here is based upon two assembly orders. The first assembly order is comprised of three work orders: one work order with eight operations, a second work order with three operations and a third work order with one operation. The other assembly order has two work orders which, on the average, can be viewed as one work order with six operations and a second work order with one operation. The choice of one assembly order comprised of three work orders and a second assembly order with two work orders has been made completely arbitrarily and has nothing to do with the use of a geometrical assembly order structure (see also Figure 7.2).

To start with, the technique of swapping allowance is not used so that each operation is given an allowance which is equal to the normative waiting time. If all of the assembly orders are released at the same time, then all of the work orders are released on the scheduled release date of the largest work order (in terms of number of operations). The allowance for the subsequent work orders is increased in this way. Assuming that the processing times are negligible, then it is apparent that the work orders belonging to the assembly orders comprised of three work orders (Type I assembly orders) are given, collectively, a total allowance equal to eight times the normative waiting time. The work orders belonging to the other assembly orders (Type II assembly orders) are given an allowance equal to six times the normative waiting time.

In this example it is also assumed that there is a continuous stream of assembly orders. This stream of assembly orders consists of two sub-streams: one sub-stream with Type I assembly orders and a econd sub-stream with Type II assembly orders. The arrival intensity of both sub streams are related to each other in a fixed ratio, whereby type I : type II, as 7 : 12. These sub-streams utilize together exactly the amount of resource capacity which is consistent with keeping the average waiting time per operation at the same level at each work station.

An allowance of 1 was assigned initially to all of the operations. The resulting allowances have become:

- **for the Type I assembly orders:**
  - **work orders with 8 operations: 1;**
  - **work orders with 3 operations: 2.67;**
  - **work orders with 1 operation : 8.**
- **for the Type II assembly orders:**
  - **work orders with 6 operations: 1;**
  - **work orders with 1 operation : 6.**

The average allowance for all of the operations associated with the Type I assembly orders is equal to 2. The average allowance for the Type II assembly order operations is 1.7. This implies that, on the average, the Type II assembly order operations will have a higher priority than the Type I assembly order operations.

A subsequent question to be answered is whether the higher priority for the Type II assembly orders also results in a shorter throughput time than in a situation where acceleration/retardation is used.

The allowance per operation needs to be normalized in such a way as to keep the average allowance equal to the normative waiting time in order to be able to calculate the throughput time in a situation whereby all of the assembly orders are released at the same time. The total increase in the amount of allowance in this example is equal to approximately 36/19 = 1.89. The normalized allowance per operation for each of the work order categories therefore becomes:

- **for the Type I assembly orders:**
  - **work orders with 8 operations: 0.53 (= 1/1.89);**
  - **work orders with 3 operations: 1.41 (= 12.67/1.89);**
  - **work orders with 1 operation : 4.23 (= 8/1.89).**
- **for the Type II assembly orders:**
  - **work orders with 6 operations: 0.53 (= 1/1.89);**
  - **work orders with 1 operation : 3.17 (= 6/1.89).**

In this way the throughput time for the Type I assembly orders becomes 4.2 and for the Type II assembly orders 3.2 (assuming that the processing times are negligible). The average assembly order throughput time is 3.7. When the acceleration/retardation technique is used, the normative throughput time for Type I assembly orders is equal to 4 and for Type II assembly orders equal to 3.5. The average assembly order throughput time in this case is 3.8. The initial throughput time for a Type I assembly order was eight and for a Type II assembly order six.

In is apparent that the throughput time for small assembly orders is shorter when the assembly order is released as a whole, as compared to the alternative of using the acceleration/retardation technique. The throughput time for the large assembly orders in this case is longer, however.

The geometrical assembly order structure

The above-mentioned effect is more pronounced with a geometrical assembly order structure. If it is assumed that a geometrical distribution is also applicable to the distribution of the number of work orders per assembly order and the assembly orders are divided into two categories, then the first category (Type I) would have an average of four work orders with, respectively, ten, four, two and one operation(s) and the second category (Type II) would have an average of one work order with three operations. If the assembly orders are all released at the same time, then the allowances and normalized allowances in this case would be:

	allowance:	**normalized allowance:**
• for the Type I assembly orders:		
work orders with 10 operations:	**1**	**0.47;**
work orders with 4 operations:	**2.5**	**1.16;**
work orders with 2 operations:	**5**	**2.33;**
work orders with 1 operation :	**10**	**4.65.**
• for the Type II assembly orders:		
work orders with 3 operations:	**1**	**0.47.**

The throughput time of the Type I assembly orders now becomes 4.7 and the Type II assembly orders becomes 1.41 (assuming negligible operation times). The average assembly order throughput time is 3.06.

If the acceleration/retardation technique were to be used, then the normative throughput time for a Type I assembly order would be 4.25 and for a Type II assembly order this would be 3. The average assembly order throughput time would then become 3.63. The original assembly order throughput time was 10 for Type I assembly orders and 3 for Type II assembly orders.

When whole assembly orders are released at one time, then the throughput times of the small assembly orders are reduced more than the throughput times of the large assembly orders. In this way the average assembly order throughput time is less when compared to the average throughput time of assembly orders for which the acceleration/retardation technique has been applied and which have been released at the work order level. This reduced average throughput time for all of the assembly orders must be seen in combination with a longer average throughput time for the large assembly orders. These assertions have been validated based upon the results of simulation experiments as described in the next section where the performance of a certain category of "large assembly orders" is explicitly measured and compared with the performance of all of the assembly orders taken together.

This evidence can be used to show an apparent improvement with respect to the average assembly order throughput time by releasing all of the assembly orders at the same time without using the acceleration/retardation technique instead of using this technique within the assembly orders. In practice, however, this apparent improvement may be undesirable due to the fact that the throughput times become longer for the large assembly orders. This aspect demonstrates the need for measuring the performance of various categories of assembly orders. It is not sufficient to just measure the average performance.

◆ *Lateness*

It is clear from the examples that the amount of normalized allowance is dependant upon the total available allowance or slack in a given job shop. As a result, estimating the throughput time for a specific order in advance becomes more difficult.

The throughput time of the largest work order and, therefore, the throughput time of the whole assembly order can be estimated based upon fairly accurate knowledge of how the allowance is to be distributed among the work orders when the acceleration/retardation technique is used. A simple condition which must be met is that the total amount of assembly order allowance must remain constant. When assembly orders are released as a whole, it is only possible to estimate the increase in the allowance in the shop as compared to a situation in which the work orders are released individually. This estimate of increased allowance can then be used to make adjustments to the allowance associated with the individual work orders so that the estimated throughput time of the assembly order can also be adjusted. In this way the average lateness can be reduced to the initial level.

In conclusion, special note should be made of the fact that the increased allowance associated with releasing at the assembly order level is ultimately dependent upon the specific composition of the order workload which happens to be present within the shop at any given moment. An estimate of the throughput time for any specific assembly order therefore becomes more dependent upon the slack situation in the shop. The extensive measurement of the amount of allowance or slack in a shop requires the collection of a significant amount of data. This approach is not feasible in a practical sense unless significant improvements can be realized in this way, which we do not expect.

◆ *Other assembly order structures*

It is assumed that the number of operations per work order can be represented by a geometrical distribution function in the example presented above. This assumption results in differences in the average size of the work orders associated with the assembly orders (the large assembly order shows an average of 4.25 operations per work order and the small assembly order has 3 operations per work order). In addition, the sizes of the work orders belonging to a single assembly order show an unbalanced distribution.

Examples of a uniform distribution of the number of operations per work order and a reciprocal geometrical structure are presented in the following sections. The three order structures are diagrammed in Figure 7.3.

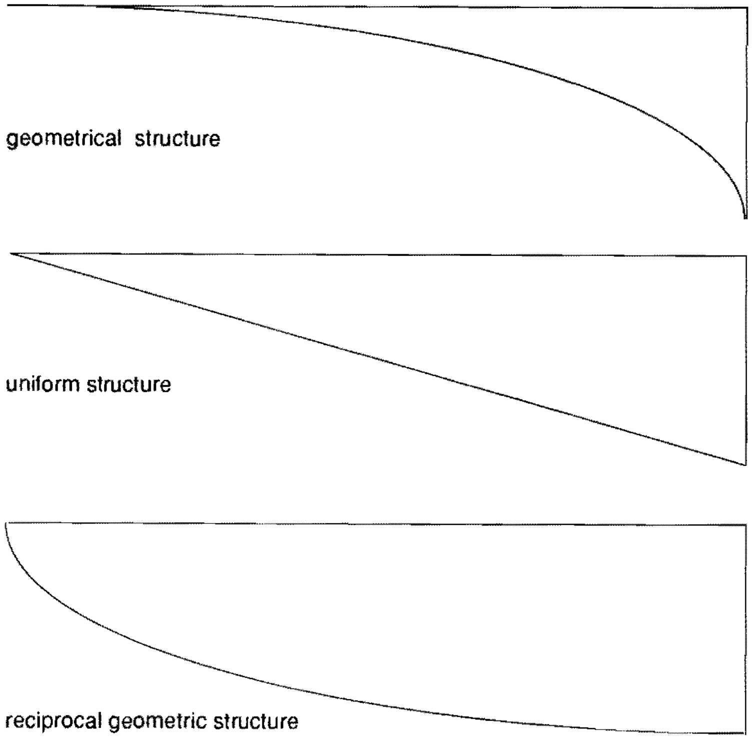


Figure 7.3: Schematic diagram of three order structures

Uniform structure

The number of operations per work order is distributed evenly in this example. The first stream of assembly orders is comprised of three work orders with five, three and one operation(s), respectively. The second stream of assembly orders has two work orders with four and two operations, respectively. Initially, an allowance of 1 was assigned to each of the operations. Releasing at the assembly order level results in allowances as follows:

- **for the Type I assembly orders:**
  - **work orders with 5 operations: 1;**
  - **work orders with 3 operations: 1.67;**
  - **work orders with 1 operation : 5.**
- **for the Type II assembly orders:**
  - **work orders with 4 operations: 1;**
  - **work orders with 2 operations: 4.**

The average allowance for all of the Type I assembly order operations is 1.67 and for the Type II assembly order operations 1.33. This means that the Type II assembly orders will have a slightly higher priority than the Type I assembly orders.

The total increase in amount of allowance is equal to approximately 23/15 = 1.53. The normalized allowance for each work order operation subsequently becomes:

- **for the Type I assembly orders:**
  - **work orders with 5 operations: 0.65;**
  - **work orders with 3 operations: 1.09;**
  - **work orders with 1 operation : 3.27.**
- **for the Type II assembly orders:**
  - **work orders with 4 operations: 0.65;**
  - **work orders with 2 operations: 1.31.**

The throughput time for the Type I assembly orders now becomes 3.3 and for the Type II assembly orders 2.6 (assuming negligible processing times). The average assembly order throughput time is 2.95.

When the acceleration/retardation technique is used, both the Type I assembly orders and the Type II assembly orders show a throughput time of 3. The initial throughput time for the Type I assembly orders was five and for the Type II assembly orders four.

It is clear that the throughput times for the small assembly orders as well as the average assembly order throughput time are shorter when an assembly order is released as a whole instead of using the acceleration/retardation technique. In this case, the throughput times of the large assembly orders are longer.

The reciprocal structure

The geometrical structure can be briefly described as "many small assembly orders with small work orders". The reciprocal structure can therefore be characterized as having "only a few small assembly orders with large work orders".

When the reciprocal assembly order structure is used, it is apparent that the results can be radically different. A reciprocal structure has been chosen in which the Type I work orders have four, three and two operations and the Type II assembly orders have five and one operation(s). The normalized allowance then becomes:

- **for the Type I assembly orders:**

work orders with 4 operations:	**0.65;**
work orders with 3 operations:	**0.87;**
work orders with 2 operation :	**1.31.**

- **for the Type II assembly orders:**

work orders with 5 operations:	**0.65;**
work orders with 1 operations:	**3.27.**

The throughput time for the Type I assembly orders now becomes 2.6 and for the Type II assembly orders 3.3 (assuming negligible processing times). The average assembly order throughput time is 2.95.

In comparison with the results of using the acceleration/retardation technique (where both Type I and Type II assembly orders show a throughput time of 3), the large assembly order now has a shorter throughput time. The assembly orders with the smallest ratio of number of operations of the largest work order to number of operations of the smallest work order have a shorter throughput time when assembly orders are released as compared to a situation in which the acceleration/retardation technique is used in conjunction with releasing the work orders.

Conclusions regarding the form of the assembly order structure

The conclusions with respect to the geometrical structure are also valid in the case of a uniform structure. In the case of a reciprocal structure, however, the results are radically different. This means that the conclusions with respect to releasing geometrically structured assembly orders at the assembly order level cannot be considered to be valid in general.

The results of the analysis in this section have been validated using simulation experiments. These results are presented in the next section.

7.3 Simulation experiments concerning the consequences of controlled allowance swapping

The quantitative analyses presented in the previous section have been validated using the simulation experiments described in this section. The first simulation run is based upon representative studies published in the literature (see e.g. [Adam et al., 1987], [Maxwell, 1969]). These results are then compared with the results of the approach developed in this study as described in Chapter 5 and Chapter 6. An evaluation is presented at the end of this section.

◆ *Generic allowance swapping*

As explained in the previous section, an "implicit" swapping of allowance takes place when the due dates for assembly orders are determined based upon the number of operations in the largest work order multiplied by the normative waiting time (plus the sum of the processing times) and when all of the work orders are released at the same time and are scheduled for completion on the same due date. The relative priorities of the operations associated with the work orders then become shifted with respect to each other in comparison with the initially planned priorities based upon the OSD scheduling rule because extra allowance, resulting in excessive "free slack", is found in the assembly orders.

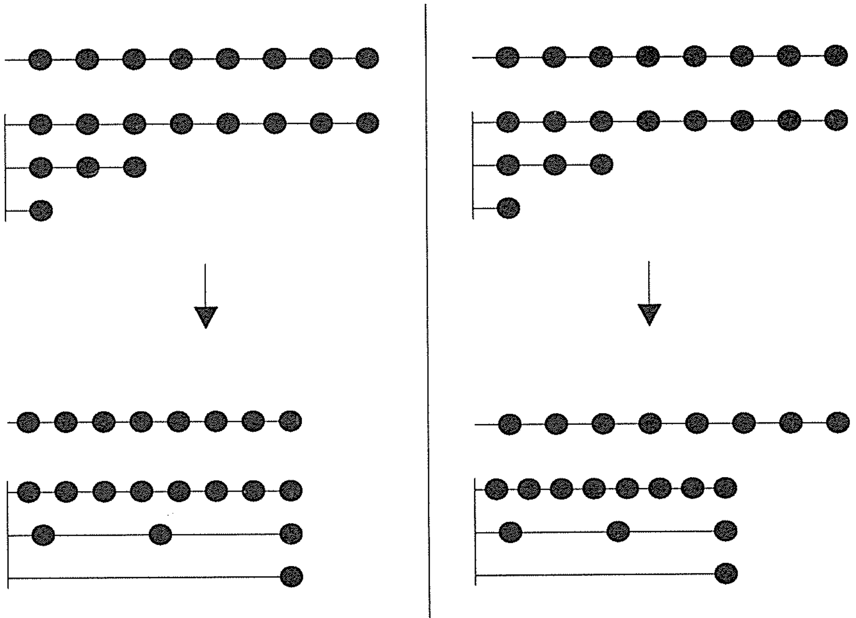
The excessive extra allowance also results in a high average assembly order lateness factor. The assembly order due dates are based upon the throughput time planned for the large work orders. Relatively speaking, a significantly higher priority than the initially planned priority is assigned to these large work orders with the implicit swapping of allowance. The normal way in which this excessive extra allowance is eliminated in the published studies is as follows. Numerous researchers make use of a single allowance factor (A) in connection with the due date assignment. All of the known rules can be seen in one way or another as variants of the rule presented as Equation (1) in Chapter 5. This equation is presented again here:

$$D_k = \text{time} + M_k \cdot A + \sum_{i=1}^{M_k} p_{k,J,i} \qquad (1)$$

In the published studies, the allowance factor is normally adjusted in such a way as to keep the average realized assembly order throughput time equal to the average planned assembly order throughput time. In order to achieve this, an iterative procedure is unavoidable. A typical iterative procedure is as follows: set the allowance factor to be equal to the normative waiting time (W_n), then measure the average planned and the average realized assembly order throughput times and, finally, calculate the final allowance factor. See also Equation (2), below.

$$A = W_n \cdot \left(\frac{\text{average realized assembly order throughput time}}{\text{average planned assembly order throughput time}}\right) \quad (2)$$

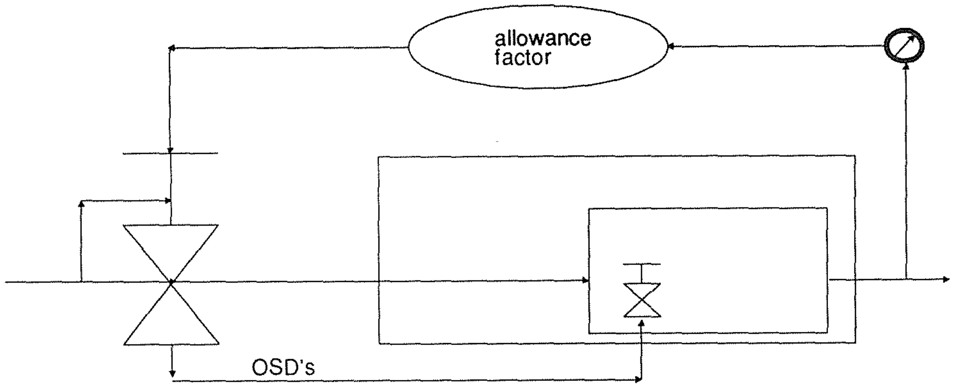
Following this approach results in an average lateness of zero. The implicit allowance swapping and the subsequent adjustment of the allowance factor ultimately leads to allowance swapping between the operations of all of the work orders. This is referred to as *generic allowance swapping*. The allowance factor is used in place of both the waiting time allowance and the structure allowance in this way. By adjusting the allowance factor, the structure allowance is changed implicitly at the same time. The fact that structure allowance is partially determined by the individual structural assembly order characteristics is ignored in this way. By taking the structural characteristics into account as done in the study presented here, a smaller lateness factor can be attained, particularly for the large assembly orders. The approach derived from published studies, which is described here, can be compared with an approach using the proposed acceleration/retardation technique, including an estimate of the structure delay time. Both of these approaches are illustrated in Figure 7.4 and Figure 7.5.



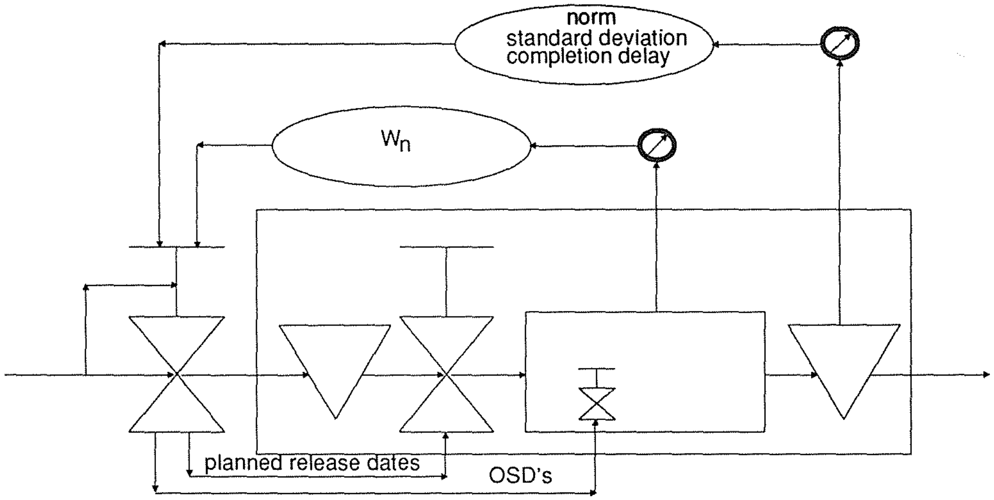
Generic allowance swapping

Allowance swapping within assembly orders

Figure 7.4:
An illustration of generic allowance swapping and allowance swapping within assembly orders



The production planning & control framework derived from published studies.



The production planning & control framework as developped in chapters 5 & 6.

Figure 7.5:
The production planning & control framework derived from published studies and the framework as developed in Chapters 5 and 6.

◆ *Design of the simulation experiment*

The simulation experiment consists of four steps which are described separately below. A new simulation run is included in each of these steps. The simulation experiment has been designed to test the following hypotheses:

- using "generic allowance swapping" will produce a shorter average throughput time than with the use of "acceleration/retardation";
- using "generic allowance swapping" will result in a longer average throughput time for large assembly orders than with the use of "acceleration/retardation";
- when the structure allowance approach is used in addition to "acceleration/retardation", then the due date reliability performance will not be worse than the performance when using "generic allowance swapping".

All of the work orders belonging to a given assembly order are released at the same time. The OSD's for the operations are determined and scheduled when the work orders are released. The allowance per work order operation is calculated based upon the difference between the scheduled assembly order due date and the release date divided by the total number of operations.

Because of the importance of the large sub runs, the simulation run length is increased in this section to be sure to get valid results. Each simulation run in this section consists of hundred subruns. Each subrun has a length of 2000 time units. A loading run of 6000 time units is used. The total results are based upon the simulation results of 20,000 time units. This corresponds with a total of 214,000 assembly orders for a utilization percentage of 90%. Each simulation experiment contains five different runs, where each run has used different initial seed values for the random number generator.

