

# **Improving Supply Chain Delivery Reliability**

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## Abstract

In today's global market environment customer expectations are no longer satisfied merely by the results of individual organizations competing, but by the outcomes of competing supply chains. In this respect for supply chains to remain competitive efficient flow of both order information and materials is essential. However, it is increasingly being recognized that along multi-tier supply chains demand amplifications arise. The primary causes of this demand amplification are the use of traditional period planning policies, the sequential nature of demand communications and the time delays within communication processes.

This work examines the potential effectiveness of traditional planning methods in enabling demand amplifications to be resolved. Here techniques such as Material Requirements Planning (MRP) and Finite Capacity Scheduling (FCS) are examined along with "pull" systems. The use of APS systems is identified within this research as a potentially suitable methodology since their memory-resident database technology enables simultaneous replanning of material and production capacity quickly.

The current work proposes a novel process for order planning within supply chain networks which when integrated with an APS system would enable demand amplifications to be reduced. The fundamental characteristic of this process is the use of information, rather than traditional use of inventory, to "pull" materials through the supply chain. A discrete event simulation model has been developed and used to perform a series of experiments designed to identify the effect on supply dynamics of the proposed processes. The results of these experiments clearly indicate that batching of customer orders during production planning and controlling their release into manufacturing enables an increase in system stability in terms of reduced cycle time variability and delivery tardiness.

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## **Glossary**

ANOM: Analysis of Means

APS: Advanced Planning and Scheduling

ATP: Available-to-Promise

BOM: Bill of Material

CPFR: Collaborative Planning, Forecasting and Replenishment

CPG: Consumer Packaged Goods

CPU: Central Processing Unit

CRP: Capacity Requirements Planning

CT: Cycle Time

CTP: Capable-to-Promise

DRP: Distribution Resource Planning

EDI: Electronic Data Interchange

EOQ: Economic Order Quantity

ERP: Enterprise Resource Planning

FCS: Finite Capacity Scheduling

GUI: Graphical User Interface

IMS: Inventory Management System

MPS: Master Production Scheduling

MRP: Material Requirements Planning

MRPII: Manufacturing Resource Planning

ROI: Return-on-Investment

SCM: Supply Chain Management

SCP: Supply Chain Planning

SME: Small and Medium-size Enterprise

VMI/CRP: Vendor Managed Inventory/Continuous Replenishment Planning

WIP: Work-in-Process

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# 1 Introduction

Because of rapid changes occurring in the global marketplace, in particular the rapid increase in use of the Internet, businesses can no longer operate as isolated entities but must co-operate within supply chains. Within such supply chains rapid dissemination of information is necessary in order to obtain an effective response to the actions of competitors particularly when these actions arise from unexpected sources distributed around the globe.

In order for companies to respond to this rapidly changing business climate, the structure of their information systems must enable them to meet *customer* expectations, since it is the customer and not the manufacturer, that now dictates (De Rosa, 1999):

- a) what goods are produced,
- b) how goods are marketed,
- c) how goods are priced,
- d) how goods are distributed, and
- e) how goods are serviced.

It is becoming increasingly difficult to meet these customer expectations using traditional Enterprise Resource Planning (ERP) systems because they were initially developed for conditions where manufacturers had responsibility for determining product configurations, defining distribution channels, establishing prices, and setting service conditions.

The quest for reduced costs and prices, whilst maintaining high quality products has led to widespread standardisation and automation of production. Consequently, ERP systems were designed with a functional orientation and focus on improving internal processes. Now the changing rules, listed in Table 1.1, are forcing companies to redefine their internal business practices such that these become externally oriented and

customer focussed. Consequently, the information systems used must be modified to support this changing environment.

Manufacturing rules under manufacturing driven trade	Manufacturing rules under customer driven trade
Automation Standardisation Improve internal processes Deliver high quality products Drive down cost and price	Customer convenience Customisation Improve customer processes Deliver high value products Drive up customer value

Table 1.1 – Manufacturing driven trade vs. Customer driven trade (De Rosa, 1999)

Existing manufacturing planning and control systems need to change from ‘transactional’ to ‘decision-support’ systems. Furthermore, all planning entities within supply chain network have to change to satisfy customers at the end of the chain.

In order to more fully understand how these changes can be attained, the current work has examined the use of a novel framework for order fulfilment within supply chains. The proposed framework is a strategy to increase the overall performance of a supply chain beyond the benefits of ‘pull’ systems. It is achieved by addressing four key imperatives for supply chains that are not addressed sufficiently by current business or operating models, ie:

- i) Fulfil customer promises with precision and consistency without causing inventory oscillations that degrade supply chain performance.
- ii) Manage to respond effectively to disruptions to the plan to minimize the customer and cost impact of those disruptions.
- iii) Synchronise the organisation and supply chain to customer priorities.
- iv) Gain competitive advantage through operations that deliver speed, accuracy, and increased inventory turns.

For implementing the proposed framework in reality it must possess the following features:



- i) Common language for business communications by defining the links between supply chain nodes, ie defined semantics (eg what is the work or purchase order), content (eg what is in the work or purchase order) and communications (eg which destination route do work or purchase orders take, which network will be used).
- ii) Common means of negotiation by defining the behaviours of the supply chain nodes, ie what happens next with work or purchase order.
- iii) Continuous planning to replace period planning processes in order to reduce oscillations in inventory costs.

The benefits of the proposed framework are the following:

- i) Increased customer satisfaction due to achieving customer commitments through rapid management of variability effects.
- ii) Lower operational costs due to higher customer satisfaction, lower inventory in the supply chain due to the use of continuous planning processes instead of period planning, and rapid recovery of the supply chain network from disruptions.
- iii) More rapid execution time due to more rapid calculation and communication of supply/demand synchronization and of supply/demand changes in the supply chain network.
- iv) Increased competitive advantage due to superior supply chain performance, including increased inventory turns and rapid resolution of disruptions in production caused by variability.

One of the main service performance factors of the order fulfilment process is on-time delivery of orders. Here, planning systems must enable organisations to promise accurate delivery dates and also assist in maintaining these promises. In order to minimise the deviations between promised and actual delivery dates:

- a) the effects of internal (eg machine breakdowns and repair times) and external (eg customer order inter-arrival times and order quantities) variability within supply chains has to be reduced, and
- b) the responsiveness of supply chains has to be improved, ie manufacturing cycle times have to be reduced.

The negative effects of external variability can be reduced through batching of customer orders into manufacturing orders. However, during the batching process it is necessary to consider the basic relationships between batch sizes and cycle times. Increased responsiveness through shorter cycle times can be achieved using smaller batches. However, if set-up times are long, then the optimal batch size may be significantly larger than one. Karmarkar (1993) defined the relationship using M/M/1 queueing models. The current work has taken this relationship as the basis for further research and attempted to analyse the batch size/cycle time function in more complex supply chain environments.

Operating at higher machine utilisation levels results in insufficient spare capacity to protect manufacturing systems from variability, hence the system can be prone to congestion. Hence, for delivery times to be more predictable the utilisation levels of manufacturing systems have to be controlled. This can be achieved by constantly monitoring work-in-progress levels throughout the whole manufacturing facility. If work-in-progress levels are too high then a release of planned manufacturing orders should be delayed to prevent congestions from arising.

In addition to controlling movements of planned or released orders, the velocity of demand information moving in the opposite direction to the work flow has also to be controlled. Forrester (1961) demonstrated that when significant delays in occurred communicating customer demand information upstream through supply chains, the oscillations in resource requirements and inventories increase. To reduce these oscillations demand has to be broadcasted rapidly and simultaneously to all entities within a supply chain network.

In reality the communication between different ERP systems has to be more effective. Considering globalisation trends, ERP systems, which often are built around traditional MRP systems, are suddenly no longer adequate to cope with these changing market conditions. That is, since external environments have changed MRP based ERP systems are now expected to operate in conditions, where they were not designed to operate.



As mentioned, APS is significantly faster than MRP, and in addition it enables to plan material and capacity simultaneously producing dynamic lead times (ie capacity is considered as finite). These benefits enable APS to plan customer orders immediately upon receipt by:

- a) batching customer orders dynamically into manufacturing orders, and
- b) determining the best route for each manufacturing order to take.

To avoid congestion effects from arising and to take into account shop-floor variability effects when promising delivery dates, APS systems must be tightly integrated with existing ERP systems. ERP systems will act as 'data warehouses' where from information, such as work centre capacity/loading, inventory and order status will be transferred into APS to perform precise calculations. The integration is important not merely from the data transfer point of view, but from the point of view of minimising the so-called 'Forrester effect' which arises when planning calculations are performed periodically in batch mode, ie real-time APS-ERP-shop floor integration is needed.

To summarise, the main objective of the current work is to analyse how, during order planning and execution across a supply chain network, batching of customer orders into manufacturing orders and release control of manufacturing orders enables reduction of cycle times (ie increase responsiveness) and minimisation of customer order tardiness (ie reduce deviations between promised and actual delivery times).

The individual tasks undertaken to achieve this objective were:

- i) Development of a discrete event simulation model which consisted of the following main elements:
  - a) planning engine:
    - to imitate simultaneous customer demand communication procedures (ie to reduce oscillations due to the 'Forrester effect'),

- to batch customer orders into manufacturing orders (in order to reduce variability in customer order inter-arrival times and quantities), and
  - to determine the best (ie least loaded) route for each manufacturing order to take.
- b) release control:
  - to control utilisation levels and thus prevent congestion effects from arising.
- ii) Validation of the supply chain planning simulation model using established relationships between cycle times and batch sizes.
- iii) Design of experiments to analyse the effects of developed batching and release control functions on cycle time variability (ie mean and standard deviation) and customer order tardiness.

The described work is presented in this thesis as follows:

Chapter 2 initially provides a brief history of supply chains which can be characterised as an evolution from ‘push’ production environments to ‘pull’ production environments. The current market trends, which are primarily characterised by the globalisation of logistics management, are then discussed. The analysis of current market trends provided in Chapter 2, identified that ‘pull’ systems are themselves becoming no longer adequate in environments where the economies of scale being attained through higher levels of outsourcing are becoming dominant competitive factors.

Within Chapter 3 the key dynamic behavioural tendencies of manufacturing plants are examined, ie the basic relationships between cycle time, inventory, and throughput. The influences of manufacturing process variability are then examined and in particular, the problems involved in operating manufacturing facilities at high utilisation levels with high levels of variability. The effects of delays in communicating customer demand upstream through the supply chain are described in terms of their effect on the amplitude of the demand oscillations that arise throughout the supply chain. In order to minimise these demand oscillations it is suggested that information should be passed



quickly to individual companies within a supply chain network. In order to achieve this, it is argued that the operational functions of enterprises should make use of current Internet based information technologies. Recent developments in information technologies are, therefore, discussed in Chapter 3 along with comparisons of the benefits and limitations of existing supply chain optimisation techniques, and those of 'push' and 'pull' production systems.