The simulation experiment steps are as follows:

- Step 1: the reference experiment.
  The due dates are determined according to Equation (1) in the reference experiment. The allowance factor is equal to the normative waiting time W_n. (The experiment code is th59gr1z.);
- Step 2: the experiment using generic allowance swapping.
  The approach described in the first part of this section is used as the basis for this experiment. Equation (1) is used to calculate the due dates and Equation (2) is used to determine the allowance. (The experiment code is thgrwb1z.);
- Step 3: the experiment using allowance swapping between work orders belonging to a single assembly order.
  The acceleration/retardation technique described in Chapter 5 is used without restrictions as the basis for this experiment. The due dates are assigned using Equation

(3). The allowance factor is equal to the normative waiting time. (The experiment code is th59gr5z.)

$$D_k = \text{time} + \frac{\sum_{j=1}^{m_k} o_{k,j}}{m_k} . A + \sum_{i=1}^{M_k} p_{k,J,i} \tag{3}$$

- Step 4: an experiment extended with the structure allowance.
The method of estimating structure time as developed in Chapter 6 is used in this experiment. Equation (4) is used to determine the work order due dates and equation (5) to determine the assembly order expected completion date. (The experiment code is th59gr57.)

d_k := due date for the work orders belonging to assembly order k

E_k := expected completion date for assembly order k

$$d_k = \text{time} + \frac{\sum_{j=1}^{m_k} o_{k,j}}{m_k} . A + \sum_{i=1}^{M_k} p_{k,J,i} \tag{4}$$

$$E_k = \text{time} + \frac{\sum_{j=1}^{m_k} o_{k,j}}{m_k} . A + \sum_{i=1}^{M_k} p_{k,J,i} + S_k \tag{5}$$

The simulation results for all of the assembly orders for each of the four experiments are presented in Table 7.1. The results for only the large assembly orders (with ten work orders) are presented in Table 7.2. In both tables are the average values per experiment given. The values per run are given in appendix C.

Table 7.1:
Simulation results for all of the assembly orders.

90% utilization percentage	th59gr1z	thgrwb1z	th59gr5z	th59gr57
average throughput time assembly orders	48.5	47.9	51.9	51.9
variance throughput time	2104	1514	1264	1264
average planned throughput time assembly orders	61.4	45.9	42.7	48.8
average lateness assembly order	-12.9	2.1	9.9	3.1
variance lateness assembly orders	415	392	464	432
average tardiness assembly orders	3.3	8.2	13.3	9.2
variance tardiness assembly orders	96	221	328	228
average waiting time	8.1	8	7.9	7.9
variance waiting time	270	197	166	166
average throughput time work orders	45	44.4	43.8	43.8
variance throughput time work orders	1864	1368	1020	1020
average lateness work orders	-29.9	-11.7	0.1	0.1
variance lateness work orders	1133	817	573	573
average completion time work orders	18.1	15.9	13.4	13.4
variance completion time work orders	799	565	356	356
structure delay time	11	9.9	8.8	8.8
structure allowance	0	0	0	6.7

The simulation results show that the average throughput time for all of the assembly orders is 8% higher (51.9) using the approach developed in this study, compared to the traditional approach of "generic allowance swapping" (47.9).

The due date reliability for the assembly orders is similar in both instances. It is apparent that the due date reliability for the work orders, however, is significantly better using the approach developed in this study.

Table 7.2:
Simulation results for all of the large assembly orders (with ten work orders)

90% utilization percentage	th59gr1z	thgrwb1z	th59gr5z	th59gr57
average throughput time assembly orders	100.9	90.8	69.1	69.1
variance throughput time	2350	1543	735	735
average planned throughput time assembly orders	107.6	80.4	47.8	65.3
average lateness assembly order	-6.7	10.3	21.3	3.9
variance lateness assembly orders	599	520	512	512
average tardiness assembly orders	6.5	14.2	22.3	10.5
variance tardiness assembly orders	189	350	459	293
structure delay time	35.3	29.7	21.6	21.6
variance completion time work orders	1356	952	453	453
structure allowance	0	0	0	17.4

Nevertheless, the average throughput time for the large assembly orders is 24% shorter (69.1) using the approach developed in this study, compared to the traditional approach (90.8). The due date reliability remains similar, with the exception of the average lateness. The average lateness is significantly better using the approach developed in this study (3.9 instead of 10.3). This is probably due to the fact that the structure allowance in the approach developed here is dependent upon the structure characteristic of the number of work orders in the assembly order.

Structure delay time makes 17% (8.8/51.9) out of the assembly order total throughout time. This percentage is 31% for the large assembly orders. Both these percentages are accurate estimates given the length of the simulation runs in this section.

With the approach developed here, work orders are also released at the assembly order level. The planned throughput times for all of the work orders belonging to a given assembly order all become equal when the acceleration/retardation technique is used. There is no alternative in this case.

As indicated in Chapter 5, it is generally not desirable to set limits for the application of acceleration/retardation. In practice, however, it is useful to limit the degree to which acceleration/retardation may be applied when the distribution of assembly orders is extremely unbalanced. In this case the planned throughput times for the work orders belonging to a given assembly order will be different. The question then is whether the scheduled work order release dates or the scheduled work order due dates should be shifted to fall on the same date. This aspect is discussed in the following section.

7.4 Releasing as soon as possible or as late as possible?

In this section the issue is discussed regarding when to release the work orders belonging to a given assembly order in a situation where these work orders have different planned throughput times. In order to isolate this specific issue, it is useful to simplify the situation by assuming that no allowance swapping has taken place. This means that there are three points in time at which the release of the work orders could be scheduled, assuming a geometric structure:

- as late as possible such that the scheduled due dates of the work orders belonging to a given assembly order are all the same (Situation A);
- as soon as possible such that the scheduled release dates are all the same and the due dates are thus different (Situation B);
- on different scheduled release dates such that an amount of slack equal to the structure allowance is planned between the scheduled due dates of subsequent work orders and the scheduled due date of the first work order. This approach has already been suggested in Chapter 6 (Situation C).

These three alternatives are represented in Figure 7.6.

A disadvantage of using the first alternative is that the structure delay time is fully included in the throughput time of the assembly order, which is not the case with the other two alternatives. The completion disturbance effects with respect to the assembly order throughput time are negligible in these other cases.

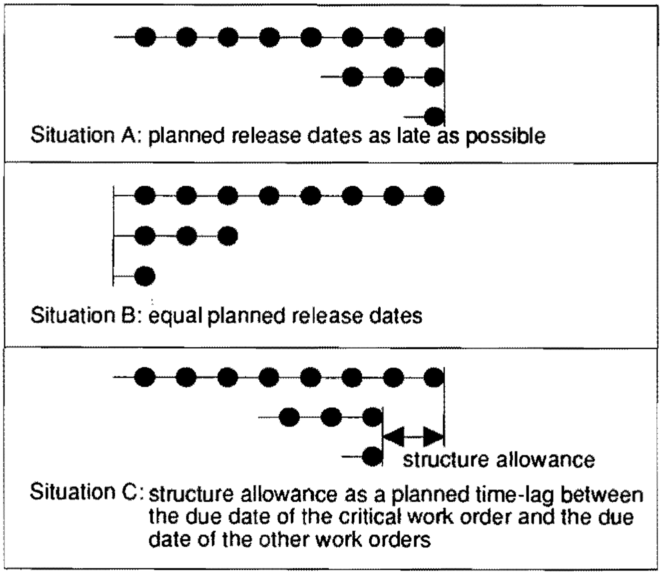


Figure 7.6: Three different scheduling methods for subsequent work orders

The second and third methods, therefore, need to be compared and evaluated to determine which method is more preferable. An apparent disadvantage of the second method is that subsequent orders are released sooner than is absolutely necessary. This means that critical resource capacities could be held by a non-critical work order. Another, higher priority work order could then arrive while this non-critical work order is being processed. This means that the processing of the higher priority work order cannot be started; it is blocked because the non-critical work order was released too soon. It is expected that this type of situation will serve to increase the throughput time of the higher priority work orders which are often the time-critical work orders which affect the throughput time of the associated assembly orders.

Nevertheless, this is only one of the aspects to be considered. Assuming that a non-critical work order is released as late as possible, then this non-critical work order (which, in effect, has now become critical) is using a critical resource capacity and a high priority work order arrives while this non-critical work order is being processed. If the non-critical work order had arrived sooner and had been processed perhaps already before the arrival of the high priority work order, then the more urgent work order might have encountered no delay. Using this line of reasoning, it is expected that scheduling the subsequent work orders sooner or later (in terms of release dates and due dates) will not affect the average assembly order throughput time.

One simulation run has been carried out for each of the three alternative methods described above. The "as late as possible" method was simulated using run code tw590q56 (without structure allowance), the "as soon as possible" method with run code tw59003z and the third alternative with run code tw590056. The normal length of a simulation run was used here. The results are presented in Table 7.3.

Table 7.3:
Results from the experiments simulating alternative methods for releasing work orders

90% utilization percentage situation:	tw590q56 A	tw59003z B	tw590056 C
average throughput time assembly orders	66.9	61.1	62.9
variance throughput time	2537	2314	2384
average planned assembly order throughput time	61.6	61.6	61.6
average assembly order lateness	5.3	-0.5	1.3
variance assembly order lateness	438	470	423
average assembly order tardiness	9.7	7.3	7.8
variance assembly order tardiness	301	230	250
average completion delay work orders	8.4	35.5	10.3
variance completion delay work orders	127	1937	159

The simulation results support the conclusion that there is no difference between releasing the subsequent work orders as soon as possible (Situation B) or as late as possible (Situation C, taking the structure delay time of the assembly orders into account).

It is nevertheless possible that, in connection with workload control, the slack between the earliest possible release date and the latest possible release date for the subsequent work orders can be used effectively. It is conceivable that this slack could be used to balance the workload levels. (See [Ooijen, 1993]). In addition to this, practical arguments also exist for delaying the release of work orders. In connection with scheduling the process planning activities it is often useful in practice to release subsequent work orders as late as possible. This aspect falls outside the scope of the study here, however.

7.5 Summary of the conclusions

- Generic allowance swapping (which is the traditional approach found in the literature) has the advantage of reducing the average assembly order throughput time by 8%, compared to using the acceleration/retardation technique. The average throughput time for the large assembly orders increases 24% in this case.

- The method of estimating the structure delay time leads to a better performance with respect to the lateness of large assembly orders, compared to using the traditional approach found in the literature.

- Allowance swapping without restrictions leads to releasing all of the work orders belonging to a given assembly order at the same point in time.

- When the distribution of assembly orders is extremely unbalanced or when limitations are imposed in connection with the use of the acceleration/retardation technique, it makes no difference whether the subsequent work orders are released as soon as possible or as late as possible, assuming that the structure delay time is taken into account. This conclusion is re-evaluated in Chapter 9 in connection with the dynamic assignment of due dates and the use of workload control.

- In this chapter are extra long simulation runs used. This resulted in more accurate estimates. Structure delay time makes 17% out of the assembly order throughput time. This percentage is 31% for the large assembly orders.

Chapter

8 DYNAMIC DUE DATE ASSIGNMENT AND WORK ORDER RELEASE

8.1 Introduction

As explained in the preceding chapters, the arrival pattern of assembly orders for processing in a manufacturing unit can be modelled based upon a negative exponential distribution function. This assembly order arrival pattern implies that there will typically be large fluctuations with respect to resource capacity loading. Such fluctuations in the utilization of resources results in increased throughput time fluctuations, generally resulting in a large variance in the lateness.

The variance in the lateness can be reduced by taking the shop's resource capacity loading situation into account when due dates are assigned (see, for example, [Baker & Bertrand, 1981,b], [Bertrand, 1983, b]). Modifications to the due date assignment rule are discussed in this chapter in order to cope with fluctuations in the resource capacity loading when due dates are assigned.

The best results in mono situations are obtained with dynamic due date assignment by means of dynamic allowances. But in situations of multi product manufacturing it is not clear whether the allowance per operation, the average or the total allowance in the assembly order or the allowance per work order should be made dynamic. This issue is investigated and solved in section 8.2.

When it is not possible to apply acceleration/retardation each assembly order contains work orders which can be released directly and contains also work orders which has to be released to the shop in future (see also Chapter 7). It is not clear whether those last work orders should be taken into account when a dynamic due date is assigned or not, because those work orders are present in the system but are not yet available for the shop. It is evident that this issue does not exist in mono situations. This issue is investigated in section 8.3.

The conclusions are presented in section 8.4.

8.2 The dynamic due date assignment rule

The due date assignment rules used until now have been based upon estimates of the assembly order throughput time using the following parameters:

- the number of operations in the work orders;
- an average allowance equal to the normative waiting time;
- the number of work orders in the assembly order.

Release dates for the subsequent work orders are scheduled immediately after the due date is calculated. The scheduled release date for the first work order is the same as the time of arrival when a non-dynamic due date assignment rule is used.

The following findings were presented in the previous chapters:

- on the average, sufficient waiting time allowance (also called short allowance) should be allocated to the operations when the work orders are scheduled, this means that the average allowance is equal to the average waiting time;
- it is advisable to make provisions for structure allowance when assembly orders are scheduled in order to take completion disturbance effects into account;
- the shortest average assembly order throughput time can be achieved by swapping allowance between work orders within assembly orders in such a way that the average planned work order throughput times are all the same.

If these findings are reformulated in terms of a specific approach, then this means that all of the work orders belonging to a given assembly order should be released at the same time, namely the time at which the assembly order arrives in the shop.

Due date assignment is said to be dynamic when the due date is determined based upon the total remaining workload in a system at the time of due date assignment (see also Figure 8.1). In published studies regarding the dynamic assignment of due dates for mono's, it has been found that the best results are obtained when the allowance is made dynamic. Bertrand ([Bertrand et al., 1990]) developed a simple formula (1) for calculating the dynamic allowance factor (A(t)). The remaining workload (RWL(t)) is defined as the total number of processing hours yet to be spent on work orders in the shop. Dynamic due date assignment is not the same as Workload Control. Only workload information is used to determine the dynamic allowance factor.

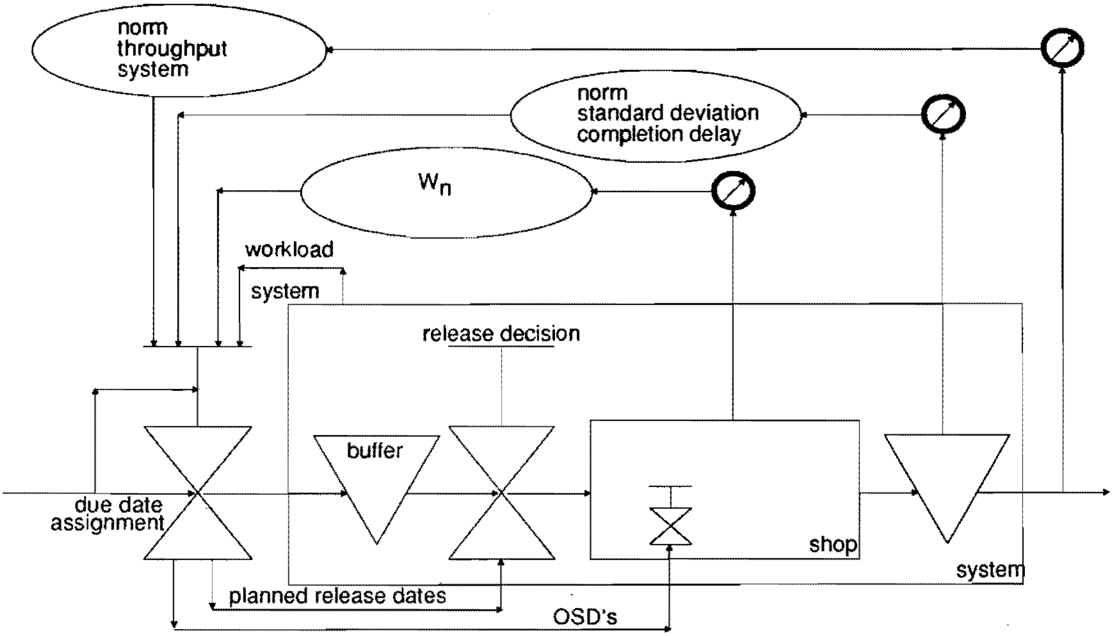


Figure 8.1: Workload feedback with dynamic due date assignment

p_o := estimated value for the average processing time per operation

c := number of machines in the shop

e_o := average remaining total processing time for a random work order in the shop

ρ_o := estimated value of the average level of utilization

$RWL(t)$:= remaining workload at time t

$A(t)$:= the planned allowance factor per operation at time t

$(\rho_o \cdot c)$ is the throughput of the shop, expressed in the number of work orders which can simultaneously be processed

$$(\text{throughput time per operation}) = \frac{p_o}{\rho_o \cdot c} \cdot (\text{number of work orders in the shop})$$

$$(\text{number of work orders in the shop}) = \frac{RWL(t)}{e_o}$$

$$(\text{throughput time per operation}) = A(t) + p_o$$

So: $$A(t) = \frac{p_o \cdot RWL(t)}{\rho_o \cdot c \cdot e_o} - p_o \qquad (1)$$

(from: [Bertrand et al., 1990])

This decision rule leads to the allocation of a considerable amount of extra allowance to a work order with many operations, in an absolute sense, during a period in which there is a heavy workload; work orders with few operations are given little allowance. Nevertheless, the assembly orders are comprised of different work orders with a different number of operations. In addition, it is extremely undesirable that the critical work orders, defined as the work orders with the largest number of operations in an assembly order, again receive more allowance than the subsequent work orders. This means that the reduction in throughput time which has been achieved by using the acceleration/retardation technique will be negated to some extent. For this reason Equation (1) has been modified to ensure that the throughput time of each work order belonging to a given assembly order is adjusted by the same amount. The factor Y(t) has been introduced, whereby Y(t) represents the total amount of allowance to be adjusted for each whole work order. The dynamic allowance per work order operation can be calculated by dividing Y(t) by the number of operations in the work order and adding this to the static allowance calculated after application of acceleration/retardation (which is based upon the normative long term waiting time). The derivation of Y(t), based upon Equation (1), is presented below as Equation (2). This formula is thus used to adjust the average allowance within an assembly order.

A_o := estimated value for the average allowance factor per operation

RWLN := estimated value for the average remaining workload (the so-called normative remaining workload)

VRZ := average shop throughput

$o_{k,j}$:= number of operations in work order j of assembly order k

$\underline{o}$:= average number of operations per work order

w_o := estimated value for the average waiting time

$Y_{k,j}(t)$:= total amount of allowance of work order j of assembly order k to be adjusted

VRZ = $\rho_o \cdot c$

derived from Equation (1):

$$A_o = \frac{p_o \cdot RWLN}{\rho_o \cdot c \cdot e_o} - p_o = w_o$$

For all j and j' from k and j ≠ j':

$$Y_{k,j}(t)/o_{k,j} = Y_{k,j'}(t)/o_{k,j'}$$

before application of acceleration/retardation:

$$A(t) = A_o + Y_{k,j}(t)/o_{k,j} \qquad \text{thus: } Y_{k,j}(t)/o_{k,j} = A(t) - A_o$$

$$= \frac{p_o \cdot RWL(t)}{\rho_o \cdot c \cdot e_o} - p_o - \frac{p_o \cdot RWLN}{\rho_o \cdot c \cdot e_o} + p_o$$

$$Y_{k,j}(t)/o_{k,j} = \frac{p_o \cdot (RWL(t) - RWLN)}{\rho_o \cdot c \cdot e_o}$$

it is not advisable to have different $Y_{k,j}(t)$'s for each j and for each k at the same moment t, therefore we define Y(t) whereby:

$$Y(t) = \left(\sum_{k=1}^{n} \sum_{j=1}^{m_k} Y_{k,j}(t)\right) \cdot 1/\left(\sum_{k=1}^{n} m_k\right)$$

Y(t) := total amount of work order allowance to be adjusted

$$\sum_{k=1}^{n} \sum_{j=1}^{m_k} Y_{k,j}(t) = \sum_{k=1}^{n} \sum_{j=1}^{m_k} \left(\frac{p_o \cdot (RWL(t) - RWLN)}{\rho_o \cdot c \cdot e_o} \cdot o_{k,j}\right)$$

$$Y(t) = \frac{(RWL(t) - RWLN) \cdot p_o \cdot \underline{o}}{\rho_o \cdot c \cdot e_o}$$

$$Y(t) = \frac{(RWL(t) - RWLN)}{VRZ} \cdot \frac{p_o \cdot \underline{o}}{e_o} \tag{2}$$

The new due date assignment rule, derived from Equation (4) in Chapter 7, is presented below as Equation (3).

t_k := arrival time of assembly order k

E_k := expected completion date of assembly order k

S_k := structure allowance of assembly order k

$$E_k = t_k + \frac{\sum_{j=1}^{m_k} o_{k,j}}{m_k} \cdot A_o + \sum_{i=1}^{M_k} p_{k,J,i} + S_k + Y(t_k) \qquad (3)$$

This is a symmetrical due date assignment rule which leads to a symmetrical approach to assigning allowance. If the workload is heavy, then more allowance is allocated per operation. If the workload is light, then the allowance per operation is reduced.

The question arises of whether this is the proper approach. An assumption here, after all, is that the fluctuations in the average waiting time are known and that the due date assignment adequately follows these fluctuations. The Y(t) per work order could also be used in the event of a heavy workload to delay the whole work order by releasing it only after the excess shop workload has dissipated. In the calculation of Y(t) is an effective indication of how much excess workload exists in the shop in relation to the normative workload admitted. This excess workload divided by the throughput gives the length of time needed to process the excess workload. In a situation with a light workload (in comparison with the normative workload) it is not possible to release the work order earlier, however. Virtually the only action to take is to adjust the allowance per operation.

In this way an asymmetrical approach is introduced in which work orders (and therefore the associated assembly orders) are delayed when the workload is heavy and the allowance per operation is adjusted when the workload is light. When work orders are delayed, a waiting time is imposed before they can be released to the shop. The wait queue in this situation is referred to as the buffer; the waiting time in the buffer is called the buffer time. The estimated buffer time is called the buffer allowance (z(t)). z(t) is calculated in exactly the same way as Y(t) in Equation (2). Equation (3) is used to calculate the due date, whereby Y(t) is then replaced by z(t). A negative buffer allowance resulting from a light workload situation is used to adjust the amount of allowance per operation. The work orders are then released as soon as the due dates are assigned. The waiting time allowance per operation is set to be equal to (E_k - S_k) less the sum of the work order processing times divided by the number of work order operations. A positive z(t) leads to scheduling a release date for the work order. The difference in time between the scheduled release date and the time of arrival is equal to z(t). The waiting time allowance therefore is not affected. Following this approach implies the existence of a specific event: "releasing orders to the shop", or "order release". A work order or assembly order is released exactly on the scheduled release date.

Using this asymmetrical approach has the advantage of potentially reducing the fluctuations in the shop waiting times. A reduction in the variance of the lateness of work orders and assembly orders is therefore expected (refer also to [Bertrand, 1983, b]). Asymmetrical dynamic due date assignment is only possible in combination with order release. In fact, this is some way or other workload control by means of scheduling order release dates.

The two alternative approaches are compared with each other using simulation experiments. The results of three simulation experiments in this respect are presented in Table 8.1 and can be described as follows:

- the experiment presented in Chapter 6 using the acceleration/retardation technique, included as a point of reference (th590093);
- an experiment using acceleration/retardation with symmetrical dynamic due date assignment (th59c15c), whereby the allowance per operation is adjusted upwards as well as downwards;
- an experiment using acceleration/retardation with asymmetrical dynamic due date assignment (th59dc09) and the release of work orders on the scheduled release date.

In each table in this chapter with simulation results from experiments are the average values per experiment given. The values per run are given in appendix C.

The measured average remaining workload from run th590001 in Chapter 6 has been used as the value for the remaining normative workload parameter in Equation (3) for the due date assignment. This value was 540. The throughput has been set at 15 because there are 15 machines in the shop. It is assumed that the utilization level (90%) is not a significant factor in this case. In addition, an assumption that $e_0 \approx p_0 \cdot \underline{o}$ has been made. This assumption does not introduce any significant margin of error due to the geometrical assembly order structure used in this study. The sensitivity of the dynamic due date assignment rule is investigated in Chapter 9 with respect to possible fluctuations in the two parameters: normative workload and throughput. It is shown there that this decision rule is highly insensitive to fluctuations in these parameters (see Section 9.2).

Table 8.1:
Symmetrical and asymmetrical dynamic due date assignment compared with the non-dynamic due date assignment using acceleration/retardation.
(Results for all of the assembly orders on the left, results for only the assembly orders with 10 work orders on the right.)

90 % utilization percentage	swapping allowance th590093		release arrival th59c15c		release at prd th59dc09	
average throughput time assembly orders	52.1	69.8	50.6	67.3	58	73.5
variance throughput time assembly orders	1227	703	1284	848	1462	991
average shop throughput time assembly orders	52.1	69.8	50.6	67.3	47.4	62.4
average buffer time assembly orders	0	0	0	0	10.7	11.1
average buffer time allowance	0	0	-3.4	-3	4.9	5.5
average lateness assembly orders	3.2	4.9	5.2	4.8	4.3	2.7
variance lateness assembly orders	401	484	152	180	97	91
spread lateness assembly orders	20	22	12	13	10	10
average tardiness assembly orders	9.0	10.9	7.3	7.4	6.2	5.2
variance tardiness assembly orders	225	281	103	127	60	53
average structure delay time	7.7	18.7	8.2	20.2	7.3	17.6
variance structure delay time	90	-	108	-	74	-

The symmetrical dynamic due date assignment experiment (th59c15c) shows a significant improvement in the due date reliability. The spread in the lateness is 40% less (the variance is 62% less). The total throughput time has remained relatively constant.

The spread in the lateness is even smaller in the case of the asymmetrical dynamic due date assignment experiment in which the work orders were released on the scheduled release date (th59dc09). There is a 20% improvement compared to the symmetrical dynamic due date assignment experiment (th59c15c) whereby the orders were released at the time of arrival. With the strict release of orders on the scheduled release date, however, the average total throughput time increases by 14%. The average total throughput time for the specific category of large assembly orders increased with 10% while the spread in the lateness was 29% less.

Based upon these results, the conclusion could be drawn that it is worthwhile defining a specific order release event with the related buffer in order to improve the due date reliability, in spite of the increase in the average total throughput time. With respect to the planning and control of the logistics within a tool & die shop, it could be useful to have a separate decision point for "order release" when the acceleration/retardation technique is used in connection with due date assignment.

In the next section, the applicability of the conclusions in this section is evaluated with respect to a similar dynamic due date assignment situation, but without the use of the acceleration/retardation technique.

8.3 Dynamic due date assignment without acceleration/retardation

As mentioned in Chapter 7, it is feasible to schedule the work orders belonging to a given assembly order in such a way that they all have the same release date and different work order due dates in a situation in which the acceleration/retardation technique is not used. In this situation it is also possible to schedule all of the work orders for completion on the same due date, but with different release dates. If all of the work orders belonging to a given assembly order are scheduled to be released at the same time, then the asymmetrical approach and the dynamic due date assignment rule described in Section 8.2 can also be used in this situation. This can not be done, however, if different release dates are to be scheduled for the work orders belonging to a given assembly order.

It is normally not convenient to release all of the work orders belonging to a given assembly order at the same time, however. As explained in Chapter 7, it makes more sense to use the acceleration/retardation technique in situations where it is actually possible to release all of the work orders together. In this section it is assumed that the acceleration/retardation technique cannot be used. This means that each work order is held in the buffer until its scheduled release date.

It is not always possible to use the acceleration/retardation technique in practice. This is the case when, for example, the order structure is not known at the time of due date assignment. In practice, people determine which work orders are on the critical path and take care that these work orders are first available for release.

Use of the dynamic due date assignment rule means that it is possible to adjust the allowance per operation upwards or downwards (with the symmetrical approach) or to adjust the buffer allowance when the workload is too heavy or otherwise reduce the allowance per operation (with the asymmetrical approach). The largest work orders are released immediately when the symmetrical approach is used. All of the work orders, including the largest, are released on their respective scheduled release dates when the asymmetrical approach is used. Use of the asymmetrical approach has a significant drawback, however, due to the geometric order structure. This is explained below.

◆ *Disadvantage of using asymmetrical dynamic due date assignment*

When the asymmetrical dynamic due date assignment approach is used without the acceleration/retardation technique, the work orders waiting in the buffer can be divided into two categories (see also Figure 8.2):

- one category of work orders with a scheduled release date which will always be earlier than the scheduled release date of any new work order yet to arrive;
- another category of work orders with a scheduled release date which will be later than the scheduled release dates of new work orders yet to arrive during the course of several inter-arrival times.

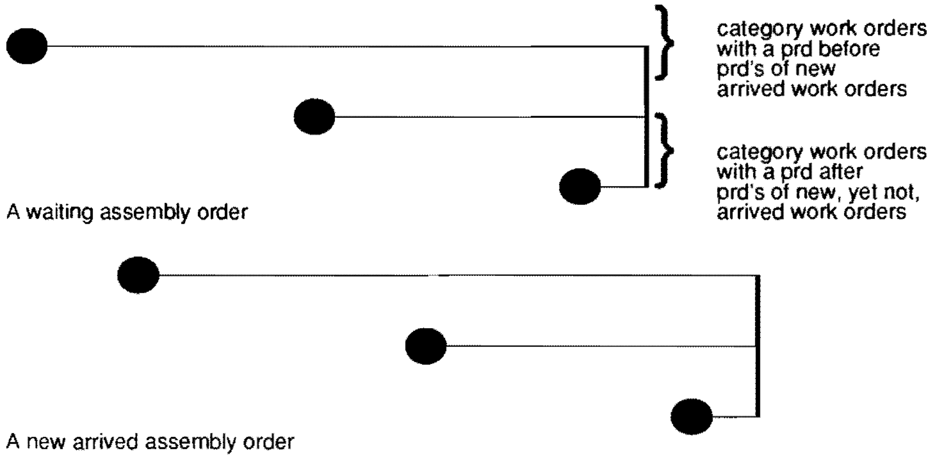


Figure 8.2: Illustration of two categories of work orders waiting in the buffer

This last category of work orders is responsible for a strange effect. Due to the dynamic rule presented in the previous section whereby the buffered work orders are included in the measurement of the workload, the buffered work orders are able to influence the due dates yet to be assigned even though they have, for the time being, not yet been added to the actual shop workload. This idiosyncrasy is illustrated here using two simple examples based upon deterministic calculations. Both examples assume the same basic situation in which the shop has five machines and the shop throughput is also equal to five (VRZ = 5). In each period, one assembly order arrives which is comprised of an initial work order with three operations and two subsequent work orders, each with a single operation. The processing time per operation is equal to one. The following values can be calculated: Y(t), $WIP_T(t)$ (the total work in progress at the end of period t in the shop and in the buffer), $WIP_S(t)$ (the work in progress in the shop at the end of period t), $WIP_B(t)$ (the work in progress in the buffer at the end of period t), $\rho(t)$ (the utilization percentage in period t), $\rho_p(t)$ (the maximum possible utilization percentage in period t if every initial work order were to be released immediately at the time of arrival) and H(t) (the scheduled throughput time of the assembly orders in period t). The label "completed" is used to indicate which operations of each assembly order are completed in each period. The asymmetrical due date assignment situation for the deterministic example described here is presented in Figure 8.3.A. The symmetrical due date assignment example is presented in Figure 8.3.B.. It is apparent that a stable state (i.e., a constant utilization level of 100%) does not occur until period 24 in Figure 8.3.A. The stable state in Figure 8.3.B is attained starting in period 5. A large amount of WIP_B is ultimately required in the stable state in the case of the asymmetrical due date assignment. Due to the fact that certain subsequent work orders are obliged to wait a relatively long time before being released (as compared to the initial work orders of the assembly order), the release of new assembly orders must be scheduled a long time in advance. This means that a large number of assembly orders needs to be present in the buffer before a balanced distribution of initial and subsequent work orders is available for release in each period. An extraordinary pattern with a "lumpy" character occurs during an initial period of time. In order to eliminate the influence of the subsequent work orders in the case of an asymmetrical due date assignment, the same calculations are repeated in Figure 8.3.C, but then for a situation in which Y(t) is determined based upon the WIP_T of only the initial work orders of the assembly orders. The subsequent work orders thus are not included in the calculations. A stable state is achieved in period 6 in this case. The throughput time is even shorter than in the Figure 8.3.B example by one unit. The same result can be obtained in the Figure 8.3.B example by including 50% of the WIP_T in the calculation of the Y(t).

The lumpy initial pattern reappears several times as time passes in the stochastic situation. This occurs particularly after a period with an abnormally small number of order arrivals (as compared to the final average utilization level) following a period with a significantly larger number of order arrivals. This is the reason for referring to this phenomenon as being "lumpy".

Period t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Arrival	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Y(t)	0	1	2	2	3	3	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
VRZ	1	1	3														1	1	3										1	1
			1	1	3													1	1	3										
					1	1	3												1	1	3									
						1	1	3												1	1	3								
								1	1	3												1	1	3						
									1	1	3												1	1	3					
											1	1	3											1	1	3				
												1	1	3											1	1	3			
													1	1	3											1	1	3		
														1	1	3											1	1	3	
																1	1	3										1	1	3
$WIP_T(t)$	4	8	9	13	14	17	18	19	22	23	24	27	27	27	28	29	32	32	32	32	28	29	32	32	32					
$WIP_S(t)$	2	1	2	1	2	3	1	2	3	1	2	3	3	3	1	2	3	3	3	3	1	2	3	3	3					
$\rho(t)$	20	20	80	20	80	40	80	80	40	80	80	40	100	100	80	80	40	100	100	100	80	80	40	100	100					
$\rho_P(t)$	20	40	100	60	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100					
$WIP_B(t)$	2	7	7	12	12	14	17	17	19	22	22	24	24	24	27	27	29	29	29	29	27	27	27	29	29					
H(t)	3	4	5	5	6	6	7	7	7	7	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9					

Stabel from 24

Figure 8.3a: Deterministic examples of three different due date assignment rules

Period t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Arrival	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Y(t)	0	1	2	2	2	2	2																							
VRZ	1	1	3																											
		1	1	1	2																									
			1	1	1	2																								
				1	1	1	2																							
					1	1	1	2																						
						1	1	1	2																					
							1	1	1	2																				
$WIP_T(t)$	4	7	7	9	9	9	9																							
$WIP_S(t)$	2	3	3	3	3	3	3																							
$\rho(t)$	20	40	100	60	100	100	100																							
$\rho_P(t)$	20	40	100	60	100	100	100																							
$WIP_B(t)$	2	4	4	6	6	6	6																							
H(t)	3	4	5	5	5	5	5																							

Stabel from 5

Figure 8.3b: Deterministic examples of three different due date assignment rules

Period t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Arrival	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
$Y(t)$	0	0	1	1	1	1	1																							
VRZ	1	1	3																											
		1	1	3																										
				1	1	3																								
					1	1	3																							
						1	1	3																						
							1	1	3																					
								1	1	3																				
$WIP_T(t)$ (longest)	2	3	4	5	6	6																								
$WIP_S(t)$	2	3	1	2	3	3																								
$\rho(t)$	20	40	80	80	40	100	100	100	100																					
$\rho_p(t)$	20	40	100	60	100	100	100																							
$H(t)$	3	3	4	4	4	4	4																							

Stabel from 6

Figure 8.3c: Deterministic examples of three different due date assignment rules

This lumpy pattern can be eliminated by excluding a portion of the workload in the buffer from the total used in the due date assignment calculation. The buffer factor (b) parameter has been defined for this purpose. The z(t) from Equation (3) is multiplied by b to determine the due date. The effect of using this approach will be evaluated based upon the results of simulation experiments. (Note that b was set up 0.5 in Figure 8.3.) (Refer also to [Wiendahl, 1987].)

The lumpy pattern is caused by the time differences between the scheduled release dates of the initial work orders in the assembly orders. When these time differences turn out to be multiples of the inter-arrival times, then the characteristic lumpy pattern appears. Any method which serves to reduce these time differences will similarly help reduce the lumpiness. The acceleration/retardation technique is an example of such a method since its use reduces the time differences and thus results in a significant reduction of the lumpiness in the buffer time. (See Table 8.1; th59dc09.)

The asymmetrical approach and then the symmetrical approach are discussed in the next two subsections.

8.3.1 Buffer behaviour with the asymmetrical approach

Two statements from the previous section need to be validated through the use of simulation experiments, namely:

- the time difference between the scheduled release dates of the subsequent work orders and the scheduled release date of the critical work order from each assembly order causes a lumpy pattern with respect to the buffer time;
- the acceleration/retardation technique can be used to prevent a lumpy pattern by ensuring that all of the work order throughput times within an assembly order are the same.

Two series of simulation experiments have been performed based upon a 90% utilization level. One series is based upon the reference situation experiment with the structure delay time presented in Chapter 6 (th590001). The other series is based upon the experiment using the unrestricted acceleration/retardation technique with the structure delay time presented in Chapter 6 (th590093).

The results of the experiment using dynamic due date assignment are compared with the results of the initial due date assignment experiment in Table 8.2. Neither of the experiments used the acceleration/retardation technique. It is expected that the dynamic due date assignment approach will produce a significant improvement in the due date reliability.

Table 8.2:
Dynamic due date assignment compared with non-dynamic due date assignment. (Results for all assembly orders on the left; results for only the assembly orders with 10 work orders on the right.)

90 % utilization percentage	reference situation th590001		dynamic due date th59dc08	
average throughput time assembly orders	68	125	205	256
variance throughput time assembly orders	2503	2279	4357	4183
average shop throughput time assembly orders	68	125	61	114
average buffer time assembly orders	0	0	144	143
average lateness assembly orders	-0.3	0.2	-7.1	-10
variance lateness assembly orders	362	439	84	75
standard deviation lateness assembly orders	19	21	9	9
average tardiness assembly orders	7.0	8.2	1.3	0.8
variance tardiness assembly orders	185	232	15	8
average structure delay time	5.9	14.8	4.6	11.7
variance structure delay time	52	-	28	-

It is apparent that the due date reliability is vastly improved. The variance in the lateness has been reduced to 23% of the original value. The throughput time is increased by more than a factor of three, however, as a result of the buffer time and the anticipated consequences of the characteristic lumpy pattern. This lumpiness can be decreased by reducing the buffer factor. The results achieved by reducing the buffer factor by various amounts is presented in Table 8.3.

Table 8.3:
Series of simulation runs with dynamic due date assignment without acceleration/retardation using various buffer factors. (1 = th59dc08, 2 = th59dc18, 3 = th59dc28, 4 = th59dc38, 5 = th59dc48, 6 = th59dc58, 7 = th59dc68, 8 = th59dc78)

90 % utilization percentage	1	2	3	4	5	6	7	8
buffer factor	1	0.9	0.7	0.5	0.3	0.1	0.01	.001
average throughput time assembly orders	203	131	92	80	73	69	67	67
average shop throughput time assembly orders	60	61	62	64	65	66	67	67
average buffer time assembly orders	143	70	30	16	8	2	0.2	0.02
average lateness assembly orders	-8	-7	-6	-4	-3	-2	-2	-1
variance lateness assembly orders	68	86	133	202	284	375	412	419
average tardiness assembly orders	1	1	2	4	5	6	7	7
variance tardiness assembly orders	8	13	33	75	133	198	225	231
average structure delay time	4.3	4.5	4.7	5	5.2	5.4	5.5	5.5
variance structure delay time	23	25	28	33	38	43	44	45
average workload in the shop	462	469	482	503	520	534	538	539
average workload in the buffer	2327	1336	727	515	399	324	298	296

The lumpiness can be eliminated by using a buffer factor value between 0 and 1. The buffer time becomes smaller as the buffer factor is reduced. A modest increase in the average shop throughput time occurs at the same time. This happens because the effects of the fluctuations in the resource capacity loading are included in the calculations to a lesser extent. The performance improvements with respect to due date reliability are also reduced. It is clear that the use of a buffer factor is not beneficial with respect to due date reliability.

When a lumpy pattern occurs, this can be seen as an unbalanced distribution of the workload over the buffer and the shop. This means that the production capacity in the shop may be under-utilized when there is, nevertheless, sufficient work waiting in the buffer. This problem disappears when workload control is used in connection with the release of work orders. This is explained further in Chapter 9.

8.3.2 Dynamic allowance: the symmetrical approach

Allowance is used in every instance in connection with the analysis of the symmetrical approach in this subsection, in contrast to the analysis of the asymmetrical approach in the previous subsection. In other words, the allowance is used dynamically. The assembly order expected completion date is determined using the rule represented by Equation (4), below.

$$E_k = t_k + \sum_{j=1}^{m_k} o_{k,J} \cdot A_o + \sum_{i=1}^{M_k} P_{k,J,i} + S_k + Y(t_k) \qquad (4)$$

The allowance per operation ($A_k(t)$) of an assembly order k can be calculated using Equation (5).

$$A_k(t) = \frac{\sum_{j=1}^{m_k} o_{k,J} \cdot A_o + Y(t)}{\sum_{j=1}^{m_k} o_{k,J}} \qquad (5)$$

This same allowance per operation ($A_k(t)$) is used for scheduling the release dates for the subsequent work orders by calculating backwards. The results of this approach are compared with the results of the asymmetrical approach in Table 8.4.

Table 8.4:
Symmetrical dynamic due date assignment compared with asymmetrical due date assignment. (Results for all assembly orders on the left; results for only the assembly orders with 10 work orders on the right.)

90 % utilization percentage	symmetric th59mc08		dynamic due date th59dc08	
average throughput time assembly orders	76	132	205	256
variance throughput time assembly orders	2775	2489	4357	4183
average shop throughput time assembly orders	76	132	61	114
average buffer time assembly orders	0	0	144	143
average lateness assembly orders	-14	-14	-7.1	-10
variance lateness assembly orders	147	134	84	75
standard deviation lateness assembly orders	12	12	9	9
average tardiness assembly orders	1.0	1.3	1.3	0.8
variance tardiness assembly orders	20	27	15	8
average structure delay time	5.9	14	4.6	11.7
variance structure delay time	48	-	28	-

The lumpy pattern does not occur in this case because the work content of the work orders in the buffer is not taken into account in the release decision of the critical work orders. The results produced by symmetrical dynamic due date assignment are much better than the results using the asymmetrical approach, even when the buffer factor is used with the asymmetrical approach (see Table 8.3). A major advantage is that the average total assembly order throughput time is significantly shorter while the variance in the lateness is, by comparison, only marginally worse.

8.4 Conclusions

- A symmetrical dynamic due date assignment rule has been developed in this chapter. Simulation experiments using this rule have demonstrated that a significant reduction in the variance of the lateness (62 percent of the original value) can be achieved in situations where the acceleration/retardation technique is used.

- In addition, an asymmetrical dynamic due date assignment rule was developed which takes an estimate of the assembly order buffer time into account. This rule assumes that order release will be used. Using this asymmetrical dynamic due date assignment rule in conjunction with order release, an additional reduction in the spread of the lateness can be achieved as compared with the symmetrical due date assignment rule. The total reduction of 50 percent is realized in this case when the acceleration/retardation technique is used. The penalty for this improvement is a 12 percent increase in the average total throughput time.