In Chapter 4 an overview of existing supply chain planning systems is provided which initially identifies the limitations of traditional planning systems including Material Requirements Planning (MRP) and Finite Capacity Scheduling (FCS). In order to overcome the limitations of these planning systems Advanced Planning and Scheduling (APS) systems have emerged. It is argued that to maximise the accuracy of planned schedules the data supplied to APS has to accurately reflect the changes occurring on the shop floor. Hence, in order to capture this information frequently there needs to be close integration between ERP and APS systems. An overview of the activities performed at the various supply chain planning levels is then provided along with an overview of the detailed planning and control functions found in existing supply chain planning systems.

Chapter 5 describes the experiments that were undertaken to investigate the system and dynamic characteristic of the proposed planning processes. A description is provided of the simulation model developed in order to perform these experiments.

In Chapter 6 the analysis of the simulation experiments' results is provided. These results indicated that the correct timing of manufacturing order releases and dynamic batch sizing of customers orders reduces cycle time variability and hence minimises tardiness. In addition, it was identified that although average cycle time decreased as batch sizes decreased, the backlog of planned orders tended to increase. Since the backlog was not recalculated to reflect the recent shop floor changes, the errors in lead times within the backlog accumulated resulting in increased deviations between promised and actual delivery dates.

In Chapter 7 the benefits and limitations of the proposed planning processes are evaluated. In particular, how these planning processes take into consideration capacity (ie finite and infinite loading) and the congestion arising on the shop floor are examined. Benefits of using APS systems are identified with respect to their ability to perform finite loading during the order planning process and then take into consideration, during scheduling, the actual loading conditions that exist at the time of release of these planned orders to the shop floor.

In final Chapters 8 and 9 the basic conclusions drawn from the current work and the areas for further research are presented, respectively.

## 2 Supply Chains

### 2.1 *Introduction*

A supply chain has been defined by Chizzo (1998) as a ‘sequence of trading partners and business processes that deliver products and services to the customer’. A similar definition is offered by Billington (1994) who defined a supply chain as a ‘network of facilities that produces raw materials, transforms them into intermediate subassemblies and final products and then delivers the products to customers through a distribution system’.

It is clear from these definitions that most companies play some role within a supply chain network, either as the head of a supply chain, as a supplier within it, or as both customer and supplier. Traditionally, management concentrated on ensuring that each individual node of a supply chain network was efficient. However, it is now realised that efficiency at individual nodes does not necessarily result in the supply chain as a whole operating optimally. Increasingly, the challenges related to improved product quality, customer service and operating efficiency cannot be effectively met by isolated change to specific organisational units, but instead depend critically on the relationships and interdependencies among different organisations (Swaminathan, et. al., 1994). As a result, the welfare of any manufacturing entity in the system directly depends on the performance of the others and their willingness and ability to co-ordinate their activities. Thus, not individual companies, but supply chain networks compete with each other and therefore, it is usually the performance of the network that assists a company in developing and sustaining a competitive and substantial future (Christopher, 2000; Lamming, et. al., 2000; Layden, 2000).

Due to recent market trends, many manufacturing companies have been attempting to move from mass production of commodities to lower volume production of higher-variety products (Horiguchi, et. al., 2000). It is not unusual, therefore, for a single company to participate in more than one supply chain.



Supply chain performance is driven by the following key metrics (Stock, et. al., 2000):

- i) **Customer service:** This marketing and service metric measures the performance of a company in supplying the precise product or service at the moment it is needed and at a competitive price. It also takes into consideration information about the customer that either adds value to the existing product or service or provides the incentive to do additional business.
- ii) **Asset management:** An operational metric, that looks at the ability of a supply chain to manage its inventory levels and its accounts receivable. Asset management can also extend into intellectual property.
- iii) **Transaction cost:** The overall cost of executing a transaction becomes a competitive factor, as the lowest overall cost can provide a substantial competitive advantage in a market.

The above metrics assist in measuring the relative performance of one supply chain versus another. It should be noted though that the overall performance measured does not reflect the use of technology. Whilst these performance measures are independent of technology, the operational structure of an organisation is built almost entirely around technology (Layden, 2000; Stock, et. al., 2000).

## ***2.2 History of Supply Chains***

From the beginning of the last century until the early 1970's, the demand for all types of products worldwide exceeded the ability of manufacturers to produce and deliver them. Products of all kinds were in short supply, and two world wars extinguished the productive capacity of entire regions (Stalk and Hout, 1990). With little global competition, those countries that had developed high production capabilities were predominantly in command of the world economy, and by the middle of the century this resulted in the formation of very large corporations. This era is characterised by the presence of infinite demand, where the most appropriate supply chain strategy was a "push" strategy (Ross, 2000). Using this strategy, an essential priority was to manufacture and sell high volumes. With high demand, it was likely that whatever was shipped would be purchased. Increased costs were passed down the supply chain to customers who, normally, were primarily satisfied with obtaining supply. Inventory



accumulation in the supply chain was seen as a means of sustaining factory capacity (Stalk and Hout, 1990).

By the 1970's, the openness that characterized the global marketplace was ending as, at first Japan, and then the "Asian tigers", (Singapore, Hong Kong, Taiwan, and South Korea), built export economies aimed at capturing market share around the world. This led to an increase in capacity that displaced existing market leaders as much as it created new demand. By the end of the 1980's, for example, it was difficult to identify a significant US producer of televisions or semiconductor memories, and in California, for example imported automobiles comprised a major share of the total marketplace (Stalk and Hout, 1990). Analysis at the time (Stalk, 1988) depicted many causes for this displacement, including the once dominant management practices of major corporations now driving customers away where once they dictated to customers. In the final analysis, however, it can be concluded that the real driver was the fact that there was more global production capacity than there was demand to absorb it.

The Toyota Production System (Ohno, 1988) established lean production practices that today are considered prime examples of a "pull" system, where the low inventory levels force attention on ensuring that material is always correct, in terms of quality, and that stock-outs do not occur. This system, termed the *kanban* system, is aimed at dramatically reducing the inventory levels encountered throughout the production cycle (Stalk and Hout, 1990). The Toyota Production System lean production 'pull' practices emphasise the importance of managing the process as opposed to the use of information technology (Hopp and Spearman, 1992; Ohno, 1988; Sandras, 1995).

Pull systems allow the work itself to dictate the pace of material flows, ie a worker is not permitted to proceed with work in one station unless there was a direct need for more parts at the next station (Ohno, 1988) further up the production process. Although this provided a considerable advantage for Toyota, this advantage was only gained whilst production plans remained static, ie static plans provide the stability necessary for production to move unimpeded (Ohno, 1988). Incursions of sudden changes to the plan lead to decreased operating efficiency and higher costs. The relevance can be

questioned, therefore, of the traditional Toyota Production Systems in today's global market economy since there are increasing demands for greater product variety, greater levels of design customisation and the ability to configure an order from standard options or features (Inman and Gonsalvez, 1997).

### *2.3 Effects of globalisation*

To establish methods by which costs can be reduced and customer service improved through the globalisation of logistics management (Laarhoven, et. al., 2000), research has focussed on inter-company supply-demand planning environments.

The trend towards globalisation is underlined by two related developments, ie the creation of focused factories (Christopher, 1992; Ernst and Kamrad, 2000; Karmarkar and Kekre, 1987) and the centralization of inventory (Christopher, 1992; Erengüç, et. al. 1999; Laarhoven, et. al., 2000). The focused factory limits the range and mix of products manufactured in a single location and hence enables a company to achieve considerable economies of scale. Similarly the centralisation of inventories can substantially reduce total inventory requirements.

The reasons for organising companies on a global basis are (Christopher, 1992; Ross, 2000; Skjoett-Larsen, 2000):

- a) to move raw material from countries with surplus natural resources to those with either the markets to consume them and/or the labour to process them,
- b) to take advantage of low regional labour costs to maximise profitability on labour-intensive manufacturing, and
- c) to concentrate only on those activities in the value chain where companies possess a distinctive competitive advantage, ie all other activities are out-sourced. These companies would, for example, concentrate research, development and manufacturing investment such that individual factory sites focused on a specific product-technology combination.

Within Europe, the additional driving forces behind changes in logistics structure and strategy are (Skjoett-Larsen, 2000):



- a) the removal of trade and transport barriers between EU countries,
- b) the opening of new markets in Eastern Europe, and
- c) the acceptance of a single European currency.

However, the increasing use of focused factories and globalisation of production resources can generate problems, which are often caused by the traditional desire to compete solely through operational excellence, existing goods, and services (Hicks, et. al., 2000; Ross, 2000). As a result, focused factories have a negative impact on production flexibility and the variety of products that a company can economically develop, manufacture and market (Ross, 2000). Moreover, the reduction in the variety of products manufactured causes a general flattening of a company's Bills of Material (BOM) (Ernst and Kamrad, 2000). As illustrated in Figure 2.1 the general trend is from complex to flat BOMs consisting of one or two levels.

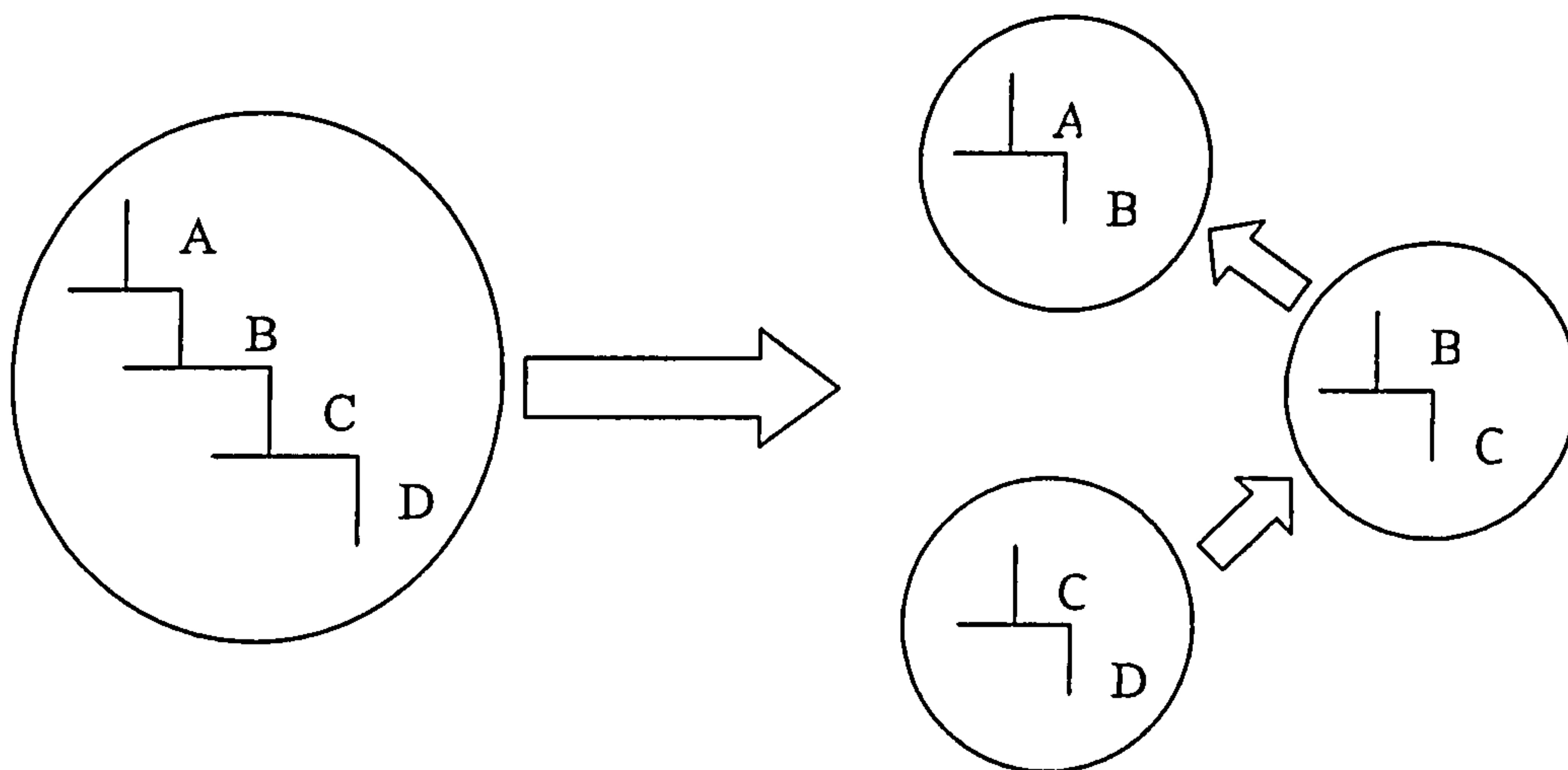


Figure 2.1 - Simplification of Bills of Material

Focused production results in companies producing the same products repeatedly according to long-term agreements with customers (Skjoett-Larsen, 2000). Within supply chains a proportion of the companies specialise in producing individual components, others produce semi-finished systems from these components and finally a proportion of companies may assemble and distribute the final products. Hence supply chains are becoming more complex and longer in terms of the companies that comprise them (Cohen, et. al., 1999). To facilitate efficient planning across supply chains and to

provide a more holistic product view, a term Bill of Manufacture is becoming accepted in the industry. As depicted in Figure 2.2, in Bill of Manufacture operations are linked together to form a structure. Components and semi-finished items are linked to operations.

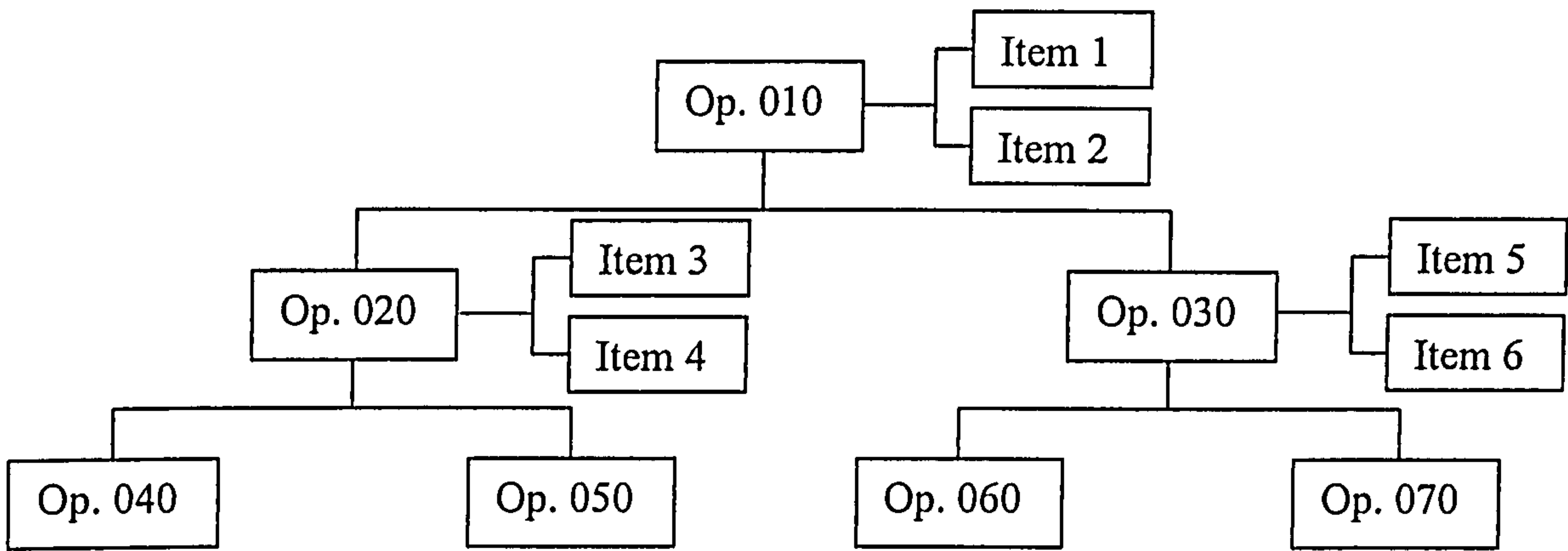


Figure 2.2 – Bill of Manufacture

The concept of focusing production on a narrow variety of products, ie with flat BOMs, is in one respect contradictory to the principles of providing a high quality service to customers (Laurence, 2000). That is, to satisfy all customers it would still be necessary to provide a large variety of product design variations with the minimum delay in order delivery lead time. In these circumstances the strategy of central warehousing has been found to be advantageous (Stalk, et. al., 1992) through an extension of their functions. Such warehouses now perform value added operations by carrying out the final configuration of a product, eg local packaging, labelling, and merge orders through transshipment. These warehouses also provide an opportunity of localising inventory (Stalk, et. al., 1992). Hence whilst centralising inventory to reduce costs it could also be possible to maintain high flexibility and respond quickly to market demand. The main pre-requisite for achieving cost reductions whilst maintaining demand flexibility is close integration between customer and supplier activities (Mason-Jones and Towill, 1997; Ross, 2000). This is a particular need where companies have out-sourced their distribution activities.

Another issue that arises through the centralisation of warehousing is that of supply lead-times which tend to increase as supply chains lengthen (Korpela and Lehmusvaara,



1999). This problem can be partly offset by ensuring that warehouses are located in the most cost effective areas, ie of importance is the need to consider where to consolidate shipments from factories and suppliers that best addresses the needs of customers (Korpela and Lehmusvaara, 1999).

Whilst the logic of warehouse centralisation is basically sound, it is becoming increasingly recognised that greater gains can be achieved by not *physically* centralising the inventory but merely by *managing* and *controlling* it centrally (Christopher, 1992). This is the concept of ‘virtual’ or ‘electronic’ inventory, which can be achieved through the use of an electronic information system (Graham and Hardaker, 2000).

The challenge to achieving competitive global logistics is to centralise control whilst maintaining decentralised operations (Christopher, 1992). The new customer driven business environment and inherent complexity of a global supply chain requires the efficient and effective co-ordination of all the resources of the enterprise.

## 2.4 *Supply chain networks*

Literature on inter-organisational networks lacks a truly comprehensive classification framework. Authors focus on different management issues or structural features. The different types of network that have been conceptualised may be viewed as a whole, providing a roughly structured classification.

Ernst and Kamrad (2000) introduced a conceptual framework for evaluating different supply chain structures in the context of modularisation and postponement. Modularisation implies a product design approach whereby the product is assembled from a set of standardised constituent units. The design of linkage mechanisms determines how conveniently a required number of combinations can be assembled. Higher modularisation supports the notion of focused factories described in Section 2.3. The higher the level of modularisation, the easier it is to outsource manufacturing. Postponement, as the name implies, aims at moving the assembly of product modules closer to the point of their purchase hence maximising the use of common processing requirements among those sets of modules. This reduces the complexity in manufacturing and also the affect of demand uncertainty on production planning

decisions. The authors conclude that a high degree of vertical integration, where an enterprise attempts to control parts of the supply chain, is not desirable. Companies should instead strive towards vertical co-ordination through developing long-term arrangements with suppliers.

Stock, et. al. (2000) describe supply chains using four constructs, ie the level of geographic dispersion, channel governance, logistics integration, and performance. An organisation with a high level of geographic dispersion exhibits a low proportion of supply chain units within any individual geographic region, ie conversely, a low level of geographic dispersion exhibits a high proportion of supply chain units within one region and low proportions in other regions. The channel governance notion compares stronger or weaker supply chain links to lower or higher vertical integration. Logistics integration is viewed across two dimensions, ie internal (integration across boundaries within a firm) and external (integration across firm boundaries) integration of logistics. Similarly, the performance is viewed both internally, ie from production and logistics efficiency and effectiveness perspective, and externally, ie from conventional business performance factors such as market share, share price and sales growth. As a result of a survey, the authors concluded that higher geographic dispersion and logistics integration, (both external and internal), resulted in higher operational performance, which is expected to result in higher financial performance.

D'Amours, et. al. (1999) address the impact of information sharing between firms of a manufacturing network. Firms of a network are selected and scheduled to produce an order based on a price-time evaluation of their bids. Networking strategies, where business relationships are characterised by different levels of shared information on price and capacity, are classified. An illustrative example sketches the impact of information sharing on networked manufacturing using three different kinds of bidding protocol expressing how firms aggregate their information to conform to networking requirements. The results show that better price-time scheduling performance is achieved when higher levels of information on price and capacity are shared.



Hinerhuber and Levin (1994) distinguish between horizontal, vertical, and diagonal networks while also recognising the different levels of internal and external integration.

Lamming, et. al. (2000) present a categorisation of supply chain networks according to the nature of the products. The results of their survey support the suggestion that there are two distinct types of supply network, ie those for ‘innovative-unique’ products and those for ‘functional’ products. Functional products such as stationary items have long product life cycles and stable easy-to-forecast demand. Margins for such products are typically low (5-20 percent). Innovative-unique items are characterised by unpredictable demand and shorter product life cycles. Margins are higher, typically 20-60 percent. They conclude that management of supply networks of functional products must focus on cost and quality issues, whereas for unique-innovative products, the emphasis is on speed and flexibility.

As part of the planning process, the structure of the supply chain needs to be represented. This is typically achieved using a network model (Erengüç, et. al., 1999; Lapide, 1998c; Layden, 2000; Lin, 1996). A network model graphically visualizes a supply chain and is used to depict the parts of a supply chain being considered in the planning process. Layden (2000) depicts supply chain structures considering recent rapid advances in information technology, ie as shown in Figure 2.3.