- If the acceleration/retardation technique is not used, then a significant improvement in the spread of the lateness (36%) can be realized by using the allowance dynamically. A symmetrical dynamic due date assignment rule is used in this case and the average total assembly order throughput time increases by 11%. The asymmetrical approach which is recommended when the acceleration/retardation technique is used, produces a characteristic lumpy pattern when acceleration/retardation is not used. The asymmetrical approach in this case implies that the work orders will be released separately. The lumpy pattern is caused by a temporarily unbalanced distribution of the workload over the buffer and the shop. By including only a portion of the buffer allowance in the calculation of the assembly order expected completion date, the lumpy pattern can be virtually eliminated and the buffer time can be significantly reduced. A better alternative will be proposed in Chapter 9: workload control in connection with work order release. An unbalanced distribution of the workload can be prevented through the use of workload control when the work orders are released.

- Use of the acceleration/retardation technique not only reduces the shop throughput time, but also significantly reduces the buffer time when the asymmetrical dynamic due date assignment rule is used because the characteristic lumpy pattern is eliminated.

- By applying the dynamic due date assignment rules, the total workload in the whole system, buffer and shop together, has to be taken into account.

The situations in which it is beneficial to use workload control in conjunction with releasing work orders, and the extent to which this should be done, is investigated in the next chapter.

Chapter

9 RELEASING WORK ORDERS USING WORKLOAD CONTROL

9.1 Introduction

Dynamic due date assignment rules have been developed in the preceding chapter. Using these rules, the current shop loading as well as the future shop loading, based upon the accepted orders waiting in the buffer, are important factors in assigning due dates.

The asymmetrical due date assignment rule produces the best results in terms of the due date reliability when the acceleration/retardation technique is used. Asymmetrical due date assignment can only be used in combination with (work) order release. If acceleration/retardation is not used, then a significantly shorter average throughput time can be attained by using the symmetrical due date rule instead of the asymmetrical rule. This is due to the characteristic lumpy pattern which results from an unbalanced distribution of the workload between the buffer and the shop. It is expected that this unbalanced distribution and the accompanying lumpy pattern can be prevented by using workload control in connection with the work order release. Within this context the workload control technique developed by Bertrand and Wortmann is utilized here (see [Bertrand & Wortmann, 1981]).

To start with, the effects of using workload control for releasing orders are evaluated in this chapter with respect to situations in which the acceleration/retardation technique is used in connection with assigning due dates and scheduling assembly orders. Subsequently, workload control is applied in a situation in which acceleration/retardation has not been used.

9.2 Workload control with the acceleration/retardation technique

◆ *The purpose of workload control*

The basic objective of workload control is to find a close match between the short term supply and demand for resource capacity. In this connection "workload" is defined as being the amount of work in a shop required to realize a certain resource capacity utilization level, aggregated over a period of time. The workload is determined to some extent by the numbers of work orders which need to be kept waiting in the work station queues in order to maintain a certain resource capacity utilization level. The workload is also determined by the lengths of the work order routings; this aspect is easy to understand. When work orders take longer to find a place in a given work station queue after being released, an increased workload is required to ensure a sufficient, continuous supply of work for this work station (see also Section 3.4). A normative workload can be defined with respect to the workload for each shop. This normative workload specifies the workload quantity required to realize the desired resource utilization level and the desired average shop throughput time for the work orders. Whenever the currently measured "remaining workload" falls below the established normative workload, a new work order can be released. A minimum value for the normative workload must be defined to ensure that a certain utilization level is maintained.

What can be expected from workload control? Workload control helps to maintain a constant flow of work to the work stations so that fluctuations in the utilization of resource capacities are minimized. The minimum normative workload value (required to maintain the desired utilization level) results in the shortest possible average waiting time and the smallest possible waiting time variance. This generally leads to short, constant average shop throughput times for the work orders and assembly orders (see also Section 3.4) ([Ooijen, 1991]).

There is one significant disadvantage of using workload control: the buffer time. Each work order must wait in the buffer until it can be released. Increasing the buffer waiting time results in an increase in the total throughput time. Reducing the shop throughput time results in a reduction in the total throughput time. The net benefit derived from using workload control is therefore dependent upon the trade-off between the resulting increase and reduction and the effect on the due date reliability.

The theoretical basis presented here for workload control focuses on the buffer behaviour. The use of acceleration/retardation is assumed in this case to eliminate all possibilities of a lumpy pattern occurring with respect to the buffer behaviour. Also, use is made of structure delay time and the dynamic due date assignment rule in order to be able to investigate the due date reliability aspects (see Figure 9.1).

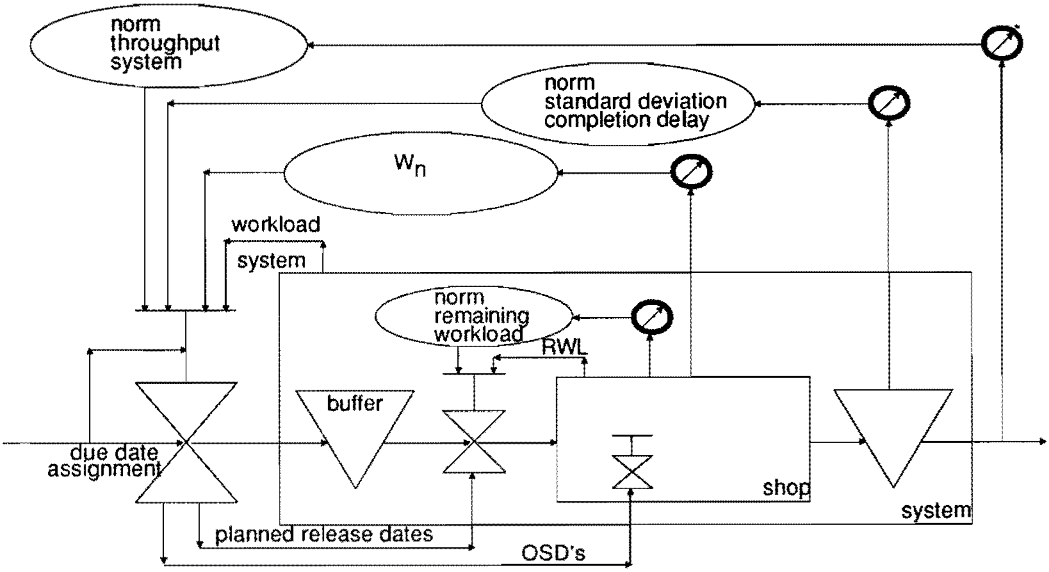


Figure 9.1:
Workload feedback in connection with due date assignment and order release

The order release decisions in this study, through to Chapter 8, have been based upon the order information. In Chapter 8 this approach led to the use of a strict method for releasing orders on the scheduled release dates. In this chapter, however, the order release decision will be based primarily on information about the shop loading conditions in terms of the current remaining workload. This measurement is used to determine whether a new order can be released. The immediate question which then arises is which of the orders waiting in the buffer should then be released. This decision is based upon the priority rule used in conjunction with order release. For this reason, a sensible priority rule must first be developed.

◆ *Design of a priority rule for releasing orders*

In view of the pacing aspects (see [Siegel, 1971] and Chapter 3), it is sensible to concentrate as much as possible on the reliability of the scheduled operation dates. This essentially means concentrating on the reliability of the scheduled release dates. The first criterion for determining the relative priorities for releasing orders is, therefore, the scheduled release date.

The work orders in Chapter 8 were released exactly according to schedule on their respectively scheduled release dates. All of the work orders belonging to a given assembly order generally have the same scheduled release date after the acceleration/retardation technique is applied. This means that the assembly orders are also released on their scheduled release date. If workload control is used in connection with releasing orders, then it is important to know whether the orders are to be released at the assembly order level, whereby all of the work orders belonging to a given assembly order are released at the same time, or at the work order level whereby the work orders are released individually. (In this last case, an assembly order is considered to be released when the first work order belonging to this assembly order is released.) Release at the work order level has the advantage, when compared to release at the assembly order level, that the work is released more as a continuous flow of orders. The average work content in an assembly order is, of course, greater than the average work content in a work order. Release at the assembly order level means that the work will be clustered to a greater extent than when release takes place at the work order level. It is therefore expected that release at the work order level will produce better results. This assumption can be validated using simulation experiments. In the following analyses it will be assumed, for the time being, that orders are released at the work order level.

All of the work orders belonging to a given assembly order are scheduled with the same release date when the acceleration/retardation technique is used. This means that relative priorities cannot be assigned to these work orders at this point in time. In addition, it is possible that work orders belonging to different assembly orders are assigned the same priority and the same scheduled release date. This second problem is addressed first, below.

Maxwell and Adam (see also Chapter 3 and Chapter 10, [Maxwell, 1969], [Adam et al., 1987], [Adam et al., 1991]) have indicated that the priority rules which take the remaining work content of assembly orders and work orders into account generally show a better performance with respect to the average total throughput time (NUSEG, or also NUB). The degree of reliability is determined primarily by the first criterion (the scheduled release date). The second criterion is used to improve the throughput time as described below. When a priority decision needs to be made with respect to the release of two assembly orders, the percentage of work orders already released is calculated for each assembly order and the assembly order with the highest percentage of released work orders is given a higher priority. If the percentages are equal, then the work order with the smallest number of operations is given a higher priority. In this way the assembly order with the least amount of work orders or operations remaining to be released is given the highest priority. The acceleration factor is also increased in this way (see Chapter 3).

It is essential to consider the consequences with respect to the degree of reliability when a priority choice is made between two work orders which belong to the same assembly order. It is important to recall that the work order with the largest number of operations is scheduled with the smallest allowance per operation. It is therefore sensible to give priority to the work order with the largest number of operations.

The first aspect to be investigated using simulation experiments is to determine whether using workload control results in any noticeable difference. Workload control can be applied in two ways, however. One way is to release work orders individually. The other way is to release assembly orders as a whole. The second aspect to be investigated is therefore whether it is more sensible to use workload control at the work order level or at the assembly order level. A potential disadvantage of releasing at the assembly order level is that the work is then released in clusters. Such clustering could lead to undesirable fluctuations in the shop workload and an increase in the average throughput time for work orders and, thus, also for assembly orders.

The results of three simulation experiments are presented in Table 9.1:

- a reference experiment from Chapter 8 incorporating acceleration/retardation, structure delay time and asymmetrical dynamic due date assignment without the buffer factor (th59dc09);
- a second experiment (th59c12c) in which:
  - workload control is used in connection with releasing the work orders;
  - the rule for determining the relative priorities for releasing orders is used as described in this section; and
  - releasing takes place at the work order level;
- a third experiment (th59c14c) in which:
  - workload control is used in connection with releasing the orders;
  - the priority for releasing orders is determined using the scheduled release date as the first criterion and the fewest number of operations in the first work order as the second criterion;
  - releasing takes place at the assembly order level.

The same normative workload value was used in all three experiments.

In each table in this chapter with simulation results from experiments are the average values per experiment given. The values per run are given in appendix C.

Table 9.1:
Simulation results comparing different methods of workload control and prioritizing the release of orders.
(Results for all assembly orders on the left; results for only the assembly orders with 10 work orders on the right.)

	no wl.c.		workload control			
90 % utilization percentage	reference situation th59dc09		release prio prd th59c12c		rel. ass embly ord th59c14c	
average throughput time assembly orders	58	73.5	60	75.4	56.5	71.9
variance throughput time assembly orders	1462	991	1569	1071	1424	944
average shop throughput time assembly orders	47.4	62.4	47	62	46.2	61.1
average buffer time assembly orders	10.7	11.1	13.2	13.5	10.5	10.8
average lateness assembly orders	4.3	2.7	5.5	4	4.5	2.7
variance lateness assembly orders	97	91	126	125	96	91
average tardiness assembly orders	6.2	5.2	7.5	6.7	6.2	5.2
variance tardiness assembly orders	60	53	80	72	60	51
average structure delay time	7.3	17.6	7.4	17.7	7.7	18.9
variance structure delay time	74	-	75	-	86	-
average waiting time delay	6.8	-	6.7	-	6.9	-
variance waiting time delay	99	-	100	-	110	-
average remaining workload shop	451	-	455	-	452	-
average workload buffer	176	-	205	-	147	-
remaining workload norm	540	-	540	-	540	-

Releasing at the assembly order level (th59c14c) produces the same results as releasing at the work order level (th59c12c). The use of workload control in conjunction with the previously described priority rule for order release (th59c12c) does not provide any improvement, nor does it produce any degradation in performance in comparison with releasing on the scheduled release date regardless of the workload situation (th59dc09). It can therefore be concluded that when the acceleration/retardation technique is used together with asymmetrical dynamic due date assignment and releasing at the work order level, then workload control is not particularly useful.

◆ *Sensitivity with respect to changes in the shop throughput*

In all of the cases simulated so far, the shop throughput has been set to be 15 (= the number of machines in the shop). It is useful to consider the validity and robustness of the proposed decision rules when this throughput is changed. The results of simulation runs in which different values for the throughput are used, are presented in Table 9.2.

Table 9.2:
Series of simulation runs in which the throughput has been varied.
(1 = th59dc1c, 2 = th59dc2c, 3 = th59dc3c, 4 = th59dc0c, 5 = th59dc4c, 6 = th59dc5c, 7 = th59dc6c)

90 % utilization percentage	1	2	3	4	5	6	7
norm output	12	13	14	15	16	17	18
average throughput time assembly orders	69	59	56	55	55	56	55
average shop throughput time assembly orders	44	45	45	45	45	46	45
average buffer time assembly orders	26	14	10	10	10	10	10
average lateness assembly orders	1	3	3	3	3	4	4
variance lateness assembly orders	72	72	78	86	94	105	110
average tardiness assembly orders	4	5	5	5	6	6	6
variance tardiness assembly orders	30	39	44	48	53	60	62
average structure delay time	6.5	6.7	6.8	6.9	6.9	6.9	6.9
variance structure delay time	58	63	66	67	67	66	66

These results show that a small change in the throughput (for example, plus or minus 1) does not have any significant influence. The complete set of decision rules developed here is insensitive to small changes in the throughput.

♦ *Reducing the normative remaining workload*

In the initial simulation experiments, the normative shop workload has been set to be equal to the average remaining workload resulting from the arrival process. The arrival process is based upon a bounded negative exponential distribution function with an average inter-arrival time which has been adjusted to obtain a specific shop utilization level (see Chapter 4).

If the normative workload value is reduced to a "minimum level", then the expected effects of workload control become noticeable, as previously described in this section. The minimum value for the normative workload is the lowest normative workload value which still maintains the utilization level needed to preserve the characteristics of the arrival process. Higher values for the normative workload will not affect the utilization level; a lower value will lead to insufficient work being released to maintain the specified utilization level (potentially resulting from the arrival process). The hypothesis to be tested using simulation experiments is that the average waiting time and the waiting time variance are both expected to decrease as the normative workload is decreased. As a result of this, the average shop throughput time for work orders and assembly orders should also decrease and the due date reliability is expected to improve. It is also expected that the buffer time will increase. This increase is dramatic as the normative workload approaches the minimum value. Of course, if the normative shop workload is too small then the prescribed utilization level will not be maintained and the buffer will overflow with orders waiting to be released.

The results of simulation experiments are presented in Table 9.3. Runs with higher normative workload values are also included to provide a complete picture.

The results for the large assembly orders are not significantly different than the results for all of the assembly orders taken together.

The simulation run using a normative workload of 350 did not run to completion, apparently due to an overflow error condition resulting from too many orders in the buffer. This means that the minimum value for the normative workload is somewhere between 350 and 400.

Table 9.3:
Series of simulation runs with various normative workload values.
(1 = th59cc7k, 2 = th59cc6k, 3 = th59c12c, 4 = th59cc4k,
5 = th59cc3k, 6 = th59cc2k)

90 % utilization percentage	1	2	3	4	5	6
norm workload	650	600	540	500	450	400
average remaining workload	469	456	437	425	407	293
variance remaining workload	6353	5265	4052	3109	1435	553
average workload buffer	47	65	105	174	391	914
variance workload buffer	625	848	1074	1283	15299	23439
average throughput time assembly orders	51	52	54	57	66	97
average shop throughput time assembly orders	46	46	45	45	44	43
average buffer time assembly orders	4	6	9	12	22	54
planned buffer time assembly orders	-8	-4	2	7	18	50
average lateness assembly orders	10	7	3	1	-1	-2
variance lateness assembly orders	98	95	88	82	70	63
average tardiness assembly orders	10	8	5	4	3	2
variance tardiness assembly orders	81	68	50	38	23	18
average waiting time delay	6.8	6.7	6.5	6.4	6.2	5.9
variance waiting time delay	110	103	92	86	75	65

The average waiting time decreased 10% when the normative workload was reduced from 540 to 400. The waiting time variance decreased 30%. The decrease in the average waiting time resulted in a 2% reduction in the average shop throughput time for assembly orders. The variance of the lateness decreased 28% and the variance of the tardiness decreased 65%. The variance of the average remaining workload was 86% less. On the other hand, the buffer time increased by 528%, resulting in a 179% increase in the average total throughput time for assembly orders.

◆ *Preliminary conclusions*

The performance is not improved by using explicit workload control in connection with releasing orders. Nevertheless, workload control makes it possible to lower the normative workload value in order to significantly improve the due date reliability. The fluctuations in the shop workload are reduced. The penalty for this improvement is an increase in the average total assembly order throughput time, caused by an increased buffer time. There is apparently sufficient implicit workload control when asymmetrical dynamic due date assignment is used in combination with the acceleration/retardation technique.

9.3 Workload control without acceleration/retardation

The following conclusion was presented in Section 7.4. When the acceleration/retardation technique cannot be used, there is no difference between releasing work orders as soon as possible (on the same scheduled release date) or as late as possible (for completion on the same scheduled due date), taking the structure delay time into account. It is assumed in this case that release is at the work order level. An implicit, unintentional and undesirable allowance swapping occurs when release takes place at the assembly order level.

The intention of workload control is to keep the remaining workload in the shop at a constant level, resulting in a fairly constant waiting time. Using the workload control approach means that work orders are kept in the buffer until the workload situation dictates that work orders can be released. A dynamic due date assignment rule is therefore needed to estimate the length of time that a work order will stay in the buffer (the buffer time). This means that the asymmetrical dynamic due date assignment rule should be used when workload control is employed. The decision rule with dynamic allowance in which the buffer time for an assembly order is defined to be zero should therefore not be used in combination with workload control for releasing work orders. (For the sake of completeness, this assertion is verified in Subsection 9.4.3.) In Chapter 8 it was determined that the use of this symmetrical rule is recommended in situations where neither workload control nor the acceleration/retardation technique is used. Use of the asymmetrical due date assignment rule results in the undesirable lumpy pattern in this case.

For the time being, the analyses in this section will assume a situation in which all of the work orders belonging to a given assembly order are scheduled on the same due date with different release dates. The allowance per operation is assumed to be equal to the normative waiting time.

In the first subsection, workload control is employed and the scheduled release date is used as a basis for determining the relative priorities for releasing the work orders. In the second subsection, the difference between scheduling the release of work orders as soon as possible versus as late as possible is investigated (as promised in Section 7.4). Subsequently, two final assumptions are discussed in the third subsection to complete the description of the simulation experiments. A summary of all of the results related to dynamic due date assignment and work load control is presented in the last subsection.

9.3.1 Using only the scheduled release date to determine priority

The possibility of eliminating the undesirable lumpy pattern through the use of workload control is investigated in this subsection. The priority rule for releasing work orders which was used in the previous section is also used here.

Two new simulation experiments have been defined in which the work orders are released as soon as possible based upon the current workload situation. The results are presented in Table 9.4 (totalst6). The simulation results for the reference situation (th590001) and the situation with symmetrical dynamic due date assignment (th59mc08) have been taken from Table 8.4. The results for the experiment with asymmetrical dynamic due date assignment (th59dc08) have been taken from Table 8.2.

Table 9.4:
Simulation results for workload control with a 90% utilization level.
(Results for all of the assembly orders on the left; results for only the assembly orders with 10 work orders on the right.)

(stat.d.a.: static due date assignment)	stat.d.a.		dynamic due date assignment							
	no workload control						workload control			
90 % utilization percentage	reference situation th590001		dyn. dd. assignmnt th59mc08		asym dyn dd assign th59dc08		new, with Struc tim totalst6		new, no Struc tim totalst1	
average throughput time assembly orders	68	125	76	132	205	256	75	126	75	125
average shop throughput time assembly orders	68	125	76	132	61	114	61	111	60	111
average buffer time	0	0	-	-	144	143	15	15	14	15
average lateness assembly orders	-0.3	0.2	-14	-14	-7	-10	-14	-19	-7	-2
variance lateness assembly orders	362	439	147	134	84	75	143	113	135	120
average tardiness assembly orders	7.0	8.2	1.0	1.3	1.3	0.8	0.9	0.2	2.0	3.3
variance tardiness assembly orders	185	232	20	27	15	8	9	2	20	34
average lateness work orders	0.9		-13		-4.9		-25		-25	
variance lateness work orders	343		160		92		894		897	

Based upon these results (totalst6) it can be concluded that the shortest average shop throughput time and shortest total throughput time for assembly orders can be achieved by using workload control in conjunction with releasing work orders based upon asymmetric dynamic due date assignment, without further restrictions. The total throughput time for assembly orders is 1% shorter with the use of asymmetric due date assignment and workload control (totalst6) then with the use of symmetric due date assignment without workload control (th59mc08) (from 76 to 75). The total throughput time for the large assembly orders is 5% shorter with the use of asymmetric due date assignment and workload control then with the use of symmetric due date assignment without workload control. The average total throughput times of the large assembly orders are equal for the reference situation and for the situation where workload control and asymmetric due date assignment are used. The spread in the lateness is slightly reduced (1% for all assembly orders and 8% for the large assembly orders).