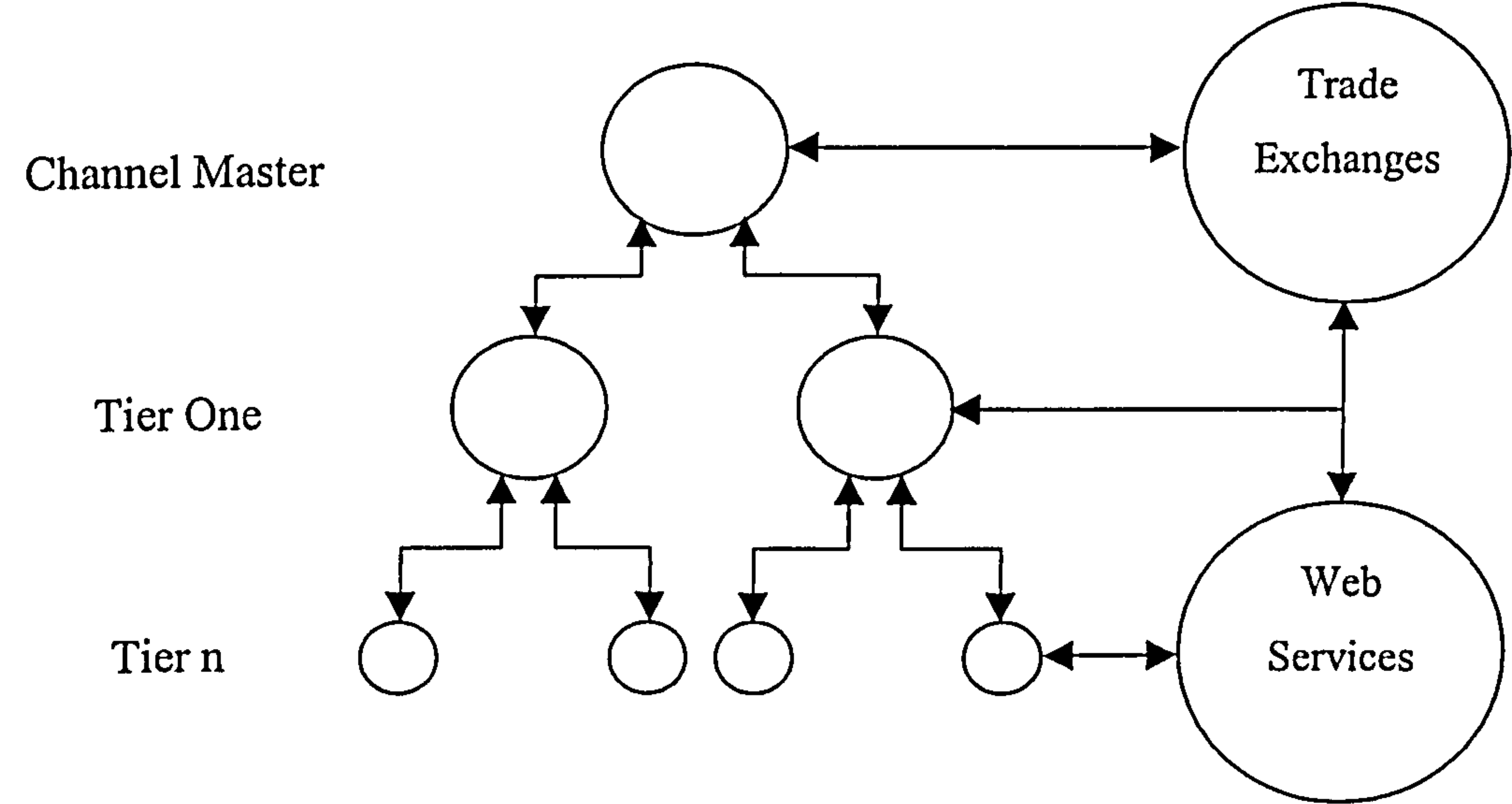


Figure 2.3 – Network representation of a supply chain (Layden, 2000)



With reference to Figure 2.3, the circles are *nodes*, which represent suppliers. A supplier is an entity that provides either a product or a service. Thus, ‘services’ that provide transportation qualify as suppliers and form part of the capacity of the supply chain. Nodes occur from the sources of raw materials (tier n) and intermediate products (tier one) to the consumers of the finished products (channel masters). Nodes can be divided into the following groups (Layden, 2000):

- i) **Line nodes:** Nodes that participate within a particular supply chain using its communication standards.
- ii) **Service nodes:** These nodes provide a service over the web, such as scheduling logistics.
- iii) **Foreign nodes:** These nodes are outside of the particular supply chain standards and need to participate within it.

The *arcs* or *links* connecting the *nodes* represent flows of (Lapide, 1998c):

- a) materials, semi-finished, and finished products by some transportation means, and
- b) information in the form of customer demand, exception messages or forecasts.

The nodes depicted in Figure 2.3 serve the following purposes (Layden, 2000):

- i) **Channel masters:** These are the main places, because of market dominance, from which customers buy products. The channel master has the market power to shape the overall performance of the suppliers who are interested in participating in the market pull they provide for products and services.
- ii) **Centralised trade/market exchanges:** Exchanges such as Commerce One (Mitchell, 2000) and the Auto Exchange (Mitchell, 2000) that drive overall demand. These are the source of collaborative plans at the head of supply chains, ie they serve as aggregators of information (particularly demand) that needs to be served.

- iii) **Customers and suppliers to exchanges:** Connected to these exchanges are many suppliers and customers that use the exchange to either buy, sell, or exchange.
- iv) **Tier One suppliers:** Line nodes that serve as suppliers of products or services to the channel masters.
- v) **Tier n suppliers:** Line nodes that serve as suppliers of products or services that exist deeper in the supply chain than Tier One.
- vi) **Web services:** Line nodes that exist as services on the Internet, for example product catalogues, in order to provide these services on the supply chain.

As described in Section 2.1 suppliers usually participate in more than one network, hence, linking with several channel masters. The number of suppliers in each tier depends on such supply chain network attributes as manufacturing process, primary business objective, product differentiation, range of product variations, assembly stages, product life cycle, and main inventory type. Based on these attributes Lin (1996) identified three main types of supply chain networks, type I, II, and III, as shown in Table 2.1.

Attributes	Type I	Type II	Type III
Manufacturing process	Convergent Assembly	Divergent Assembly	Divergent Differentiation
Primary business objectives	Lean production	Customisation	Responsiveness
Product differentiation	Early	Late	Late
Range of product variations	Small	Medium	Large
Assembly process	Concentrating at the manufacturing stage	Distributed to the distribution stage	Concentrating at the manufacturing stage
Product life cycle	Years	Months to years	Weeks to months
Main inventory type	End products	Semi-products	Raw materials
Example industries	Automobile and aerospace	Appliance, electronics and computers	Apparel/fashion
Manufacturing categories	Engineer-to-order	Assemble-to-order	Make-to-order

Table 2.1 - The properties of type I, II, and III supply chain networks



Automotive and aerospace industries are associated with type I networks, where the main issues (Inman and Gonsalvez, 1997; Thomas and Griffin, 1996) are how to efficiently meet customer demand without carrying excessive inventory, and how to co-ordinate suppliers and assemblers to create smooth material flows. Because structurally there can be many suppliers the wide range of materials and sub-components emanating from these suppliers converges through a series of manufacturing stages until the final product is assembled at one location. The final product is then shipped to several distributors and ultimately to a large number of retailers.

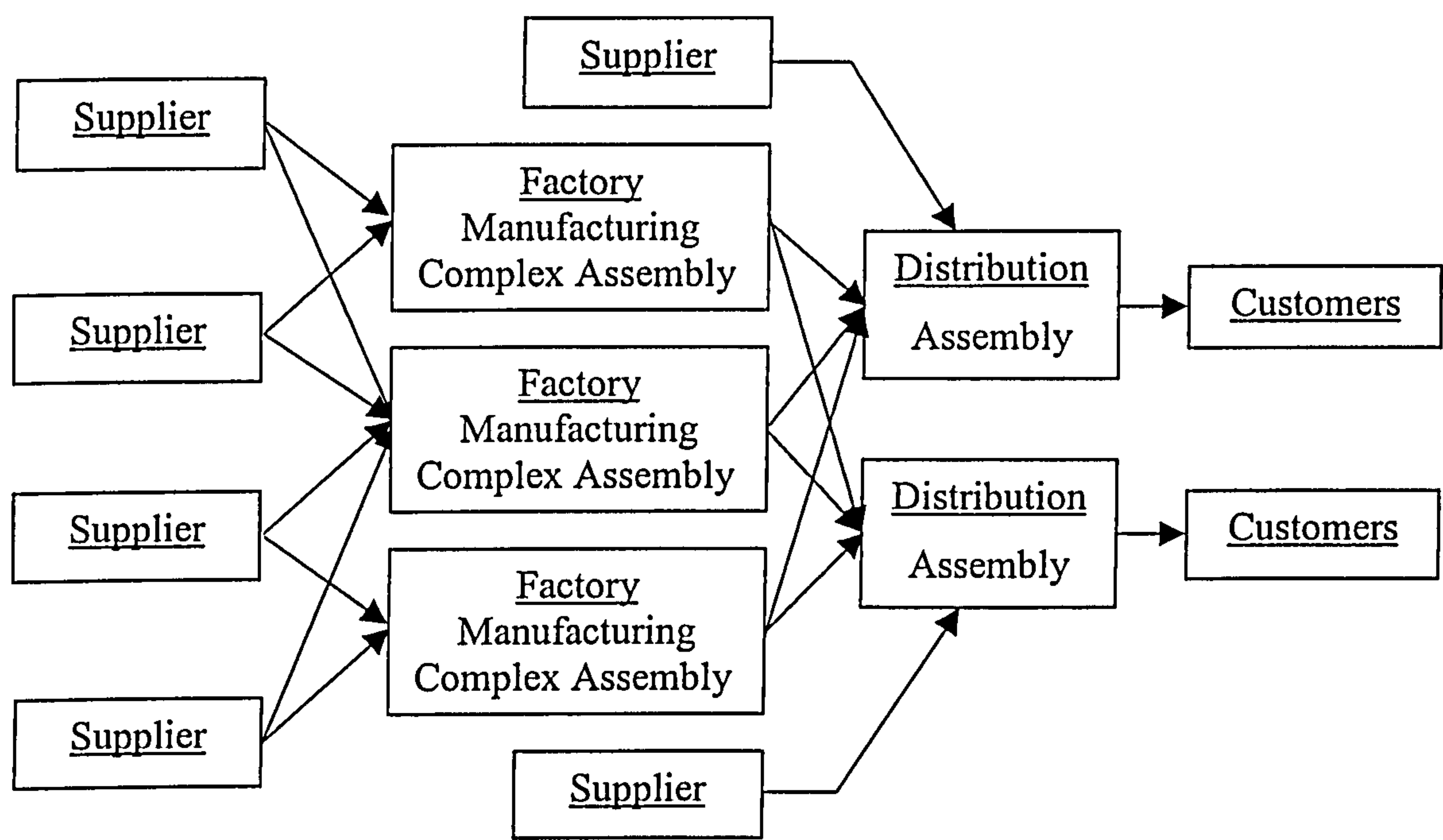


Figure 2.4 – Type II supply chain network (Lamming, et. al., 2000)

The appliance, electronics, and computer industries can be classified as type II networks, where the main issues (Lee and Billington, 1993) are reducing the lead-time of the assembly-to-order process, and managing the inventory and purchasing for the assembly. Within these supply chain networks, a relatively small number of suppliers provide materials and sub-components that are used to produce a large number of generic product models (ie modularisation). Complex assembly processes for generic models (semi-products) are executed at factory sites, and simple assembly processes for customised models are executed at distribution sites. A number of distribution points



may be required to quickly respond to 'customised' orders. An illustration of the type II network has been provided in Figure 2.4.