Actually a dynamic estimation should be made regarding when a work order can be released in addition to the dynamic estimation of the completion date. This approach could be seen as dynamic scheduling of the release date. Workload control should be used to ensure that this dynamic scheduling of the release date does not result, in practice, in an unnecessary, temporary under-utilization of shop resource capacity.

The average total throughput time increases by ten percent in comparison with the reference situation. There is a 60 percent reduction in the variance of the lateness. The high negative value of the average lateness (-14) indicates that the subsequent work orders are consistently released earlier than their scheduled release dates. In this way the completion disturbance is reduced and significant assembly order structure delay times are avoided. In this case it is no longer necessary to make a distinction between the scheduled due date and the expected completion date for an assembly order. The parameters for the last experiment presented in Table 9.4 (totalst1) are almost identical to those for experiment totalst6, with the difference that no structure allowance has been planned ($S = 0$). This results in an average lateness which is less negative (half of the previous value) and a variance in the lateness which is somewhat less. These aspects are analyzed in more detail in the last part of this section.

The most important conclusion presented in this section is that in a situation in which the acceleration/retardation technique cannot be applied, workload control is required in order to eliminate the characteristic lumpy buffer behaviour when the asymmetrical dynamic due date assignment rule is used.

Two investigated alternatives in Chapter 8: symmetric due date assignment and the buffer factor approach, do not perform as well as workload control. A deterministic example of a third alternative is given in figure 8.3. In this alternative only the system workload of the critical path work orders is used in the due date assignment procedure. But it is not likely that this alternative performs well in a stochastic situation with a large variety of order structures. It is not obvious in such a situation whether a new assembly order has to wait until the processing of all old non-critical-path work orders is finished. Whether an assembly order has to wait, depends on the individual planned dates of the old non-critical-path work orders, on the arrival moment of the new assembly order and on the workload situation. Possible valuable information is neglected when only information about the system workload of the critical path work orders is used.

In conclusion, an additional note should be made. When workload control is used, regardless of whether the acceleration/retardation technique is applied, a minimum buffer time of approximately fifteen is required with the specific geometrical order structure used here. No approach was found which served to reduce this buffer time.

9.3.2 Releasing as soon as possible or as late as possible?

The question of whether work orders should be released as soon as possible or as late as possible in a situation without dynamic due date assignment and without workload control was investigated in Chapter 7, Section 7.4. Three situations were evaluated: situation A in which all of the work orders had the same scheduled due date (assuming no structure allowance) and different scheduled release dates; situation B in which all of the work orders were scheduled for release on the same date and had different scheduled due dates; and situation C in which the critical work order was scheduled for completion on the expected assembly order completion date and all of the other work orders were scheduled for completion on the same date as the assembly order, but with different scheduled release dates (refer also to Figure 7.6 in Chapter 7).

In Chapter 7 it was determined that the structure delay time needs to be included as part of the total scheduled assembly order throughput time in the case of situation A, but not for situations B and C. Based upon the results of the simulation experiments, no significant difference in performance could be found between situations B and C.

By using workload control, it should be possible to make use of the potential margin between releasing subsequent orders as soon as possible and releasing them as late as possible to reduce peaks in the workload. The simulation experiments have been repeated with the addition of dynamic due date assignment and workload control. The results are presented in Table 9.5. In this case the work order release dates are scheduled using the planned release date as the criterion for determining the relative priorities for releasing the work orders. The workload situation is the only factor which dictates whether a waiting work order can be released.

Table 9.5:
Results of scheduling the release of orders when using workload control.

90% utilization percentage situation:	tbw90q56 A	tbwt003z B	tbw90056 C
average throughput time assembly orders	69.1	76.8	69.6
variance throughput time	2533	2734	2495
average planned assembly order throughput time	76.7	75.4	76.3
average buffer time	10.1	19.5	11.9
average lateness assembly orders	-7.6	1.5	-6.7
variance lateness assembly orders	130	101	116
average tardiness assembly orders	1.7	4.5	1.7
variance tardiness assembly orders	15.7	36.6	16.1
average completion delay work orders	19.7	35.2	20.9
variance completion delay work orders	922	1854	922
average lateness workorder	-26.2	-0.1	-19.7
var lateness work orders	892	133	720

The most striking result is that the worst throughput time performance occurs when the subsequent work orders are scheduled for release as soon as possible. This is caused by the longer assembly order buffer time (20 as compared to 10). The longer buffer time can be explained by the fact that the work orders are released at the assembly order level in situation B. Subsequent work orders which are non-critical (with respect to the assembly order due date) are released with a higher priority than would otherwise be the case if the critical work orders belonging to other assembly orders were taken into consideration. It is not sensible to schedule the release of work orders as early as possible when asymmetrical dynamic due date assignment and workload control are used.

A second surprising result is that the results of situations A and C are similar. The subsequent work orders are apparently released earlier than scheduled when workload control is used. As a result, the completion disturbance and the undesirable structure delay time are eliminated. This means that the scheduling of work orders and plan dates in situation C have been carried out more realistically than in the case of situation A. "Realistic" in this case means that the plan dates can be realized with a high degree of probability. This is supported by the results concerning the lateness of the work orders.

The negative average lateness of the assembly orders (-8 and -7) in this case is caused primarily by the difference between the normative waiting time (7) and the actual average waiting time (6).

The following conclusions can therefore be drawn with respect to a situation in which the acceleration/retardation technique is not used and the options of whether or not to use a combination of asymmetrical dynamic due date assignment and workload control are compared:

- it is sensible to schedule the work order release dates as late as possible (situations C and A);
- the completion disturbance effects in the assembly orders are eliminated;
- the spread in the lateness is reduced by half (11 as compared to 21; see also Table 7.3);
- the average total assembly order throughput time increases somewhat: by three percent in situation A (69 as compared to 67, refer also to Table 7.3) and by eleven percent in situation C (70 as compared to 63, refer also to Table 7.3).

9.3.3 Completing the simulation studies

Two final assumptions need to be verified in order to complete the simulation studies, namely:

- it is not useful to use workload control in conjunction with symmetrical dynamic due date assignment (simulation run: th59jj08 compared with th59mc08);
- using a static due date assignment rule in conjunction with workload control results in poor performance with respect to the variance in the lateness of assembly orders (simulation run: th59mm3m compared with totalst1).

The simulation results are presented in Table 9.6.

Table 9.6:
Simulation results without acceleration/retardation for:
- **symmetrical dynamic due date assignment, with and without workload control,**
- **statistic and dynamic due date assignment with workload control.**

(Results for all of the assembly orders on the left, results for only the assembly orders with 10 work orders on the right.)

90 % utilization percentage	sym dyn a no wrklc th59mc08		workloadc sym dyn a th59jj08		release prio prd totalst1		static da workloadc th59mm3m	
average throughput time assembly orders	75	130	88	144	69	115	59	106
variance throughput time assembly orders	2873	2837	3572	3778	2535	2634	2690	2624
average shop throughput time assembly orders	75	130	75	132	59	106	49	99
average buffer time assembly orders	-	-	12	12	10	9	10	7
average lateness assembly orders	-15	-16	-13	-12	-8	-5	-13	-10
variance lateness assembly orders	139	116	187	251	130	128	1029	945
average tardiness assembly orders	1	1	2	3	2	2	8	7
variance tardiness assembly orders	19	20	42	86	16	25	374	343
average structure delay time	-13	-	-11	-	-8	-	-26	-
variance structure delay time	157	-	219	-	130	-	1790	-

The results show that both of these assumptions are not rejected.

9.3.4 The external throughput time

The results of different simulation experiments are presented in this section to compare the average total throughput times and the spreads in the lateness of assembly orders. In the literature (see [Bertrand, 1983, b]) the "average realized external throughput time" is defined as being equal to the sum of the average throughput time and a certain safety margin. This safety margin is equal to a one-sided reliability interval which represents a reliability of 97.5% with respect to the lateness; this interval is equal to approximately twice the spread of the lateness. It is assumed here that the average lateness is equal to zero. Also note that this reliability percentage has been chosen arbitrarily; in practice, however, the reliability percentage should be determined based upon the specific (shop) situation. The average realized external assembly order throughput times have been calculated for all of the relevant experiments presented in this section and are presented below in Table 9.7.

Table 9.7:
Average realized external assembly order throughput times for all of the relevant experiments discussed in this section.
(Results for all of the assembly orders on the left, results for only the assembly orders with 10 work orders on the right.)

only assembly orders experiments:	average throughput time		spread lateness		average lateness		external throughput time		description:
th590001	68	125	19.0	21	0	0	106	167	reference situation no allowance swapping
th59dc08	205	256	9.2	8.7	-7	-10	216	264	asymmetric due date assignmnt no allowance swapping
th59mc08	76	132	12.1	11.6	-14	-14	86	141	symmetric due date assignment no allowance swapping
totalst6	75	126	12	10.6	-14	-19	85	128	asymmetric due date assignmnt workload control structure time no allowance swapping
totalstl	75	125	11.6	11	-7	-2	91	145	asymmetric due date assignmnt workload control no structure time no allowance swapping
th59c12c	60	75	11.2	11.2	6	4	88	101	asymmetric due date assignmnt workload control structure time allowance swapping
th59dc09	58	74	9.8	9.5	4	3	82	96	asymmetric due date assignmnt no workload control structure time allowance swapping
th59c15c	51	67	12.3	13.4	5	5	80	98	symmetric due date assignment no workload control structure time allowance swapping release at arrival of orders

When the acceleration/retardation technique cannot be applied, the best results with respect to the average realized external throughput time are achieved when the asymmetrical due date assignment rule is used in conjunction with workload control without further restrictions for releasing work orders. The results are even better when the acceleration/retardation technique is used; in this case workload control does not provide any added value since the average results are not improved when workload control is applied. Releasing work orders without use of workload control (asymmetric dynamic due date assignment) is a little better for the large assembly orders compared with symmetric dynamic due date assignment.

9.4 Conclusions

- The use of workload control for releasing orders does not provide any general improvement with respect to the performance when the acceleration/retardation technique is used in connection with assembly order scheduling and the assignment of due dates. The use of workload control however does make it possible to reduce the normative remaining workload value to a minimum level. This reduction provides a 28% improvement in the variance of the lateness (from 88 to 63) and a 65% improvement in the variance of the tardiness (from 50 to 18), at the cost of a 179% increase in the average throughput time (from 54 to 97). The results are not significantly different when orders are released at the assembly order level instead of the work order level.

- Workload control is useful when the acceleration/retardation technique is or cannot be employed in connection with assembly order scheduling and the assignment of due dates. The scheduled release date should be used as the criterion for establishing the relative priority for each work order in this case. When workload control is used in conjunction with asymmetrical dynamic due date assignment, then an 1% reduction in the average total throughput time is realized, as compared to a situation with symmetrical dynamic due date assignment. An 5% reduction in the average total throughput time is realized for the large assembly orders. The spread in the lateness is slightly reduced. Therefore, it is advantageous to use workload control in conjunction with releasing work orders when dynamic due date assignment is used and the acceleration/retardation technique is not applicable.

9.5 Workload control in practice

The conclusions from this chapter can have far-reaching consequences in practical situations. It is important to realize that the assembly order structure must be completely defined at the time of due date assignment if the acceleration/retardation technique is to be applied fully. This approach also assumes that all of the work orders belonging to a given assembly order will be available for release on the same scheduled release date. It is difficult to fully satisfy both of these conditions in practice. This means that the acceleration/retardation technique often cannot be (completely) applied and that it is then sensible to use workload control for releasing the work orders. On the other hand, if the assembly orders are fully defined and can be scheduled at the time of due date assignment and are also completely available for release at the same time, then workload control will only be useful to explicitly improve the due date reliability at the cost of an increased throughput time.

Chapter

10 TRANSLATING THEORY TO PRACTICE

The analyses presented in the last chapter complete the theoretical part of this study. In this chapter, the practical problems encountered in the CGM case as described in Chapter 2 are reviewed in the light of the results of the theoretical experiments.

10.1 Introduction

An evaluation is made in this chapter to determine the extent to which the subject of this research as derived from the case study presented in Chapter 2 has been covered by the findings and conclusions from the theoretical analyses. A brief review and summary of the research results are presented in the second section for each of the problem areas identified in Chapter 2. The dilemmas encountered in interpreting these research results in practice are covered in the third section. The practical consequences of the research results are then formulated and summarized in terms of several rules-of-thumb in the fourth section.

10.2 Coverage of the identified problem areas

Four core decisions were identified in Chapter 2 which need to be considered during the course of processing a customer order. These decisions must be taken in the following order:

- order acceptance and due date assignment;
- assembly order allocation and outsourcing;
- work order release;
- operation sequencing on the shop floor.

The focus of this study has been limited to the production planning and control issues within a single manufacturing unit or shop. This means that the second core decision listed above has not been included within the scope of this study.

As indicated in Chapter 3 and Chapter 4, this study has been designed based on the use of the OSD priority rule. This choice has been made based upon the results of previous studies.

The following two core decision aspects, as indicated in Chapter 2, have been analyzed more extensively:

- due date assignment;
- work order release.

Four separate problem areas have been identified, as follows:

- how to use the typical characteristics of the order structure effectively to reduce the throughput time;
- how to reliably estimate throughput times;
- whether an assembly order and all of the associated work orders should be released at one time (i.e., at the assembly order level), or the work orders should be released individually (i.e., at the work-order level);
- whether the technique of workload control is sensible to use with respect to releasing work orders.

The research results with respect to each of these problem areas are reviewed and summarized in the following subsections.

10.2.1 Reducing assembly order throughput times

In the case of a geometrical order structure, the differences in the work order throughput times are derived from the differences in the numbers of operations per work order within the assembly orders. The work order throughput time is directly related to the number of operations per work order. The differences in the work order throughput time can be fully utilized to reduce the average assembly order throughput time by swapping the allowance per operation between the operations belonging to a given assembly order in such a way that the planned throughput times for the work orders belonging to that assembly order are all equal. A reduction of approximately 23% can be realized with respect to the average shop throughput time for assembly orders when the utilization level is 90% (see Chapter 5).

Nevertheless, it is recommended that an upper limit and lower limit be imposed in practice for determining the allowance per operation when an assembly order has an extremely unbalanced distribution with respect to the numbers of operations per work order. In this way the due date reliability of the individual assembly order is likely to improve without noticeably affecting the total performance adversely.

The effect of not planning for allowance swapping (i.e., not using the acceleration/retardation technique) in connection with due date assignment and scheduling assembly orders is described in Chapter 7. The performance of the so-called large assembly orders is affected. In this case, a sort of implicit, uncontrolled allowance swapping takes place which produces the same results as in the case of acceleration/retardation in terms of the average performance. The performance for the specific category of large assembly orders is extremely poor, however. Furthermore, obtaining a good performance for the category of large assembly orders tends to be more important in practice than the average performance for all of the assembly orders taken together. The acceleration/retardation technique used here within assembly orders provides a 44% reduction in the average shop throughput time for the large assembly orders.

10.2.2 Estimating reliable throughput times

It is useful to make a distinction between scheduled work order due dates and expected assembly order completion dates for the purpose of calculating reliable assembly order throughput times. In reality, work orders scheduled with the same due date will never be completed at exactly the same time due to the completion disturbance. The structure characteristic of the number of work orders in a given assembly order must be taken into account when estimating the time gap between the scheduled work order due date and the expected assembly order completion date. This time gap is therefore referred to as the structure delay time. A practical method for estimating this structure delay time is developed in Chapter 6. When the acceleration/retardation technique is used, the structure delay time appears to account for approximately 17% of the total assembly order throughput time (see also Chapter 7). This factor also is largely dependent upon the particular order structure used.

If the acceleration/retardation technique is not used, then the effect of the completion disturbance can be reduced by scheduling a due date for the subsequent work orders within an assembly order which is earlier than the due date of the time-critical work order. The method of calculating the structure allowance which is developed in Chapter 6 can still be used in conjunction with this type of scheduling approach.

Using dynamic due date assignment leads to a high degree of due date reliability, as could be expected from the results published in the literature. The due date reliability can be improved even more by using the acceleration/retardation technique and releasing work orders for production in the shop exactly on their respectively scheduled release dates. It has been demonstrated that it is advantageous to release work orders in this way. By scheduling the release dates in this way, the planning process indirectly takes the workload into account. This could be called implicit workload control. Releasing work orders in this way also results in a small increase in the throughput time.

10.2.3 Whether or not to release work orders as a single group

The question arises of whether it is better to release all of the work orders belonging to a given assembly order at the same time (as a single group of work orders) or to release the work orders individually. This question is not relevant when the acceleration/retardation technique is used, since all of the work orders belonging to a given assembly order are then, in principle, scheduled for release at the same point in time. The question is not easily answered when workload control is used. Practical organizational arguments, however, should be considered in while answering the question whether or not to release work orders as a single group. Releasing work orders as a single group implies, for example, that the total number of release decisions which need to be taken is reduced by a factor of three. On the other hand, it would be inadvisable to release a group of work orders at the same time when a minimum and maximum allowance per operation is imposed for assembly orders with an extremely unbalanced distribution.

It is similarly inadvisable to release a group of work orders at the same time when the acceleration/retardation technique is not used. Allowance is swapped implicitly in this case and the grouping of work orders would then lead to a different, uncontrollable streams of assembly orders to a certain degree. Work orders should therefore be scheduled for release at the latest possible point in time.

10.2.4 Whether to use workload control

As indicated in the previous subsection, it is sensible to release work orders exactly as planned on their respectively scheduled release dates. Workload control can be used in conjunction with work order release to ensure that a work order is released only when capacity becomes available based upon the workload situation in the shop.

Workload control in conjunction with releasing orders provides neither an improvement in performance nor a degradation in performance when the acceleration/retardation technique is used. Nevertheless, the normative remaining workload can be reduced to a minimum level when workload control is used, resulting in an improvement of the due date reliability at the expense of a significant increase in the total average throughput time.

When the acceleration/retardation technique is not (fully) used, then it is useful to use workload control in conjunction with asymmetrical dynamic due date assignment. The priority rule used for releasing work orders in this case should be based upon the use of the scheduled release date as the first priority criterion. Workload control should be seen primarily as a useful technique for eliminating the characteristic lumpy buffer pattern while, at the same time, preventing the occurrence of unintentional, implicit allowance swapping.

10.3 Dilemmas interpreting the research results

A number of conditions need to be satisfied before the approaches developed in this study can be applied in practice. These conditions may in some instances conflict with the normal working procedures found in real-life situations such as described in the CGM case study in Chapter 2. This leads to a number of dilemmas which are encountered when an attempt is made to interpret the research results and apply these to practical situations. The most important dilemmas encountered in connection with the CGM case study are described in this section. These are:

- uncertainties with respect to information about the order structure;
  this study has been based upon the assumption that assembly orders can be scheduled at the time of order acceptance and assignment of due dates. This means that it is possible to schedule the plan dates, release dates and due dates for assembly orders, work orders and operations in advance. In the CGM situation, however, the product specifications and production instructions are normally not known when the order is accepted. As a result, assembly orders cannot be scheduled.
- the influence of pre-manufacturing activities,
  the engineering and process planning activities are typically carried out between the time of order acceptance and the processing of an assembly order in the shop. The influence of these pre-manufacturing activities has not been taken into account in the study presented here,
- the consequences of rush orders;
  a special order category, rush orders, exists within every shop, including the CGM,
- a more complicated planning and control situation;
  a number of simplifications have been made in order to limit the scope of this study to a meaningful research objective. Three of these simplifications are discussed here in more detail: the homogeneous arrival process, the absence of planning and control of the materials flow and the absence of an assembly task with multiple convergent nodes.

Each of these dilemmas are discussed below in a separate subsection.

10.3.1 Uncertainties about the order structure information

Use of the acceleration/retardation technique assumes that the product specifications are fully defined (i.e., there are no uncertainties about the product to be manufactured) and that the production specifications are fully defined (i.e., there are no uncertainties about how to manufacture the product). It is necessary to know how many work orders are in each assembly order and how many operations there are in each work order. In a normal tool & die shop, however, there is always a certain degree of uncertainty about the product specifications and production specifications when due dates are assigned. Often only general information is available at the time of due date assignment. In addition, specifications are often modified after the order has already been accepted.

This means that the structure information, particularly the "number of operations per work order" and "number of work orders per assembly order" characteristics, needs to be defined as soon as possible by the pre-manufacturing activities. This information is needed in order to be able to estimate the assembly order throughput time. This estimate of the throughput time can be used as the basis for the preliminary resource capacity planning as described in subsection 2.7.2 so that due dates can be assigned. An estimate of the degree of uncertainty with respect to the structure information is then used to determine how much extra safety margin will need to be included in the due date assignment to ensure an adequate due date reliability.

The fact that there is some degree of uncertainty with respect to the structure information at the time of due date assignment implies that it is impossible to use the acceleration/retardation technique fully in practice. There is insufficient information available about the two essential structure characteristics. Even in the best case, only estimates can be used which will always result in a certain degree of inaccuracy with respect to the acceleration/retardation calculations. In addition, it is normally not possible in practice to process a whole customer order or an assembly order as a whole during the pre-manufacturing activities. It is often necessary to perform activities in parallel with the manufacturing and assembly of components. This means that it is normally not possible to ensure that all of the work orders belonging to a given assembly order will be available at a single point in time for manufacturing the components. This means that it will not be possible to make optimal use of the acceleration/retardation technique in practical situations. As a result, it will normally be necessary to use workload control in conjunction with releasing work orders.

10.3.2 The influence of pre-manufacturing activities

A tool & die shop normally requires engineering and process planning activities to be carried out for a customer order before the actual manufacturing can be performed. Such engineering and process planning activities are referred to here as the pre-manufacturing activities. These pre-manufacturing activities have a certain throughput time. The time lag resulting from the throughput time of the pre-manufacturing activities needs to be taken into account when the throughput time for the actual manufacturing activities is calculated. When the due date is assigned, the total throughput time therefore consists of the estimated throughput time for the pre-manufacturing activities plus an estimate of the throughput time for the actual manufacturing activities. This last estimate thus must be made a certain time in advance.

The fact that the pre-manufacturing activities have not been included in the model used for this study limits the practical applicability of the findings and conclusions from this study.

The consequences of the pre-manufacturing activities for the assignment of due dates are described in more detail in this subsection.

◆ *Dynamic consequences*

Three components of the planned integral assembly order throughput time have been identified in section 4.3. A fourth component needs to be added when pre-manufacturing activities are also performed: the planned throughput time for the pre-manufacturing phase (see Figure 10.1).

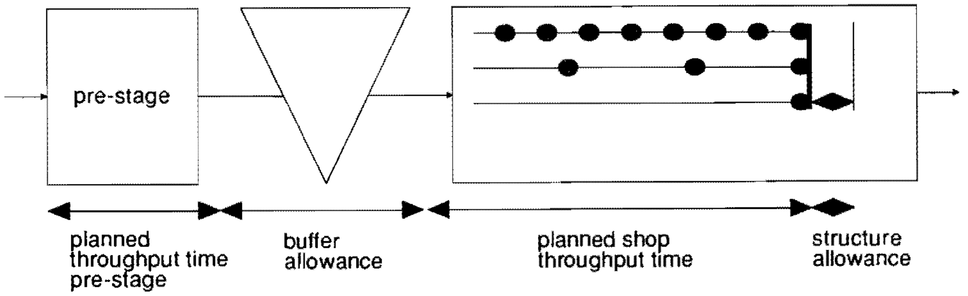


Figure 10.1: Four components of the throughput time

To start with, it should be possible to estimate the throughput time for the pre-manufacturing phase. In connection with this it can be assumed that the average realized throughput in terms of the number of orders processed in this pre-manufacturing phase is equal to the average realized throughput during the actual manufacturing phase. When there is an imbalance between these two phases, then either the total system will overflow with orders or the shop will not be able to achieve the desired utilization level. Batches with approximately equivalent workloads are created for processing by the engineers and planners in the pre-manufacturing phase. If too much time needs to be budgeted for the throughput time for a batch in the pre-manufacturing phase, then the batch can normally be split up and distributed over multiple engineers and planners. As opposed to the situation in the actual manufacturing phase, there are no specific operations which can be identified in the pre-manufacturing phase. Each batch of work must be processed in its entirety, without interruption, by the designated employee(s). The throughput time in the pre-manufacturing phase is determined to a large extent by the degree of parallelism achieved in distributing the workload among multiple employees. Another important factor in estimating the throughput time is the point in time at which the processing of the batch can be started. This is primarily a question of capacity planning.

In order to dynamically estimate the throughput time for the manufacturing phase, the static estimate for the total throughput time needs to be adjusted based upon the difference between the actual workload and the normative workload in the total system, divided by the quantity of work processed. This is expressed below as Equation (1).

$RWL_s(t)$:= remaining workload in the shop at time t

$RWL_b(t)$:= remaining workload in the buffer at time t

$RWL_p(t)$:= remaining workload expressed in actual manufacturing hours during the pre-manufacturing phase at time t

$RWLN_s$:= remaining workload in the shop

$RWLN_p$:= remaining workload in the pre-manufacturing phase

$F(t)$:= correction factor for the integral throughput time at time t

VRZ := throughput, i.e., the quantity of work processed, expressed in shop production hours

G_k := planned throughput time in the pre-manufacturing phase for assembly order k

$$F(t) = \frac{RWL_s(t+G_k) + RWL_b(t+G_k) + RWL_p(t) - RWLN_s - RWLN_p}{VRZ} \qquad (1)$$

This equation can be explained as follows. When a new assembly order arrives and there is too much work in the pre-manufacturing phase, this excessive work must first be completed before processing of the new assembly order can begin. Extra throughput time must be planned to accommodate this waiting period. The normative workload therefore consists of the normative workload for the pre-manufacturing phase and the normative workload for the manufacturing phase. Both of these quantities are expressed in terms of production hours (as opposed to pre-manufacturing hours).

An additional complicating dynamic aspect with respect to the assignment of due dates is the following. When the due date is assigned, an estimate of the expected workload situation in the buffer and in the shop must be made for the point in time at which the assembly order completes the pre-manufacturing phase and arrives in the buffer. The period to be forecasted in this way is approximately equal to the throughput time in the pre-manufacturing phase. The workload situation is known at the time of due date assignment. This is worked out in detail in Equation (2).

$Q(T)$:= total work content of the assembly orders which arrived in period T

$$RWL_s(t+G_k) + RWL_b(t+G_k) + RWL_p(t) =$$

$$= RWL_s(t) + RWL_b(t) + RWL_p(t) + Q(G_k) - (G_k * VRZ) \qquad (2)$$

It is important to note that this process is partially dependent upon the previous workload. The shop workload at time t is, in one way or another, a function of the previous workload in the total system.

◆ *Uncertainty*

It is apparently necessary to estimate the quantity of work which is received and processed in the period of time represented by the throughput time in the pre-manufacturing phase. Refer to Equation (3).

$Q'(T)$:= incremental quantity of work in period T

$$Q'(G_k) = Q(G_k) - (G_k * VRZ) \tag{3}$$

The quantity of work processed during the pre-manufacturing throughput time can be approximated by a constant. Particularly when workload control is used, the rate at which work is processed remains fairly constant. The shop throughput will only be somewhat lower than normal during periods in which there is a lower utilization level.

The quantity of work which arrives during the pre-manufacturing throughput time often fluctuates to a much greater degree.

This factor therefore cannot be represented accurately by a constant. At the time of due date assignment it is not known how much work will arrive during the pre-manufacturing throughput time. Nevertheless, the fluctuations in the quantity of work which has not yet arrived will have some influence on the throughput time. This can be explained by the fact that future work may arrive which can be processed more rapidly in the pre-manufacturing phase than the current order for which a due date is being assigned. This means that in connection with the due date assignment for the current order in the component manufacturing phase, it is possible that a future order which has not yet arrived will nevertheless be ready for processing in the component manufacturing phase ahead of the current order. In this case the future order should also be released for processing in the component manufacturing phase before the current order. To account for this eventuality, a safety margin needs to be included in the assignment of the due date. The required value for this safety margin can be approximated as indicated in Equation (4).

σ := safety margin (time)

Q := average quantity of work arriving in each period

VAR(Q) := variance of Q

σ(Q) := distribution spread of Q

Q ≈ VRZ

It is assumed that Q corresponds to a Poisson distribution:

VAR(Q) ≈ Q ≈ VRZ

During period G_k the following excess quantity of work, on the average, will arrive with a reliability of 95%:

$$½ * (2 * \sigma(Q)) * G_k = \sigma(Q) * G_k$$

$$\sigma = (\sigma(Q) * G_k)/ VRZ = G_k/\sqrt{(VRZ)}$$

Therefore:

$$F(t) \approx \frac{RWL_s(t) + RWL_b(t) + RWL_p(t) - RWLN_s - RWLN_p}{VRZ} + \frac{G_k}{\sqrt{(VRZ)}} \qquad (4)$$

This means that both an internal and external due date must be determined in connection with the due date assignment. The difference between the internal and external due dates can be determined, on the one hand, using the safety margin (σ) as described above. On the other hand, this difference can also be calculated based upon the distribution spread in the assembly order lateness as typically found in the literature ([Bertrand, 1983, b]).

In principle, one can envisage two alternative approaches with respect to the pre-manufacturing phase. One approach is to allow the batches belonging to a given assembly order to have different throughput times in the pre-manufacturing phase. This situation could occur when only a limited resource capacity is available for processing a certain batch. In this case it may be desirable to carry out activities with respect to a given assembly order in the pre-manufacturing phase and in the component manufacturing phase simultaneously in order to reduce the total throughput time. The capacity within the assembly order which is released and becomes available in the pre-manufacturing phase in this way can then be used more effectively by the time-critical batches. The non-critical batches in this assembly order are then processed later. The other approach is to ensure that all of the batches belonging to a given assembly order have approximately the same throughput times. An assumption in this case is that there is sufficient resource capacity to process each type of batch. It is advisable to recalculate and fix the internal due date in this case when the assembly order arrives in the buffer. This effectively removes the uncertainties surrounding the length of the pre-manufacturing throughput time. The decision rules developed in this study can be used directly to fix the second internal due date since all of the uncertainties surrounding the product and the processing have been removed.

It is clear that not all of the product information and production information will be available when the assembly order is received and the due date is assigned. In practice this means that rough estimates of the most important structure characteristics of the orders will need to be made. It is sensible to make use of historical data in this situation to improve the reliability of these rough estimates. In this way experience can be used to determine the probable structure characteristics based upon relationships with other characteristics which can be forecasted with a higher degree of accuracy.

- *Disturbances in the pre-manufacturing phase*

No attention has been paid to possible disturbances which could occur in the pre-manufacturing phase in this section. Such disturbances could lead to delays in the arrival of work orders in the buffer, for example, so that the original schedule cannot be met. A high degree of due date reliability in the pre-manufacturing phase is important for the total performance of the whole system.

- *Size of the work order release buffer*

In the first place, the size of the buffer should be determined based upon the minimum quantity of work orders required to ensure a sufficient supply of work for the work order release function. Workload control will only be effective if a work order is always available for release whenever the workload situation dictates that a work order should be released. This means in practice that the composition of the order mix will be an important factor. In addition, the size of the buffer should be determined by the safety stock of work orders needed to absorb the effects of any disturbances which may occur in the pre-manufacturing phase.

Fluctuations in the arrival pattern of customer orders (read: assembly orders) do not need to be absorbed by the work order release buffer as in the case of the theoretical experiments performed in this study. These fluctuations can also be absorbed through the use of the available flexibility, specifically in the pre-manufacturing phase. For example, if the quantity of orders received is down, then the number of orders being dealt with in the pre-manufacturing phase can be reduced (i.e., the processing of orders can be accelerated) by increasing the number of parallel tasks. If the quantity of orders received is more than expected, then the number of orders in the pre-manufacturing phase can be increased to ensure that the flow of work orders to the subsequent manufacturing phase is kept constant. The disadvantages of increasing the buffer time through the use of workload control can be reduced in this way.

10.3.3 The consequences of rush orders

The consequences and implications of "rush orders" apply primarily to the actual manufacturing phase. A rush order needs to have a shorter shop throughput time and a shorter buffer time than the average assembly order.

- *Shorter shop throughput time*

A shorter shop throughput time can be realized by swapping allowance between the rush orders and all of the other work order belonging to other assembly orders. If an estimate of the volume of rush orders can be made, then this estimate can subsequently be used to determine the degree of allowance swapping.

- *Shorter buffer time*

A shorter buffer time can be realized by allocating a smaller buffer allowance. This also applies to specific categories of orders such as rush orders. A smaller average buffer allowance can be allocated to the rush orders, as compared to the average buffer allowance for all of the assembly orders taken together, by (artificially) increasing the RWL_b for the rush order category. In this way due date assignments for the "normal" assembly orders will already have accounted for the yet to arrive rush orders which will be released at a future point in time with a higher priority.

10.3.4 A more complicated planning and control situation

A number of assumptions have been made in order to develop meaningful research objective. The three most important assumptions are discussed here.

◆ *Homogeneous arrival process*

A truncated Poisson arrival process has been used as the basis for the theoretical experiments in this study. This type of arrival process is homogeneous in the sense that the average number of arrivals per period is constant. This is generally not true in practice. Fluctuations can be expected over a longer period of time. A certain amount of flexibility is needed within a shop (such as the CGM) in order to be able to absorb these fluctuations.

In this study, no attention has been paid to the possibility of taking certain measures to ensure that there will be an adequate amount of flexibility for production planning and control. This type of measure could be the provision of a specific source of flexibility in a resource capacity so that a bottleneck or problem in the production planning and control can be resolved. Possible sources of flexibility are, for example:

- outsourcing or, conversely, accepting work from third parties. Fluctuations in the capacity loading can often be (partially) absorbed in practice by outsourcing work to third parties when the internal resource capacities are overloaded. Work from third parties can be contracted in to fill under-utilized capacity when there is insufficient work in the shop;
- multi-skilled workers can be employed as opposed to workers with limited skills. When workers are trained to be able to carry out additional types of operations, more flexibility is created with respect to the possibilities for reassignment to perform different tasks as necessary;
- flexible labor contracts. Shops are increasingly making use of pools of qualified workers who can be called in on short notice as needed. Pool workers are generally not full-time employees.

By establishing sources of flexibility in this way, a business is in a better position to deal with uncertainties with respect to, for example, the market demand. Taking measures to utilize flexibility is therefore also a production planning and control issue. Decisions concerning measures to utilize flexibility need to be taken together with the four core decisions. The objective of the second core decision area with respect to "assembly order allocation and outsourcing", in particular, is to ensure the timely deployment of the most appropriate flexibility measures. Workload control, for example, can be seen as a powerful technique for use in deciding which measures are most appropriate for utilizing the flexibility. It is probably true in most practical situations that the short term fluctuations in resource capacity loading can be identified more quickly by using workload control as opposed to not using workload control.

The conclusions from this study may no longer be valid when measures to utilize flexibility and additional sources of flexibility are introduced. Additional research in these areas would be welcome.

◆ *Planning and control of the materials flow*

The materials flow aspects have not been included in the study here. It is assumed that the materials flow issues are of secondary importance in comparison with the problems of planning and controlling resource capacity utilization and throughput times in tool & die shops.

The importance of planning and control of materials flow is evident in practical situations. (There are, of course, also other areas of concern with respect to, for example, the available machinery and the production documentation.) It should be considered that a work order can never be released before the required materials have been made available. This means that a special check to ensure that all materials are available needs to be performed in practice as part of the work order release procedure, prior to the work order release evaluation step.

The due date assignment is another example. The lead times for the delivery of critical materials need to be taken into account when scheduling due dates in practice.

The findings and conclusions in this study are not affected by the materials management issues. Nevertheless, production planning and control becomes much more complicated in real-life situations because the materials flow issues also need to be addressed.

◆ *Assembly with multiple convergent nodes*

This study has been limited to the component manufacturing process. Tool & die shops often perform a limited number of minor assembly operations which are typically included as part of the total component manufacturing activity. Tool & die shops should be seen as a special type of equipment manufacturing plant, however. Many of the characteristics of component manufacturing in a tool & die shop are similar to the characteristics of component manufacturing in an equipment manufacturing plant. The major difference lies in the fact that equipment manufacturing plants often have a major, separate assembly activity which is often realized in the form of separate, multiple assembly units.

"Equipment" assembly-orders typically have many more convergent nodes in their network structure as compared to "component manufacturing" orders. The method developed in this study for estimating structure delay time can be used at any convergent node. In addition, the acceleration/retardation technique can be used to swap allowance between the parallel paths in such a network. The use of dynamic due date assignment for the "equipment" assembly-orders can also lead to a significant improvement in the due date reliability. With respect to determining the priorities for releasing work orders, it is important to account for the fact that not releasing certain work orders could result in delays in processing other work orders which have already been released for processing. This situation can occur at convergent nodes. At the same time, releasing other work orders may have no direct effect on the progress of work orders which have already been released for processing in the shop. This means that whenever one or more work orders are released which converge at a subsequent node, then all of the work orders which converge at that node should be released with sufficient lead time. Additional research is required to determine exactly how much lead time is "sufficient" in this case.

10.4 Practical rules-of-thumb

The following rules-of-thumb have been formulated for use in practical situations:

1. The control over all of the different streams of orders can be improved by using a time-based approach. The OSD's should be planned as realistically as possible. In this way the OSD's can be used as realistic targets while the work orders are being processed. With this approach, a release date can be scheduled for each work order. It is then important to ensure that, on the average, the work orders are actually released on their respectively scheduled release dates.

   Planning and control rules based upon a *time-based approach* show the best performance for all of the different categories of order streams, taken together. In order to be able to use a time-based approach on the shop floor, a time-based approach must be followed for scheduling the work.

2. The assembly order throughput time can be reduced in a controlled manner by using the acceleration/retardation technique. The operations associated with work orders are paced differently with respect to each other within the total work flow of the shop when the allowance is swapped between the work orders belonging to a given assembly order. When a relatively higher work tempo is assigned to the largest work order in the shop, the assembly order throughput time can be reduced. The amount of reduction can be calculated at the time of due date assignment, provided that the average allowance per operation remains unchanged. In practice, this is referred to as the *work pace management* of orders.

3. A shop which processes assembly orders should not be held accountable for the due date reliability with respect to the scheduled internal due date for the work orders belonging to a given assembly order. Accountability should be based, instead, on the due date reliability with respect to the expected assembly order completion date. The production schedule should allow for completion disturbance by taking the structure delay time into account when the *expected completion date* for an assembly order is determined.

4. *Performance measurement per category* is better than an integral performance measurement. The usefulness of a specific planning and control decision rule should be determined based upon the performance per order (assembly order) category as well as the total performance for all orders.

5. In practical situations where geometrical assembly order structures are encountered, the shortest average assembly order throughput time can be achieved by using the acceleration/retardation technique, without restriction, between the work orders belonging to a given assembly order. This can be referred to as a *batch-oriented approach*.

6. With this batch-oriented approach, the most reliable due dates can be realized using asymmetrical dynamic due date assignment. This implies that orders must be released on the scheduled release date. Workload control in conjunction with releasing orders is not necessary in this case because sufficient *implicit workload control* is present in connection with the due date assignment.

7. When the acceleration/retardation technique cannot be used, then the shortest average assembly order throughput times and the most reliable due dates can be determined by using asymmetrical dynamic due date assignment in conjunction with workload control for releasing work orders. Both *implicit and explicit workload control* should be used in this case.

Chapter

11 CONCLUSIONS

11.1 Introduction

The most important conclusions from this study are summarized in this chapter. This study was carried out to investigate issues concerning the planning and control of the production of assembly orders in component manufacturing units of tool & die shops. The following points are reviewed:

- deficiencies of the traditional approach;
- development of a new set of planning and control decision rules;
- evaluation of the effectiveness of different planning and control techniques in different situations.

In conclusion, an evaluation is made with respect to the extent to which the research objective of this study have been achieved.

11.2 Deficiencies of the traditional approach

The traditional approach typically described in the literature has three deficiencies:

- when an assembly order arrives in a shop, the entire assembly order is released as a whole. This results in what could be called an "implicit" swapping of allowance, leading to a situation in which the throughput time for the small assembly orders is less than the average throughput time, but at the expense of the large assembly orders;
- when scheduling the production of an assembly order, no distinction is made between waiting time allowance and structure allowance. As a result, the completion disturbance within assembly orders is ignored, leading to a partially avoidable variance in the tardiness of assembly orders;
- the performance of various categories of assembly orders is not considered in the

evaluations of the effectiveness of planning and control decision rules. The performance of the category of large assembly orders, in particular, is often more important in practice than the average performance for all of the assembly orders taken together.

11.3 A new set of planning and control decision rules

The OSD rule has been chosen as the basic priority rule for use in this study. Based upon this approach, the following decision rules were developed:

- a dynamic due date assignment rule in which the individual characteristics of an assembly order are taken into account;
- an order releasing rule for use in situations in which there is no question of product uncertainty when the order is received;
- an order releasing rule based on workload control for use in situations in which product uncertainty exists;
- a priority rule for releasing orders when workload control is used.

The due date assignment rule used in a situation involving product uncertainty can be seen as a simplified version of the due date assignment rule designed for use in situations in which there is no question of product uncertainty.

The following conclusions can be made based on analyses of the effectiveness of these planning and control decision rules.

♦ *Accurate and practical scheduling*

It appears that the best performance can be attained through deterministic scheduling of the assembly orders, as accurately as possible, in advance. This means that the expected assembly order completion date, the work order completion dates, the work order release dates and the operation plan dates all need to be scheduled. In addition, this schedule must be made as practical as possible. Having a practical schedule implies that the expected dates will actually be realized within narrow margins of error. The practicality of a schedule can be enhanced through the use of an asymmetrical dynamic due date assignment rule to improve the due date reliability (see Chapter 8) as well as by recognizing the structure delay time (see Chapter 6). In connection with this the allowance for waiting time should be chosen in such a manner as to ensure that the average work order lateness is close to zero (see Chapter 3).

◆ *Schedule realization*

The planning and control activity should focus on ensuring that the established schedule is actually realized. The plan dates are used to determine the sequencing of operations at the work stations. The scheduled release dates are used in conjunction with releasing the work orders.

◆ *Utilizing the assembly order structure characteristics*

The shortest possible average throughput times for all categories of assembly orders with geometrical structures can be achieved by using the acceleration/retardation technique when scheduling the assembly orders. The best throughput time and due date reliability performance can be realized by releasing the work orders according to schedule on the planned release dates and by using the plan dates to determine the processing priorities at each work station.

11.4 Evaluation of different planning and control techniques

Use of the acceleration/retardation technique assumes that the whole order structure of an assembly order is known at the time of order receipt and the whole assembly order is available for immediate processing in the shop. These conditions cannot always be satisfied in practice. This means that the acceleration/retardation technique often cannot be (fully) utilized in practical situations. In this case it is clear that using an asymmetrical dynamic due date assignment rule can produce extremely adverse side-effects in connection with a geometrical assembly order structure. These negative effects can be avoided completely by using workload control in connection with releasing the work orders. It is not advisable to schedule the release of work orders as soon as possible in this situation. The inherent latitude incorporated in the order structures must be utilized to reduce the workload fluctuations in this case. The work orders, particularly the subsequent work orders, need to be released earlier whenever possible. As a result, it is necessary to release work orders individually rather than releasing assembly orders as a whole.