The apparel/fashion industry is a type III network, where the main issues (Battezzati and Magnani, 2000) are acquiring market information to respond to demand, and deferring product differentiation (ie postponement) to maintain flexibility to handle constantly changing markets. In these supply chain networks, the number of end items is larger than the number of raw materials. There are a small number of suppliers and manufacturers, but a larger number of distributors and retailers.

## **2.5 Supply Chain Strategies**

It has been recognised that new supply chain strategies are required for the modern enterprise in order to increase responsiveness to markets, partners, and customers. Current attempts at developing and implementing such strategies involved two main approaches, ie inter-enterprise collaboration and supply chain integration.

### **2.5.1 Inter-Enterprise Collaboration**

It has been shown that 40% to 60% of an organisation's variable operating costs arise from decisions made outside that organisation (Chizzo, 1998). Leading enterprises are addressing this challenge by moving beyond internal supply chain management initiatives to embrace collaborative solutions that incorporate key upstream and downstream trading partners.

Collaborative opportunities exist throughout the supply chain. Each interface point between trading partners is a source of discontinuity that can be addressed using a *collaborative* business process. Several industry initiatives are currently focussing on evaluating electronic commerce and inter-enterprise supply chain collaboration, ie:

**1. Collaborative Planning, Forecasting and Replenishment (CPFR) (Snitkin, 2000)** is a process whereby a retailer and a supplier can develop a negotiated, consensus product forecast that can be integrated with both companies' planning and scheduling systems automatically. Use of a common forecast has the potential of providing benefits in terms of reduced inventories, predictable capacity, and lower costs.

**2. Collaborative Supplier Management** (Czupryna, 2000) processes can integrate suppliers into engineering, purchasing and production decisions. One example (Owen, 2000) involves an automotive supplier with a highly dynamic demand pattern that placed constant pressure on its purchasing department. If a component sourcing problem emerged, the company frequently cross-referenced its BOM to determine possible substitutions of various subassemblies or components. Unfortunately, this was frequently ineffective because of demands placed on alternative sources. In collaboration with its suppliers, the company built a system that integrated its BOM with its suppliers' BOM so it could view not only its own supplier and substitution network, but also those of its suppliers. The company was able to pull components several layers down the supply chain.

**Collaborative Quality Management** (Hill, 2000) where Quality Information Systems that allow for faster, real-time problem solving are emerging in highly competitive, quality-driven industries. One such system (Hollinger, 2000) integrates supplier quality information into a common database with query capabilities. The company then monitors product performance online, in real time, and can work on issues with suppliers as they arise. This system enables the company to collaborate with its suppliers to ensure quality not by managing and controlling its suppliers' processes, but by opening up its manufacturing processes to its suppliers. Thus, quality management can transcend the written specifications typically exchanged between suppliers, manufacturers, and customers.

Several industry analysts and academic institutions (Lapide, 1998a; Ellinger, 2000) have examined the trends in inter-enterprise supply chain collaboration and the manner in which technology providers are beginning to support this concept. These reports concluded that:

- i) The basic types of relationships within business-to-business electronic commerce are *transactional*, *information sharing*, and *collaborative*. Electronic commerce relationships begin typically with electronic data interchange (EDI) to automate



transactions such as purchase orders and invoices. They then progress to information sharing such as exchanging production schedules. Electronic collaboration is the final stage, which builds on these relationships.

- ii) The current interest in SCM is driving the industry to look towards integrating its supply chains. E-commerce, especially trading partner collaboration, is viewed as an intriguing and important element toward synchronising supply chain operations. E-commerce is expected to yield significant performance improvements.
- iii) A few companies have started collaborative initiatives with their suppliers and customers. While industry interest in this area is large, electronic collaboration is currently in an experimental phase of development.
- iv) Technology vendors are beginning to develop products to enable e-commerce with the majority focussing on transaction and information sharing systems. A small number of vendors have developed collaborative solutions and have started to respond to the challenges involved in connecting disparate enterprise applications.

Realising benefits by collaborating with supply chain partners requires changes in the methods by which enterprises transact business (Lancioni, et. al., 2000). Partners must move away from the business documents that serve as formal interfaces between partners and, instead, develop inter-enterprise business processes that serve the customer. Partners must also learn to operate in an environment in which there is no ultimate authority (Min and Galle, 1999). Hence they must overcome problems in terms of levels of trust and privacy to work with partners who may also be working simultaneously with their competitors.

## 2.5.2 Supply Chain Integration

When Material Requirements Planning (MRP) (Orlicky and Plossl, 1994) and Manufacturing Resource Planning (MRPII) (Vollman, et. al., 1997; Wallace, 1994; Wight, 2000) were introduced in the 1970s and 1980s, they were considered breakthroughs for manufacturing planning and control. However, these tools were



limited to managing resources within individual manufacturing plants or production functions (Chambers, 1996). They allowed companies to determine requirements, order supplies, and create a master schedule to meet projected demand. Enterprises today, however, realise that their businesses are more than pure manufacturing functions (Chambers, 1996). The integrated supply chain, encapsulating diverse business functions including manufacturing, logistics, sales, and marketing, connects the entire enterprise together, from management decision-making to real time execution (Christopher, 1992; Ross, 2000). Best-in-class enterprises (Daugherty and Ellinger, 1995; Kotzab, 1999; Mason-Jones and Towill, 1997; Stalk and Hout, 1990) are creating horizontal business process structures to plan and manage more responsively, ie:

- i) **Sales and Marketing** - Real-time sales information is essential to drive manufacturing and logistics activities. Demand plans must be evaluated against capacity and resource constraints. If orders change, production plans must respond *quickly*. Customers should know their order status in *real time*.
- ii) **Logistics** - Distribution requirements are integral to responding to customers. Integrated supply chain planning combines logistics and manufacturing to optimise execution across the network.
- iii) **Procurement** - New, integrated processes allow closer relationships with trading partners. It allows buyers/planners to synchronise purchases with a customer-driven requirement and see critical issues in time to resolve them.
- iv) **Engineering** - Engineer-to-order brings value to the customer and leverages product development investments. Therefore, engineering must become increasingly integrated with manufacturing to increase responsiveness to the customer.
- v) **Finance** - Traditional functional or departmental budgeting and accounting must give way to a more integrated approach. Financial management is increasingly recognising how the drivers of cost often occur outside the functions that incur the cost. Optimising the total supply chain cost will dominate rather than optimising the costs of individual functions.
- vi) **Manufacturing** - Integrated planning allows manufacturing to plan for materials and capacity simultaneously. Additionally, all resource and scheduling elements,

including human resource planning and maintenance are considered. Manufacturing is synchronised with sales to build products based on real customer demand.

According to a survey undertaken by the UK Institute of Logistics (Fulcher, 2000), the integrated supply chain does not exist in industry today, ie manufacturers provided the following information:

- i) 100% replied that an integrated supply chain was not possible.
- ii) 100% replied that their organisation did not have an integrated supply chain.
- iii) 65% replied that only certain elements of their supply chain were integrated.

When conducting the survey individual supply chain activities were placed into three broad planes of operation, ie :

- i) The *Logical* plane has processes which any business has to undertake to ensure products get to the right place, that they are managed through the right channels and moved in appropriate quantities and time frames.
- ii) The *Physical* plane which is a well-established set of sub processes, taking the movement of product from its raw material form, through added value manufacture to consumption.
- iii) The *Commercial* plane which has both corporate and transactional functions within incorporating both financial and legal activity.

The main issues arising from the survey are listed in Table 2.2.

	Inbound (Purchasing)	Value Added (Production & Warehousing)	Outbound (Distribution & Sales)
Logical	Lack of clear information referring demand forecast No stock policy Poor supplier product availability	No effective forecast – belief that, for example, 60 units/period could be “about right”, therefore there was buy in. Capacity planning issues not communicated Limited view of lead- time from demand to response or understanding of whole supply chain process. Limited planning between cycles.	Sales had a forecast but did not know what to do with it!
Physical	Inaccuracy of product receipt. No lead-time visibility. No control of returns/rework.	Limited production control or order processing process. No rework control or returns process. Activity constrained by labour resource. Poor initial specification of delivery unit and handling method.	Customer requirements not pushed down the chain. Rework sent back to customer and accepted still in Q.C. failed status.
Commercial	No communication of raw material cost price from purchasing. No supplier promotions communication.	No stock policy No corporate view/direction on inventory management No sales or operations planning	No agreement on service level criteria eg price/quality targets not effectively communicated.

Table 2.2 - Main issues preventing integrated supply chains (Fulcher, 2000)

The UK Survey identified key problem areas and suggested methods of remedying them, ie:

- i) Poor information flows across the whole supply chain where the remedy suggested was the use of EDI/Internet.



- ii) Poor communication processes and lack of a common understanding of supply chain processes where the suggested remedy was the use of cross-functional teams and simple mapping of supply chain processes.

To alter the concept of an integrated supply chain from myth to reality the following actions have been recommended (Laarhoven, et. al., 2000; Lewis, et. al., 1997; Pawar and Driva, 2000; Ross, 2000), ie:

- i) Establish a clear corporate strategy for supply chain integration which has the buy-in of senior managers and board directors.
- ii) Set clearly focused customer targets which all parts of the business can identify with.
- iii) Involve internal and external supply chain partners in the process.
- iv) Establish a cross-functional team to review supply chain processes. It should have at its core improving the communication process and information flows across the supply chain. Information flow should be timely, accurate, and accessible to all organisations within the supply chain.
- v) Establish clearly defined and relevant forecasting measures and performance indicators.
- vi) Use simple reordering policies incorporating regular order patterns, frequent deliveries, and small batch quantities.
- vii) Identify the key areas of improvement and rank them in order of priority. Integration of supply and demand must initially be achieved by eliminating organisational boundaries and thereafter external integration can commence.
- viii) Determine what are the associated enablers to move forward.
- ix) Begin with a project which will provide highly visible outcome.

### 3 Supply Chain Dynamics

#### 3.1 *Factors Influencing Supply Chain Behaviour*

The main factors influencing supply chain behaviour, identified by Hopp and Spearman (1996), are work-in-progress (WIP), cycle time (CT), lead time and its components, throughput rate, service level, order lateness and tardiness. These are defined by these researchers as follows:

- a) work-in-progress (WIP) is a set of semi completed items that accumulate at various points in the production process,
- b) cycle time (CT) is a random variable relating the time it takes for a job to traverse a given routing,
- c) lead-time is a management constant used to indicate the maximum allowable cycle time for a job,
- d) throughput is the average quantity of good (no defective) parts produced per unit time,
- e) service level is a measure of performance which is defined as  $\text{service level} = \Pr\{\text{cycle time} < \text{lead-time}\}$  which implies that for a given distribution of cycle time, service level can be influenced by manipulating the lead-time, ie the higher the lead-time the higher the service level,
- f) lateness is the difference between the order due time and the completion time, and
- g) tardiness is lateness of an order if it is late or zero otherwise.

Relationships exist between batch sizes, cycle times, WIP, queueing and congestion phenomena which have been thoroughly explored by a number of researchers. Hopp and Spearman (1996) illustrate how at a single-machine workstation high variability in order arrival times and processing times leads to increased queueing and cycle times. Little's Law (Hopp and Spearman, 1996) states that the average WIP and the average

cycle time are directly proportional. Hence, under these conditions WIP levels would also be expected to increase.

Variability in arrival rates has also a great effect on the behaviour of supply chains. In this respect the impact of such variability at one station on arrival variability at downstream stations is magnified, when station utilisation is increased (Hopp and Spearman, 1996). As seen in Figure 3.1 this relationship is exponential in character with higher levels of variability magnifying the extent of this exponential effect. This extreme sensitivity, of system performance to utilisation, makes it difficult to choose a release rate that achieves both high processing equipment efficiency and short cycle times.

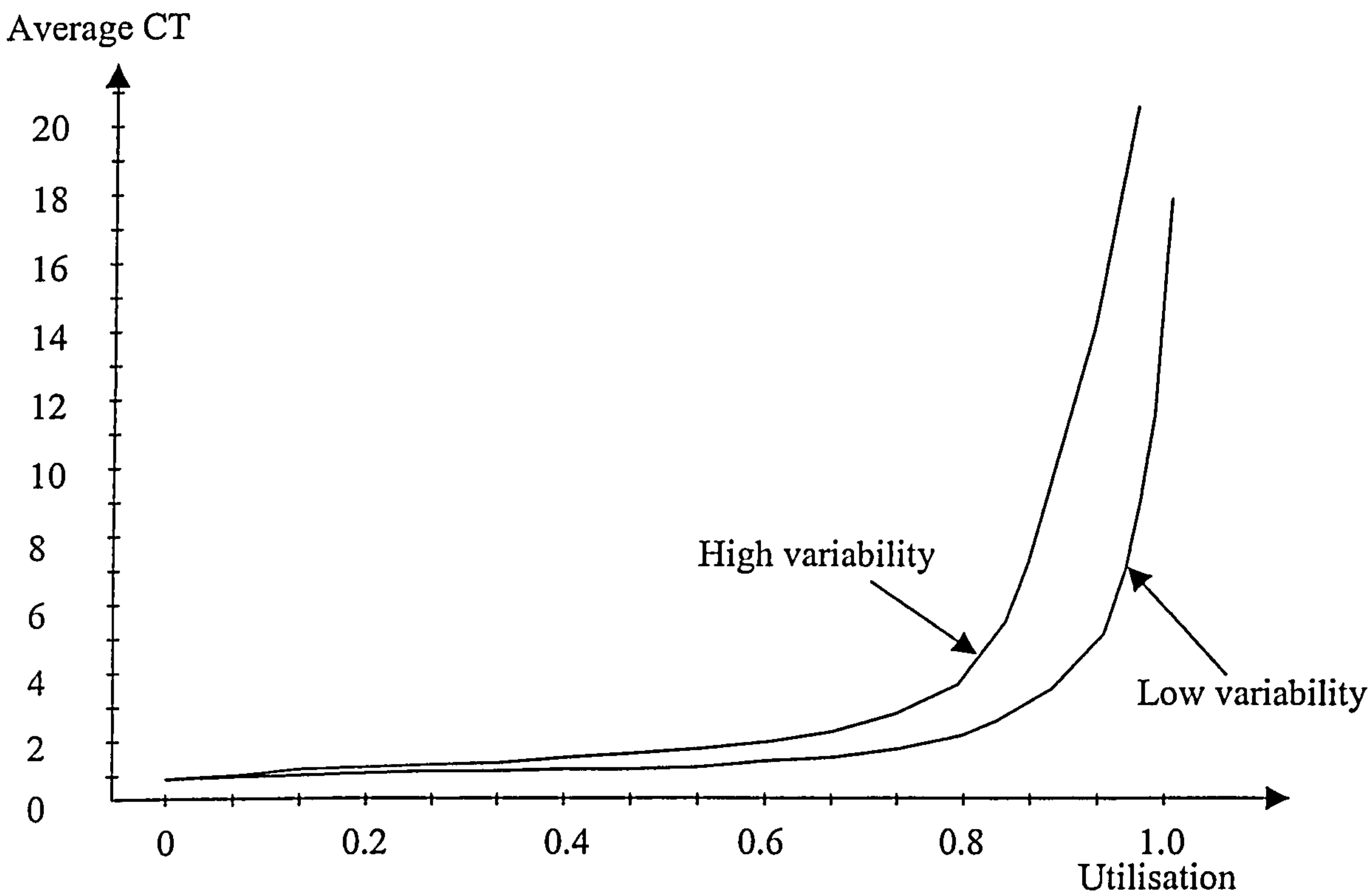


Figure 3.1 – Relation between cycle time and utilisation (Hopp and Spearman, 1996)

Research undertaken to measure factory performance based on the relationship between cycle times and batch sizes (Hopp and Spearman, 1996; Karmarkar, 1987) has identified that:



- i) Larger cycle times lead to proportionally larger WIP inventories.
- ii) Larger variability in cycle times causes customer lead times to increase and forces companies to carry excess inventories.
- iii) The increased delay between manufacture and use results in a loss of quality information and more opportunities for deterioration or loss.

The variability in cycle times is due to queueing or sequencing delays that arise from complex material flow patterns within such manufacturing areas as the shop floor. There are several decision variables that affect the queueing behaviour in such complex environments, including (Hopp and Spearman, 1996; Karmarkar, 1987; Karmarkar, 1993):

- a) batch sizes,
- b) set-up times,
- c) release times of batches to the shop,
- d) co-ordination of batch release times,
- e) sequencing at machines, and
- f) product mix and heterogeneity of items.

For simple situations, such as those represented by a M/M/1 queueing situation, cycle time can be calculated using the formula derived by Karmarkar (1993):

$$CT = \frac{t + \frac{Q}{P}}{1 - \frac{D}{P} - \frac{tD}{Q}} \quad (1)$$

Where:

D = Average throughput rate (units/time),

P = Average processing rate (units/time),

Q = Batch size,

CT = Average cycle time, and

t = Set-up time.

and where:

Utilisation = D/P.

The effects of these variables are illustrated in Figure 3.2. The batch size Q is bounded by the value Dt/(1-(D/P)) (Karmarkar, 1987). As Q becomes smaller and approaches its lower bound, CT grows rapidly and without bound, since a high traffic intensity system becomes congested, as Q becomes larger, CT becomes approximately linear related to Q. An asymptotic lower bound to CT is given by Karmarkar (1987), ie

$$CT > \frac{t + \frac{Q}{P}}{1 - \frac{D}{P}} \tag{2}$$

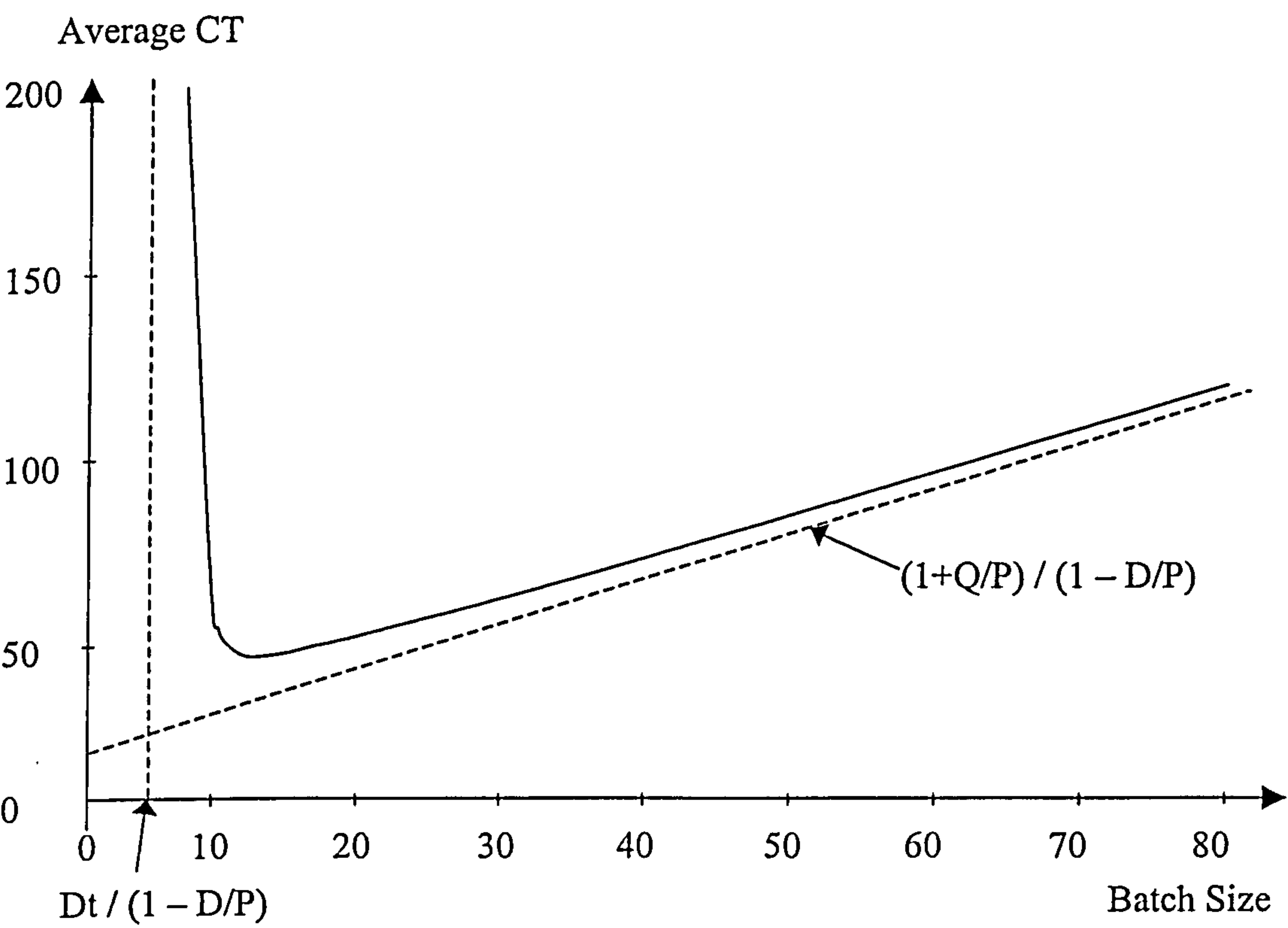


Figure 3.2 – Average cycle time as a function of batch size in M/M/1 model  
(Karmarkar, 1993)