If the acceleration/retardation technique can be fully applied in a given situation, then the use of workload control in conjunction with releasing work orders provides no added value. It should also be noted that the use of workload control in this case similarly does not cause a deterioration in performance.

11.5 Research objective

A brief recap of the research issues from Chapter 3 is presented here:

- The first research issue was to determine whether Van Ooijen's approach of using different flow rates can lead to shorter throughput times for assembly orders. This research objective had three parts:
  - determining how Van Ooijen's approach should be utilized;
  - determining the expected reduction in throughput time for assembly orders;
  - determining the effects on the performance of assembly orders, given the effects on the performance of the associated work orders.

- The second research issue was to develop a due date assignment rule to provide a minimum throughput time in conjunction with reliable due dates for assembly orders.

- The third research issue was to determine in which situations orders should be released at the work order level versus the assembly order level and how the release of work orders should be sequenced.

- The fourth research issue was to determine to what extent the principles of workload control are applicable and can improve the performance in a component manufacturing unit environment in which assembly order structures are used.

The first research issue is discussed at length in Chapter 5. In Chapter 7, the resulting performance is compared with the performance when using the traditional approach. It is clearly advisable to make use of the acceleration/retardation technique within assembly orders. No further restrictions are required. The second research issue is covered in Chapter 6 and Chapter 8. Chapter 6 deals with the structure delay time while Chapter 8 evaluates the dynamic due date assignment rule for assembly orders. The performance effects of using structure delay time are compared to the results of the traditional approach in Chapter 7. The third research issue is dealt with in Chapter 7 and in Chapter 9. The findings presented in Chapter 8 support the hypothesis that order release also should be used in situations with assembly orders. If the acceleration/retardation technique can be used, then it is advisable to release work orders according to schedule on the planned release dates. If this is not possible, however, then workload control should be used in conjunction with releasing the work orders at the work order level. In this case, the scheduled release date becomes the first priority criterion for determining the sequence for releasing work orders. The considerations in this regard are discussed in Chapter 9. The fourth research issue is also covered in Chapter 9. It is clear that workload control is not useful in every situation. However, in practice, workload control is usually required in situations with geometrical assembly order structures because the order structure is not fully known at the time of due date assignment. In addition, it often occurs that all of the work orders belonging to a given assembly order are not available for release at the same time. An overview of the developed and investigated production planning & control framework for a Tool & Die Shop is given in Figure 11.1.

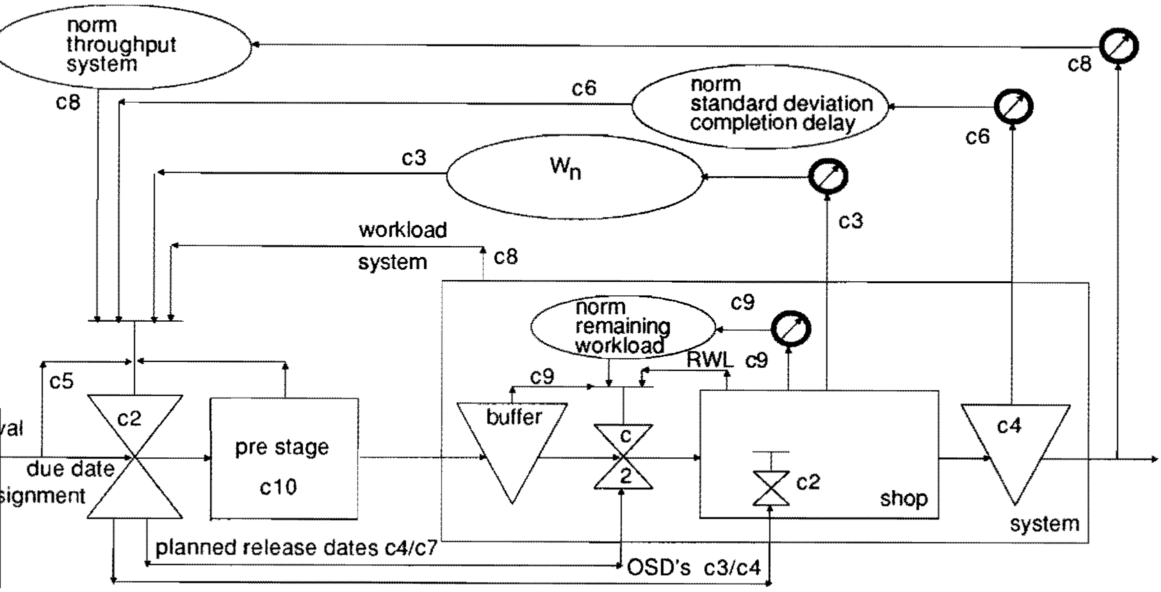


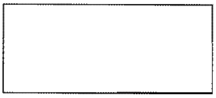
Figure 11.1:
An overview of the developed and investigated production planning & control framework for a Tool & Die Shop. (In the figure is indicated in which chapter a subject is treated.)

In view of the above, all of the research issues of this study have been fully met. The simulation studies have been based on the specific case of a geometrical order structure and a specific shop structure to ensure that clear results would be obtained. Further research is required to determine to what extent the conclusions presented here are valid under different circumstances and in different settings. It is recommended that similar studies be carried out to extend the applicability of the planning and control decision rules and conclusions presented here.

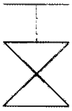
Appendix
A DRAWING CONVENTIONS

: an operation with its processing time and with the preceding waiting time

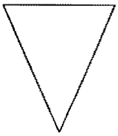
: date



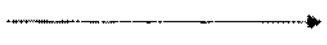
: manufacturing unit (shop)



: planning and control decision



: inventory of orders



: flow of orders or of (control) information

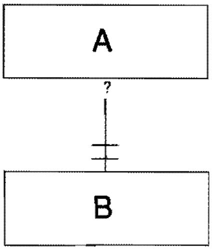
: measurement of a parameter

: determination of a norm

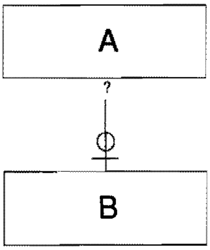
Appendix

B NOTATION CONVENTIONS FOR ENTITY MODELS

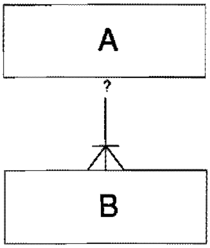
Four different relation types are defined:



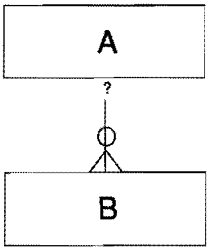
relation type I
"precisely one"



relation type II
"none or one"



relation type III
"one or more"



relation type IV
"none or more"

- Relation type I:
  for each entity a of type A exists precisely one entity b of type B.
- Relation type II:
  for each entity a of type A exists none or one entity b of type B.
- Relation type III:
  for each entity a of type A exists one or more entities b of type B.
- Relation type IV:
  for each entity a of type A exists none or more entities b of type B.

There exists per definition a reverse relation between entity b of type B and entity a of type A when a relation is described between entity a of type A and entity b of type B.

Appendix

C RESULTS OF SIMULATION RUNS

Results of runs of the next experiments are tabulated:

Experiment:	Page:
th59gr1z	226
thgrwb1z	227
th59gr5z	228
th59gr57	229
th59gr1z (large assembly orders)	230
thgrwb1z (large assembly orders)	231
th59gr5z (large assembly orders)	232
th59gr57 (large assembly orders)	233
h590001	234
h590093	236
h59c15c	238
h59dc09	240
h59dc08	242
h59mc08	244
h59c12c	246
h59c14c	248
totals6	250
totals1	252

Table 7.1.a The main results of all assembly orders from the reference simulation experiment (th59gr1z).

run	1	2	3	4	5	average
average throughput time assembly orders	49.4	47.7	49.2	47.5	48.5	48.5
variance throughput time	2180	2058	2131	2051	2101	2104
average planned throughput time assembly orders	61.5	61.3	61.3	61.4	61.4	61.4
average lateness assembly order	-12.1	-13.6	-12.2	-13.9	-12.9	-12.9
variance lateness assembly orders	500	371	407	377	422	415
average tardiness assembly orders	4.2	2.7	3.4	2.7	3.4	3.3
variance tardiness assembly orders	137	71	100	72	99	96
average waiting time	8.4	8.0	8.2	7.9	8.1	8.1
variance waiting time	244	223	235	222	231	270
average throughput time work orders	46.3	44.4	45.4	44	44.8	45
variance throughput time work orders	1966	1827	1867	1807	1855	1864
average lateness work orders	-28.9	-30.7	-29.5	-31.2	-30.2	-29.9
variance lateness work orders	1209	1094	1124	1103	1137	1133
average completion time work orders	17.7	18	18.4	18.1	18.2	18.1
variance completion time work orders	772	787	827	803	806	799
structure delay time	10.8	10.9	11.2	11	11.1	11

Table 7.1.b The main results of all assembly orders from the simulation experiment using generic allowance swapping (thgrwb1z).

run	1	2	3	4	5	average
average throughput time assembly orders	48.9	47.2	48.7	47	47.9	47.9
variance throughput time	1593	1463	1531	1463	1519	1514
average planned throughput time assembly orders	45.9	45.8	45.8	45.9	45.9	45.9
average lateness assembly order	3	1.4	2.8	1.1	2.1	2.1
variance lateness assembly orders	475	343	391	348	402	392
average tardiness assembly orders	9.3	7.5	8.6	7.4	8.3	8.2
variance tardiness assembly orders	283	181	229	182	229	221
average waiting time	8.2	7.9	8.1	7.8	8	8
variance waiting time	210	188	201	187	197	197
average throughput time work orders	45.6	43.8	44.8	43.4	44.2	44.4
variance throughput time work orders	1458	1327	1370	1319	1366	1368
average lateness work orders	-10.6	-12.3	-11.2	-12.8	-11.8	-11.7
variance lateness work orders	891	773	815	782	824	817
average completion time work orders	15.6	15.8	16.2	15.9	16.1	15.9
variance completion time work orders	501	564	599	577	585	565
structure delay time	9.7	9.8	10.1	9.9	10	9.9

Table 7.1.c The main results of all assembly orders from the simulation experiment with allowance swapping between work orders belonging to a single assembly order (th59gr5z).

run	1	2	3	4	5	average
average throughput time assembly orders	52.9	51.2	52.6	50.8	52.1	51.9
variance throughput time	1352	1211	1269	1204	1282	1264
average planned throughput time assembly orders	42.1	42.1	44.3	42.8	42.2	42.7
average lateness assembly order	10.8	9.2	10.6	8.9	9.9	9.9
variance lateness assembly orders	554	413	460	413	479	464
average tardiness assembly orders	14.4	12.7	13.8	12.3	13.4	13.3
variance tardiness assembly orders	403	282	333	278	343	328
average waiting time	8.1	7.8	8	7.7	7.9	7.9
variance waiting time	181	157	169	155	168	166
average throughput time work orders	45.0	43.3	44.3	42.8	43.8	43.8
variance throughput time work orders	1104	978	1018	970	1029	1020
average lateness work orders	1.2	-0.4	0.6	-1	0.1	0.1
variance lateness work orders	655	531	568	530	582	573
average completion time work orders	13.2	13.2	13.7	13.3	13.6	13.4
variance completion time work orders	351	341	373	346	370	356
structure delay time	8.7	8.7	9.0	8.7	8.9	8.8

Table 7.1.d The main results of all assembly orders from the simulation experiment with allowance swapping and structure allowance (th59gr57).

run	1	2	3	4	5	average
average throughput time assembly orders	52.9	51.2	52.6	50.8	52.1	51.9
variance throughput time	1352	1211	1269	1204	1282	1264
average planned throughput time assembly orders	48.9	48.8	48.8	48.8	48.9	48.8
average lateness assembly order	4.0	2.4	3.8	2	3.1	3.1
variance lateness assembly orders	523	382	426	382	445	432
average tardiness assembly orders	10.4	8.6	9.6	8.3	9.3	9.2
variance tardiness assembly orders	313	203	249	120	257	228
average waiting time	8.1	7.8	8	7.7	7.9	7.9
variance waiting time	181	157	169	155	168	166
average throughput time work orders	45.0	43.3	44.3	42.8	43.8	43.8
variance throughput time work orders	1104	978	1018	970	1029	1020
average lateness work orders	1.2	-0.4	0.6	-1	0.1	0.1
variance lateness work orders	655	531	568	530	582	573
average completion time work orders	13.2	13.2	13.7	13.3	13.6	13.4
variance completion time work orders	351	341	374	346	370	356
structure delay time	8.7	8.7	9.0	8.7	8.9	8.8
structure allowance	6.7	6.7	6.7	6.7	6.7	6.7

Table 7.2.a The main results of the large assembly orders from the reference simulation experiment (th59gr1z).

run	1	2	3	4	5	average
average throughput time assembly orders	101.1	101.3	101.8	100.2	100.1	100.9
variance throughput time	2440	2373	2356	2246	2335	2350
average planned throughput time assembly orders	107.0	108.8	107.4	107.7	107.3	107.6
average lateness assembly order	-5.9	-7.5	-5.6	-7.4	-7.2	-6.7
variance lateness assembly orders	707	551	599	550	590	599
average tardiness assembly orders	7.7	5.7	6.8	5.9	6.2	6.5
variance tardiness assembly orders	241	157	203	158	184	189
structure delay time	33.9	35.8	35.7	35.9	35.3	35.3
variance completion time work orders	1310	1369	1368	1369	1366	1356

Table 7.2.b The main results of the large assembly orders from the simulation experiment using generic allowance swapping (thgrwb1z).

run	1	2	3	4	5	average
average throughput time assembly orders	90.9	90.8	91.6	90.2	90.3	90.8
variance throughput time	1623	1531	1542	1473	1546	1543
average planned throughput time assembly orders	79.9	81.3	80.2	80.5	80.2	80.4
average lateness assembly order	11	9.5	11.4	9.7	10.1	10.3
variance lateness assembly orders	615	468	533	468	514	520
average tardiness assembly orders	15.2	13.4	15	13.6	14	14.2
variance tardiness assembly orders	426	302	367	306	350	350
structure delay time	28.6	29.8	30.2	30.1	29.7	29.7
variance completion time work orders	925	942	974	951	970	952

Table 7.2.c The main results of the large assembly orders from the simulation experiment with allowance swapping between work orders belonging to a single assembly order (th59gr5z).

run	1	2	3	4	5	average
average throughput time assembly orders	70	68.4	69.9	68.2	69.2	69.1
variance throughput time	844	691	736	665	737	735
average planned throughput time assembly orders	47.7	48.1	47.6	47.7	47.9	47.8
average lateness assembly order	22.2	20.3	22.3	20.5	21.3	21.3
variance lateness assembly orders	616	458	513	446	527	512
average tardiness assembly orders	23.4	21.4	23.2	21.4	22.2	22.3
variance tardiness assembly orders	553	403	465	398	478	459
structure delay time	21.1	21.1	22.0	21.6	22.0	21.6
variance completion time work orders	453	422	479	449	463	453

Table 7.2.d The main results of large assembly orders from the simulation experiment with allowance swapping and structure allowance (th59gr57).

run	1	2	3	4	5	average
average throughput time assembly orders	70	68.4	69.9	68.2	69.2	69.1
variance throughput time	844	691	736	665	737	735
average planned throughput time assembly orders	65.2	65.6	65.0	65.2	65.3	65.3
average lateness assembly order	4.8	2.9	4.9	3.1	3.9	3.9
variance lateness assembly orders	616	458	513	446	527	512
average tardiness assembly orders	11.8	9.6	11.0	9.5	10.5	10.5
variance tardiness assembly orders	365	244	302	246	308	293
structure delay time	21.1	21.1	22.0	21.6	22.0	21.6
variance completion time work orders	453	422	479	449	463	453
structure allowance	17.4	17.4	17.4	17.4	17.4	17.4

Experiment: h590001						
run	1	2	3	4	5	average
average throughput time assembly orders	67.0	65.2	69.1	69.4	69.3	68
variance throughput time	2540	2375	2451	2490	2659	2503
average shop throughput time assembly orders	67.0	65.2	69.1	69.4	69.3	68
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness assembly order	-1.4	-3	0.8	0.7	1.4	-0.3
variance lateness assembly orders	421	272	304	321	492	362
average tardiness assembly orders	6.7	5.2	7.3	7.4	8.6	7.0
variance tardiness assembly orders	232	108	148	147	292	185
average waiting time	7	6.7	7.3	7.3	7.4	7.1
variance waiting time	107.1	86.4	104.6	105.1	125.8	105.8
average structure time	5.6	5.4	5.9	6.1	6.3	5.9
variance structure time	45	43	49	52	72	52
average lateness work orders	0.1	-1.5	1.8	1.7	2.2	0.9
variance lateness work orders	405	266	292	321	432	343
average remaining workload in the shop	540	515	564	561	568	550
average workload in the buffer	296	302	291	299	294	296
norm workload	-	-	-	-	-	-

Experiment: h590001, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	122.0	116.3	127.8	126.4	131.0	124.7
variance throughput time	2335	1693	2328	2280	2758	2279
average shop throughput time large assembly orders	122.0	116.3	127.8	126.4	131.0	124.7
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness large assembly order	-1.9	-4.8	0.3	2.2	5.1	0.2
variance lateness large assembly orders	514	264	320	422	675	439
average tardiness large assembly orders	7.7	4.5	7.5	9.2	12.1	8.2
variance tardiness large assembly orders	274	92	142	220	432	232
average structure time	13.4	13.5	14.9	16	16.0	14.8

Experiment: h590093						
run	1	2	3	4	5	average
average throughput time assembly orders	50.7	49.9	53.3	52.6	53.9	52.1
variance throughput time	1284	1100	1188	1147	1415	1227
average shop throughput time assembly orders	50.7	49.9	53.3	52.6	53.9	52.1
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness assembly order	1.7	1	4.5	3.6	5.2	3.2
variance lateness assembly orders	465	301	356	326	556	401
average tardiness assembly orders	8.4	7.1	9.7	9	10.9	9.0
variance tardiness assembly orders	270	142	198	158	359	225
average waiting time	7.2	7.0	7.6	7.5	7.7	7.4
variance waiting time	136	116	140	133	163	138
average structure time	7.2	7.4	8	7.7	8.3	7.7
variance structure time	80	78	89	83	122	90
average lateness work orders	0.9	0.0	2.9	2.5	3.5	2
variance lateness work orders	510	375	434	410	564	459
average remaining workload in the shop	475	457	500	492	507	486
average workload in the buffer	33	34	33	34	33	33
norm workload	540	540	540	540	540	540

Experiment: h590093, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	68.8	65.2	70.7	71	76.4	69.8
variance throughput time	834	502	612	560	1006	703
average shop throughput time large assembly orders	68.8	65.2	70.7	71	76.4	69.8
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness large assembly order	3.2	0.8	5	5.6	10.1	4.9
variance lateness large assembly orders	606	323	406	355	728	484
average tardiness large assembly orders	10.7	7.4	10.9	10.4	15.3	10.9
variance tardiness large assembly orders	360	142	209	189	507	281
average structure time	17.4	17.4	19.9	18.5	20.1	18.7

Experiment: h59c15c						
run	1	2	3	4	5	average
average throughput time assembly orders	49.4	48.2	52.1	50.7	52.6	50.6
variance throughput time	1396	1114	1240	1171	1497	1284
average shop throughput time assembly orders	49.4	48.2	52.1	50.7	52.6	50.6
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness assembly order	4.4	4.5	5.8	5.1	6.3	5.2
variance lateness assembly orders	145	114	144	129	230	152
average tardiness assembly orders	6.7	6.5	7.8	7.1	8.5	7.3
variance tardiness assembly orders	97	73	96	81	170	103
average waiting time	7.5	7.3	7.9	7.7	8.1	7.7
variance waiting time	157	131	160	147	185	156
average structure time	7.7	7.8	8.5	8.2	8.9	8.2
variance structure time	96	92	109	100	144	108
average lateness work orders	2.5	2.4	3.1	2.7	3.2	2.8
variance lateness work orders	295	275	320	300	371	312
average remaining workload in the shop	482	466	505	491	510	491
average workload in the buffer	-	-	-	-	-	-
norm workload	540	540	540	540	540	540
average buffer allowance	-4	-5.1	-2.5	-3.4	-2.2	-3.4

Experiment: h59c15c, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	65.9	61.2	67.4	67.5	74.4	67.3
variance throughput time	1057	545	736	631	1269	848
average shop throughput time large assembly orders	65.9	61.2	67.4	67.5	74.4	67.3
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness large assembly order	3.2	2.9	4.8	4.7	8.4	4.8
variance lateness large assembly orders	192	103	145	148	311	180
average tardiness large assembly orders	6.6	5.3	7.2	7.0	10.8	7.4
variance tardiness large assembly orders	131	63	95	100	245	127
average buffer allowance	-3	-6.0	-2.9	-2.7	-0.3	-3
average structure time	19.1	18.3	21.1	20.5	21.9	20.2