The implication derived from Equations 1 and 2 is that batch sizing and set-up time reduction must be used in concert to achieve high throughput and efficient WIP levels

and cycles. If set-up times can be made sufficiently short, then using batch sizes of one is an effective way to reduce cycle times. However, if short set-up times are not feasible, at least not in the near term, then cycle time can be sensitive to the choice of batch size and the optimum batch size may be significantly greater than one (Hopp and Spearman, 1996). A useful rule of thumb suggested by Karmarkar, et. al. (1992) is that the ratio of batch run time to set-up time should be constant across all items being manufactured. Furthermore, this ratio should range between 2 and 20.

Karmarkar (1989) has investigated methods of capturing lead times and WIP effects in a deterministic planning model using the construct of a ‘clearing function’. Such a function describes the amount of output ‘cleared’ from a manufacturing facility as a function of its work-in-process. The basic form of the function is as follows (Karmarkar, 1989):

$$D = P \frac{WIP}{WIP + k} \quad (3)$$

Where:

P = nominal (maximum) production rate, and

k = a parameter for determining the clearing rate.

Karmarkar (1989) considers it possible to adapt clearing functions to a discrete period dynamic planning model that directly models WIP as well as finished inventories. Most importantly, Karmarkar (1989) notes that since lead times and output vary with loading, emphasis shifts to release plans, facility loading and WIP, rather than production plans and finished inventories as in the conventional linear planning models.

To depict the influence of variability Hopp and Spearman (1996) examined changes in factory throughput as a function of cycle times measured in multiples of raw process time. Raw process time is the average time it takes a job to be processed and does not include elements of queueing times. Figure 3.3 illustrates that in both cases cycle time can be reduced at the expense of throughput. Hopp and Spearman (1996) suggest,



however, it is of greater benefit to focus on the variability reduction as the preferred method of improvement.

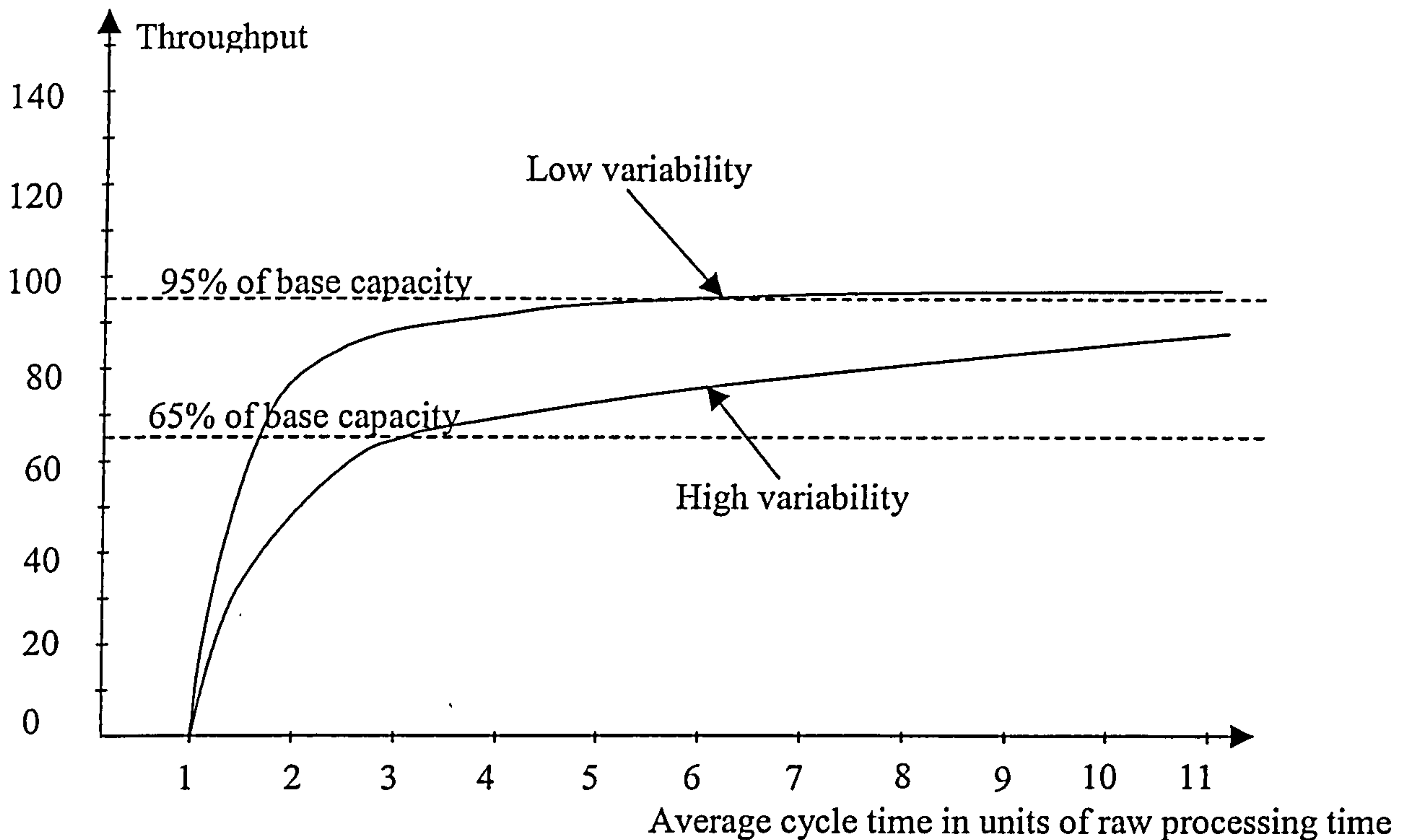


Figure 3.3 – Throughput as a function of cycle time (Hopp and Spearman, 1996)

All real systems contain some element of variability and, therefore, perfect customer service in terms of on-time deliveries is not possible. Since service levels depend on both lead times and cycle times it is important to clarify the distinction between them, ie cycle time is a random variable and lead time is a management constant. Here the two types of lead time are customer and manufacturing lead time where customer lead time is the amount of time allowed to fill a customer order from start to finish (ie all routings), while a manufacturing lead time is the time allowed on a particular routing.

Assuming that cycle times are normally distributed, manufacturing lead time ( $L$ ) can be defined, according to Hopp and Spearman (1996) as:

$$L = CT + z_s \sigma_{CT} \quad (4)$$

Where:

$CT$  = mean cycle time,  
 $\sigma^2_{CT}$  = cycle time variance, and  
 $z_s$  = desired service level.

An example of the above relationship is illustrated in Figure 3.4 which depicts cycle time distribution  $F(t)$ , density  $f(t)$  functions and the lead time  $LT$  required to guarantee 95 percent service levels. The additional 5 days above the mean, shown on the diagram, is called the safety time. Thus, the manufacturing lead time that yields a given service level is an increasing function of both the mean and variance of the cycle time of the routing (Hopp and Spearman, 1996).

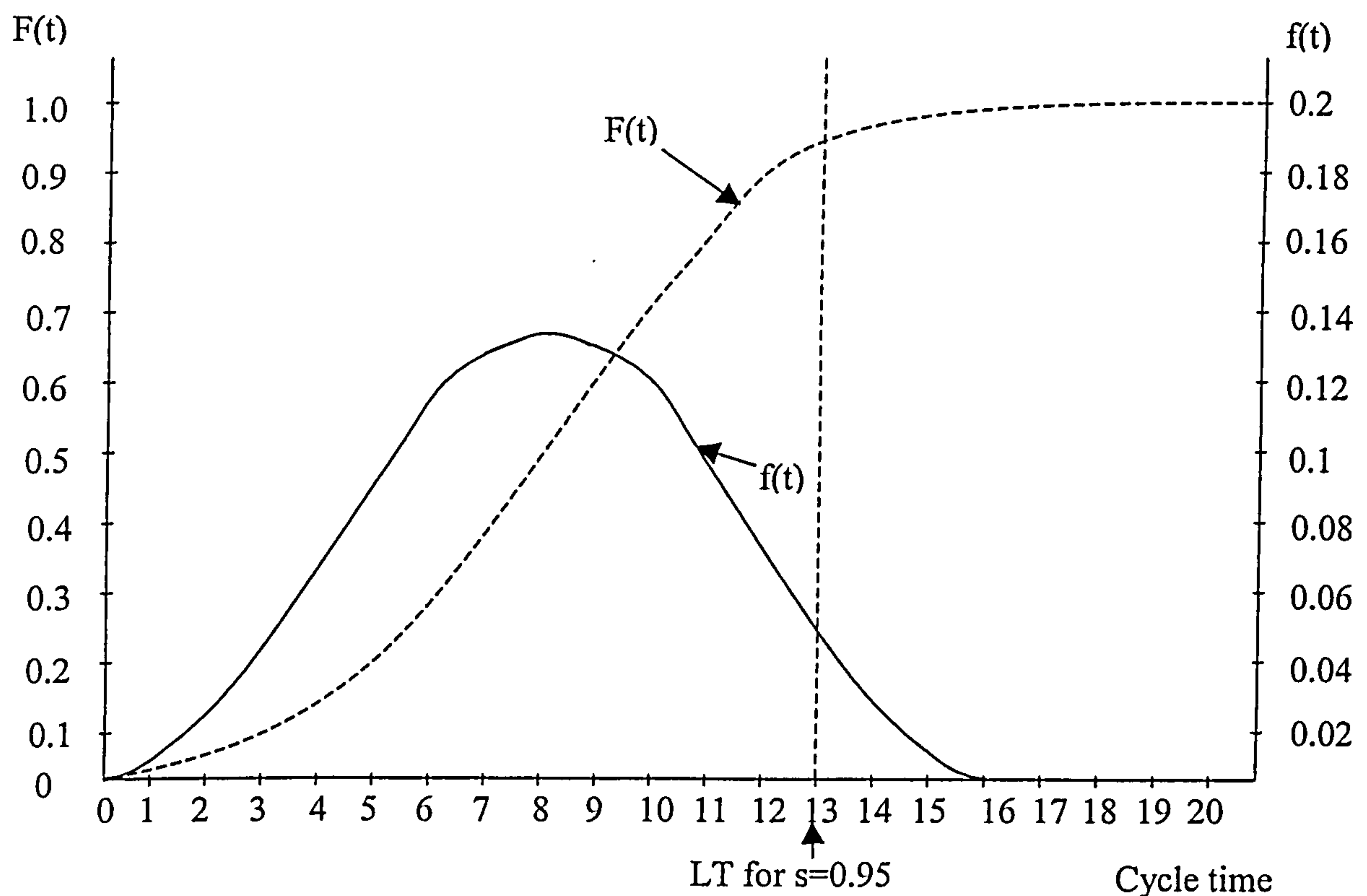


Figure 3.4 Distribution function for cycle time and required lead time (Hopp and Spearman, 1996)