Experiment: h59dc09						
run	1	2	3	4	5	average
average throughput time assembly orders	54.0	55.4	58.3	58.4	63.8	58
variance throughput time	1439	1398	1313	1301	1860	1462
average shop throughput time assembly orders	45.5	46.5	48.4	48.4	48.0	47.4
average buffer time	8.6	9.0	9.9	10.0	16.2	10.7
variance buffer time	286	251	189	162	507	279
average lateness assembly order	3.2	4.1	4.8	4.6	4.8	4.3
variance lateness assembly orders	87	92	97	100	108	97
average tardiness assembly orders	5.3	5.9	6.6	6.4	6.7	6.2
variance tardiness assembly orders	49	57	62	62	68	60
average waiting time	6.5	6.6	6.9	6.9	6.9	6.8
variance waiting time	89	95	103	102	104	99
average structure time	6.9	7.3	7.6	7.4	7.3	7.3
variance structure time	68	73	77	76	74	74
average lateness work orders	2.3	2.7	3.3	3.2	3.6	3.0
variance lateness work orders	203	218	226	223	226	219
average remaining workload in the shop	435	441	461	459	461	451
average workload in the buffer	120	188	136	169	269	176
norm workload	540	540	540	540	540	540
average buffer allowance	1.9	2.6	4.7	4.9	10.6	4.9

Experiment: h59dc09, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	68.0	68.1	73.3	74.1	83.9	73.5
variance throughput time	1002	828	792	756	1575	991
average shop throughput time large assembly orders	58.7	59.7	63.6	64.4	65.6	62.4
average buffer time	9.4	8.5	9.7	9.8	18.3	11.1
variance buffer time	303	261	170	149	571	291
average lateness large assembly order	0.0	2.1	3.3	3.8	4.2	2.7
variance lateness large assembly orders	76	71	81	118	109	91
average tardiness large assembly orders	3.4	4.4	5.3	6.1	6.6	5.2
variance tardiness large assembly orders	36	41	48	75	63	53
average buffer allowance	2.7	1.7	4.4	5.1	13.4	5.5
average structure time	15.8	16.9	19.0	18.5	18.0	17.6

Experiment: h59dc08						
run	1	2	3	4	5	average
average throughput time assembly orders	203.4	199.6	202.4	210.1	207.0	204.5
variance throughput time	3720	5412	3996	3709	4949	4357
average shop throughput time assembly orders	60.4	60.3	61.7	62.0	61.4	61.2
average buffer time	143.4	139.5	141.3	148.5	146.5	143.8
variance buffer time	1413	2889	1627	1347	2432	1942
average lateness assembly order	-8.0	-7.9	-6.6	-6.6	-6.6	-7.1
variance lateness assembly orders	68	83	88	89	92	84
average tardiness assembly orders	0.9	1.1	1.5	1.5	1.6	1.3
variance tardiness assembly orders	8	14	17	18	19	15
average waiting time	5.9	5.9	6.1	6.1	6.1	6.0
variance waiting time	53	57	62	61	61	59
average structure time	4.3	4.5	4.8	4.7	4.5	4.6
variance structure time	23	28	31	30	27	28
average lateness work orders	-5.5	-5.6	-4.5	-4.4	-4.3	-4.9
variance lateness work orders	78	89	96	97	101	92
average remaining workload in the shop	462	458	472	476	474	468
average workload in the buffer	2327	2460	1824	2190	2064	2173
norm workload	540	540	540	540	540	540
average buffer allowance	143.4	139.5	141.3	148.5	146.5	143.8

Experiment: h59dc08, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	250.5	249.4	257.3	262.7	260.7	256.1
variance throughput time	3750	4798	4176	3474	4716	4183
average shop throughput time large assembly orders	111.2	109.7	118.4	115.1	115.2	113.9
average buffer time	139.2	139.6	140.0	148.2	147.4	142.9
variance buffer time	1500	3059	1730	1515	2236	2008
average lateness large assembly order	-12.7	-11.7	-9.2	-8.6	-9.9	-10.4
variance lateness large assembly orders	49	66	83	101	74	75
average tardiness large assembly orders	0.2	0.5	1	1.4	0.7	0.8
variance tardiness large assembly orders	2	5	13	17	5	8
average buffer allowance	139.2	139.6	140.0	148.2	147.4	142.9
average structure time	10.6	11.2	12.6	12.5	11.6	11.7

Experiment: h59mc08						
run	1	2	3	4	5	average
average throughput time assembly orders	74.5	71.8	77.3	76.3	77.4	75.5
variance throughput time	2873	2597	2697	2724	2986	2775
average shop throughput time assembly orders	74.5	71.8	77.3	76.3	77.4	75.5
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness assembly order	-14.7	-15.5	-13.8	-14.5	-13.5	-14.4
variance lateness assembly orders	139	118	140	141	199	147
average tardiness assembly orders	0.9	0.6	1	0.9	1.7	1.0
variance tardiness assembly orders	18.7	10.5	14.7	13.8	43.0	20.1
average waiting time	6.9	6.6	7.3	7.1	7.4	7.1
variance waiting time	100	88	106	100	122	103
average structure time	5.7	5.6	6.1	6.0	6.3	5.9
variance structure time	42	41	49	48	62	48
average lateness work orders	-12.9	-13.5	-12.1	-12.7	-12	-12.6
variance lateness work orders	157	138	155	158	191	160
average remaining workload in the shop	501	479	526	511	527	509
average workload in the buffer	358	368	352	365	364	361
norm workload	540	540	540	540	540	540
average buffer allowance	20.9	19.3	23.1	22.2	23.3	21.8

Experiment: h59mc08, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	129.5	123.3	135.1	133.1	140.3	132.3
variance throughput time	2838	1862	2290	2370	3085	2489
average shop throughput time large assembly orders	129.5	123.3	135.1	133.1	140.3	132.3
average buffer time	-	-	-	-	-	-
variance buffer time	-	-	-	-	-	-
average lateness large assembly order	-16.1	-16.2	-14.4	-13.6	-11.6	-14.4
variance lateness large assembly orders	116	82	97	161	213	134
average tardiness large assembly orders	1.0	0.4	0.7	1.5	2.7	1.3
variance tardiness large assembly orders	20	6	11	45	55	27
average buffer allowance	22.1	18.4	22.9	22.9	26.0	22.5
average structure time	12.7	13.6	13.8	14.7	15.1	14

Experiment: h59c12c						
run	1	2	3	4	5	average
average throughput time assembly orders	53.9	55.5	58.8	60.2	71.5	60
variance throughput time	1458	1411	1317	1345	2315	1569
average shop throughput time assembly orders	45.4	46.1	48.1	48.3	47.1	47
average buffer time	8.6	9.6	10.8	12.1	24.9	13.2
variance buffer time	328	339	251	232	1151	460
average lateness assembly order	3.3	4.5	5.7	5.8	8.2	5.5
variance lateness assembly orders	88	117	120	128	176	126
average tardiness assembly orders	5.4	6.6	7.6	7.8	10.1	7.5
variance tardiness assembly orders	50	72	77	81	119	80
average waiting time	6.5	6.6	6.9	6.9	6.8	6.7
variance waiting time	92	96	104	105	102	100
average structure time	7.0	7.4	7.7	7.5	7.2	7.4
variance structure time	71	75	80	78	71	75
average lateness work orders	2.2	2.9	4	4.3	7	4.1
variance lateness work orders	214	256	260	261	302	259
average remaining workload in the shop	437	443	464	465	467	455
average workload in the buffer	105	193	137	194	396	205
norm workload	540	540	540	540	540	540
average buffer allowance	1.6	2.3	4.3	5.5	15	5.7

Experiment: h59c12c, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	67.6	69.0	74.3	76.2	89.9	75.4
variance throughput time	1013	891	772	794	1884	1071
average shop throughput time large assembly orders	58.6	59.4	63.8	64.1	63.9	62
average buffer time	9.0	9.6	10.5	12.2	26	13.5
variance buffer time	344	399	228	233	1185	478
average lateness large assembly order	0.1	2.9	4.4	5.1	7.4	4
variance lateness large assembly orders	79	112	109	153	172	125
average tardiness large assembly orders	3.5	5.7	6.7	7.7	9.8	6.7
variance tardiness large assembly orders	37	59	63	93	108	72
average buffer allowance	2.1	1.8	4.2	5.9	16.1	6.0
average structure time	15.9	17.2	19.4	18.7	17.4	17.7

Experiment: h59c14c						
run	1	2	3	4	5	average
average throughput time assembly orders	53.3	52.9	57.1	56.2	63.2	56.5
variance throughput time	1435	1276	1299	1257	1853	1424
average shop throughput time assembly orders	44.7	45.4	47.3	47.3	46.4	46.2
average buffer time	8.6	7.6	9.9	9.0	17.2	10.5
variance buffer time	328	202	216	156	613	303
average lateness assembly order	3.5	4.1	5	4.7	5	4.5
variance lateness assembly orders	90	90	97	102	103	96
average tardiness assembly orders	5.5	5.9	6.6	6.5	6.7	6.2
variance tardiness assembly orders	53	56	62	64	65	60
average waiting time	6.7	6.7	7.1	7.1	7.0	6.9
variance waiting time	101	105	114	116	113	110
average structure time	7.4	7.6	8.0	7.9	7.6	7.7
variance structure time	82	84	91	91	84	86
average lateness work orders	1.8	2.0	2.7	2.4	3.0	2.4
variance lateness work orders	239	251	266	271	259	257
average remaining workload in the shop	438	441	462	461	458	452
average workload in the buffer	90	140	118	126	259	147
norm workload	540	540	540	540	540	540
average buffer allowance	0.9	0	3.4	2.6	9.9	3.4

Experiment: h59c14c, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	67.1	65.7	71.9	71.8	82.9	71.9
variance throughput time	982	716	774	718	1530	944
average shop throughput time large assembly orders	57.8	58.6	62.3	62.9	63.6	61.1
average buffer time	9.3	7.1	9.6	8.9	19.2	10.8
variance buffer time	341	211	190	141	693	315
average lateness large assembly order	0.2	2.2	3.2	3.7	4.0	2.7
variance lateness large assembly orders	80	73	82	122	98	91
average tardiness large assembly orders	3.6	4.5	5.3	6.0	6.4	5.2
variance tardiness large assembly orders	39	40	47	78	53	51
average buffer allowance	1.4	-0.9	3	2.9	12.5	3.8
average structure time	17.0	18.0	20.2	19.9	19.4	18.9

Experiment: totalst6						
run	1	2	3	4	5	average
average throughput time assembly orders	69.2	70.1	70.3	77.0	88.4	75
variance throughput time	2535	2800	2362	2731	3733	2832
average shop throughput time assembly orders	59.1	59.1	61.5	61.6	61.1	60.5
average buffer time	10.1	11.6	8.9	15.6	27.8	14.8
variance buffer time	329	560	202	427	1314	566
average lateness assembly order	-14.3	-12.4	-13.3	-14.0	-13.5	-13.5
variance lateness assembly orders	143	144	146	147	136	143
average tardiness assembly orders	0.7	0.9	1	0.9	0.8	0.9
variance tardiness assembly orders	7	9	11	9	9	9
average waiting time	6.2	6.3	6.6	6.5	6.5	6.4
variance waiting time	58	61	69	66	64	64
average structure time	12.4	13.9	13.0	12	10.8	12.4
variance structure time	400	454	419	367	339	396
average lateness work orders	-26.2	-27.3	-25.6	-24.7	-22.5	-25.3
variance lateness work orders	892	1034	914	841	787	894
average remaining workload in the shop	484	486	506	502	501	496
average workload in the buffer	325	385	223	375	609	383
norm workload	540	540	540	540	540	540
average buffer allowance	15.2	15.2	15.6	22.6	34.6	20.6

Experiment: totalst6, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	115.3	116.1	123.8	129.8	142.7	125.5
variance throughput time	2634	2575	2251	2619	4080	2832
average shop throughput time large assembly orders	106.2	104.0	115.4	113.3	114.7	110.7
average buffer time	9.3	12.1	9.2	16.6	28.2	15.1
variance buffer time	335	653	199	483	1378	610
average lateness large assembly order	-22.8	-19.4	-18.4	-17.5	-18.5	-19.3
variance lateness large assembly orders	128	109	117	128	84	113
average tardiness large assembly orders	0.2	0.2	0.4	0.3	0.1	0.2
variance tardiness large assembly orders	2	1	3	3	0	2
average buffer allowance	14.4	14.4	15.8	23.9	35.5	20.8
average structure time	33.8	39.1	38.6	38.9	31.1	36.3

Experiment: totalst1						
run	1	2	3	4	5	average
average throughput time assembly orders	69.2	70.6	70.3	76.4	86.7	74.6
variance throughput time	2535	2800	2362	2709	3658	2813
average shop throughput time assembly orders	59.1	59.1	61.5	61.4	60.9	60.4
average buffer time	10.1	11.6	8.9	15.1	26.4	14.4
variance buffer time	329	560	202	408	1244	549
average lateness assembly order	-7.5	-6	-6.6	-7.3	-6.8	-6.8
variance lateness assembly orders	130	131	141	143	131	135
average tardiness assembly orders	1.7	2.2	2.2	2	1.9	2
variance tardiness assembly orders	16	20	24	21	19	20
average waiting time	6.2	6.3	6.6	6.5	6.5	6.4
variance waiting time	58	61	69	66	63	63
average structure time	12.4	13.9	13.0	12.0	10.9	12.4
variance structure time	400	454	419	371	342	397
average lateness work orders	-26.2	-27.3	-25.6	-24.9	-22.8	-25.4
variance lateness work orders	892	1034	914	851	794	897
average remaining workload in the shop	484	486	506	501	498	495
average workload in the buffer	325	384	223	370	589	378
norm workload	540	540	540	540	540	540
average buffer allowance	15.2	15.2	15.6	22	33	20.2

Experiment: totalst1, large assembly orders						
run	1	2	3	4	5	average
average throughput time large assembly orders	115.3	116.1	123.8	129.2	140.9	125.1
variance throughput time	2634	2575	2251	2607	3988	2811
average shop throughput time large assembly orders	106.2	104.0	115.4	113.2	114.2	110.6
average buffer time	9.3	12.1	9.2	16.1	26.8	14.7
variance buffer time	335	653	199	456	1304	589
average lateness large assembly order	-5.3	-1.9	-1	-0.0	-1.5	-1.9
variance lateness large assembly orders	128	109	117	160	87	120
average tardiness large assembly orders	2.2	3.2	3.7	4.6	3	3.3
variance tardiness large assembly orders	25	30	41	49	24	34
average buffer allowance	14.4	14.4	15.8	23	34.1	20.3
average structure time	33.8	39.1	38.6	39.1	31.0	36.3

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GLOSSARY OF SYMBOLS

A : allowance

$\underline{A}$: average allowance per operation

$A(o)$: allowance per operation in a work order with o operations after acceleration/retardation

A_o : estimated value for the average allowance factor per operation

$A(t)$: the planned allowance factor per operation at time t

b : buffer factor

$b_{k,j}$: buffer time of work order j in assembly order k

C_k : completion date of assembly order k

$c_{k,j}$: completion date of work order j of assembly order k

c : number of machines in the shop

D_k : due date of assembly order k and all associated work orders

$d_{k,j}$: due date of work order j of assembly order k

d_k : due date of all work orders of assembly order k when the due dates of the work orders from k are equal to each other

E_k : expected completion date for assembly order k

e_o : average remaining total processing time for a random work order in the shop

$f(o)$: fraction, the quotient of $A(o)$ and W_N, per operation in a work order with o operations

$f_{k,j}$: acceleration/retardation fraction

$F(t)$: correction factor for the integral throughput time at time t

$g_{k,j}$: shop throughput time for work order j in assembly order k

G_k : planned throughput time in the pre-manufacturing phase for assembly order k

$\underline{h}$: average throughput time for work orders

$h(o)$: throughput time of a work order with o operations

H_k : actual throughput time for assembly order k

$h_{k,j}$: actual throughput time for work order j of assembly order k

$\underline{H}$: average throughput time of assembly orders

i : index indicating operation (i) of the work order

j : index indicating work order (j) of the assembly order

J : index indicating the largest work order of an assembly order

k : index indicating assembly order (k)

$k_{k,j}$: completion delay of work order j in assembly order k

L : lower restriction acceleration/retardation fraction

L : index associated with the last work order of an assembly order

m_k : number of work orders in assembly order k

M_k : number of operations in the largest work order (as indicated by J) of assembly order k

n : total number of assembly orders

$o_{k,j}$: total number of operations in work order j of assembly order k

o : number of operations in a work order, $1 \le o \le 39$

$\underline{o}$: average number of operations per work order

$p_{k,j,i}$: processing time of operation i in work order j of assembly order k

$\underline{p}$: average processing time per operation

p_o : estimated value for the average processing time per

$p(o)$: probability of the occurrence of o operations within a work order

$Q(T)$: total work content of the assembly orders which arrived in period T

$Q'(T)$: incremental quantity of work in period T

$RWL(t)$: remaining workload at time t

$RWLN$: estimated value for the average remaining workload (the so-called normative remaining workload)

$RWL_s(t)$: remaining workload in the shop at time t

$RWL_b(t)$: remaining workload in the buffer at time t

$RWL_p(t)$: remaining workload expressed in actual manufacturing hours during the pre-manufacturing phase at time t

$RWLN_s$: remaining workload in the shop

$RWLN_p$: remaining workload in the pre-manufacturing phase

s_k : structure delay time of assembly order k

S_k : structure allowance of assembly order k

t_k : arrival time of assembly order k

U : upper limit restriction acceleration/retardation fraction

var(..) : variance of ..

VRZ : average shop throughput, i.e., the quantity of work processed, expressed in shop production hours

WIP : work in progress

W_n : normative waiting time

w_o : estimated value for the average waiting time

x_k : average completion date of the work orders belonging to assembly order k

$Y(t)$: total amount of work order allowance to be adjusted

$z(t)$: the buffer allowance

$\underline{\alpha}_{k,j}$: dependent disturbance

$\underline{\beta}_{k,j}$: independent disturbance

ρ_o : estimated value of the average level of utilization

ρ : correlation coefficient

$\rho(m_k)$: correlation coefficient for the assembly order category with m_k work orders per assembly order of max $(\underline{\beta}_{k,j})$ and $\underline{\beta}_{k,j}$

$\sigma(..)$: standard deviation of ..

$\underline{\Phi}_{k,j}$: random disturbance between completion and due date of work order j of assembly order k

INDEX

STELLINGEN

behorende bij het proefschrift

"Throughput Time Control and
Due Date Reliability in
Tool & Die Shops"

van

Ton van de Wakker

I

Bij het uitwisselen van wachttijd-toeslag tussen categorieën van werkorders kunnen de consequenties voor doorlooptijden en leverbetrouwbaarheid per categorie voorspeld worden, indien de gemiddelde toeslag een goede voorspelling is van de gemiddelde wachttijd.

Kleinrock, L. (1976), *Queueing Systems, Volume II: computer applications*, John Wiley & Sons, New York.

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Hoofdstuk 5 van dit proefschrift.

II

Het werken met een OSD (Operation Start Date) of ODD (Operation Due Date) prioriteitsregel heeft tot gevolg dat bij opvolgende bewerkingen een slechte lateness performance bij een voorafgaande bewerking ten dele geneutraliseerd wordt. Op basis hiervan vermoeden wij dat er geen verband waarneembaar is tussen het aantal bewerkingen van een werkorder (de werkorder lengte) en de structuurtijd.

Hoofdstuk 6 van dit proefschrift.

III

Wanneer in een produktiesysteem het aantal bewerkingen per werkorder en het aantal werkorders per assemblage-order fluctueert, dan is het onvoldoende voor de beoordeling van de praktische toepasbaarheid om de effecten van besturingsregels alleen te evalueren aan de hand van de gemeten performance over alle orders.

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Hoofdstuk 7 van dit proefschrift.

IV

Aangezien in de praktijk van gereedschapmakerijen op de één of andere wijze meestal sprake is van asymmetrische dynamische levertijdafgifte en de methode versnellen/vertragen niet volledig toegepast kan worden, is het verstandig om bij de ordervrijgave altijd de methode Beheersing Werklast toe te passen.

Hoofdstuk 9 en 10 van dit proefschrift.

V

Het in dit proefschrift beschreven mechanisme van ordervrijgave op basis van geplande vrijgave data doet zich in MRP-omgevingen vaak voor in de vorm van het op een bepaalde datum gepland beschikbaar hebben van uitgangsmateriaal voor verdere bewerking.

VI

Structuurtijd is een doorlooptijdcomponent die kan optreden bij convergente knooppunten in stuklijststructuren en die in de MRP-literatuur over het hoofd gezien is.

VII

Standaardisatie en normalisatie van standaard produktie besturingssoftware zal in de toekomst automatiseringskosten van vele produktie bedrijven aanzienlijk kunnen verlagen.

VIII

De intuïtie van een "oude rot" in een bedrijf leidt vaak sneller tot vaak betere probleemoplossingen dan de originaliteit van een nieuweling. De originaliteit van een nieuweling kan derhalve beter gebruikt worden om het potentieel aanwezige probleemoplossende vermogen in een bedrijf te activeren dan om die originaliteit te gebruiken om een probleemoplossing te genereren.

IX

File-rijden is een vorm van maatschappelijke kapitaalvernietiging met nadelige milieuconsequenties. Een gestage groei van het file-probleem, zoals die momenteel waarneembaar is, is daarom maatschappelijk gezien ontoelaatbaar. Deze gestage groei wordt hoofdzakelijk bepaald door een gestage groei van het verkeersaanbod. Omdat files in de ochtendspits en in de avondspits doorgaans op dezelfde wegen staan, maar tegengesteld aan elkaar, zou onderzocht moeten worden of er flexibel met het capaciteitsaanbod omgegaan kan worden door afhankelijk van het verkeersaanbod in de loop van iedere dag de rijrichting op enkele rijbanen van de betrokken wegen om te keren.

X

Bedrijven die in vergelijking met concurrenten op logistiek gebied beter presteren, hebben vaak een gedetailleerder en beter inzicht in de mogelijkheden en onmogelijkheden van de eigen operationele processen.

XI

Het beheersen van de werklast van een promovendus in de produktiebesturing is onbegonnen werk.

Eindhoven, 26 maart 1993.