### 3.2 Effects of Communication Time Delays

A primary goal of any manufacturing company is to maximise profitability through achieving competitive advantage over its rivals. However, it is becoming increasingly

difficult to gain such advantage through lower prices and better product functionality only, ie customers purchase products for the benefits to be derived from them and not from the products themselves. In an industrial market the benefits a customer expects to receive can be determined by different service performance factors such as (Christopher, 1992; Ross, 2000):

- a) order lead times that meet customer requirements,
- b) elimination of order-size constraints that enable just-in-time deliveries,
- c) frequency of delivery,
- d) order completeness, and
- e) delivery reliability.

In terms of logistics systems their purpose is to provide customers with high service performance levels through enabling faster and more efficient business processes, eg improved delivery performance derived from the ability to generate improved production plans.

An essential requirement needed to improve the validity of planning is the timely passing of information throughout the business (Souza, et. al., 2000; Parker, 2000a). A major constraint to this objective, within a typical company, is the wide variety of business processes on each of the main organisational levels and many processes on many levels as illustrated by Figure 3.5 (Towill, 1996). These processes range from planning and control processes at the management level, through major processes covering aspects of activities, such as design, purchasing, manufacturing, delivery and customer services, to large numbers of processes and procedures covering such functions as inventory picking, delivery and invoicing.



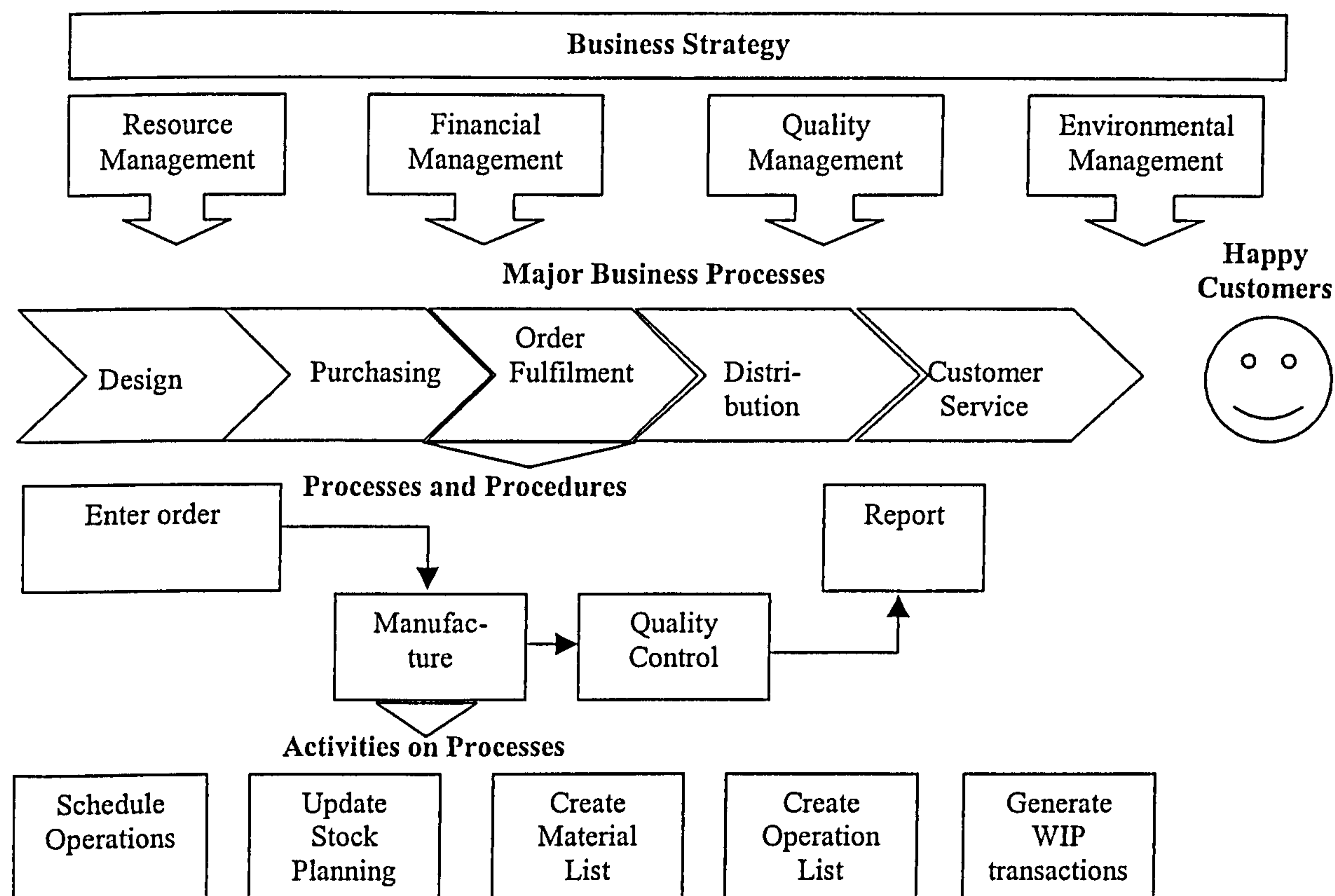


Figure 3.5 Levels of Business Processes

Of particular importance in terms of speed at which information is exchanged is the transfer of demand level data to production (Layden, 1998; Souza, et. al., 2000). MRP batch processing methods have been shown to result in long time delays in this communication process. These delays, in turn, lead to system oscillations with high amplitude (Layden, 1998). The consequences of long time delays within a supply chain is shown in Figure 3.6 (Forrester, 1961) which illustrates the dynamic response of a 3-stage supply chain, manufacturer-distributor-retailer, with 2-week time delays (reorder cycle) between stages. This system has zero forecast error, but response to a single input event of a one-time 10% increase in order rate produces a 50% increase in demand against the factory several weeks after the initial 10% increase took place. The system then oscillates for 15 months in response to this single event, ie clearly emphasising the importance of reducing communication times delays through improved supply chain integration activities.

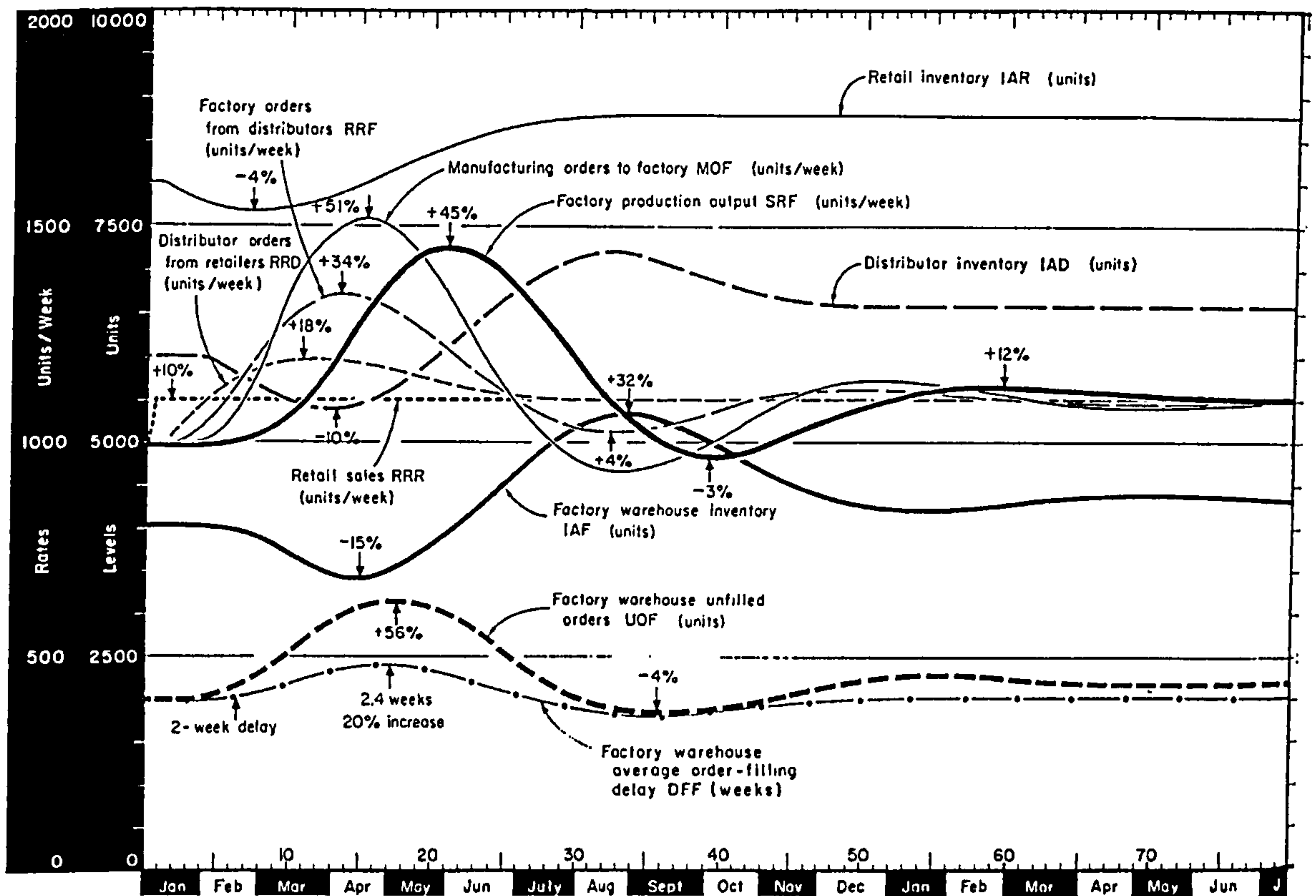


Figure 3.6 - Supply Chain Response to 10 % Increase in Sales Demand (Forrester, 1961)

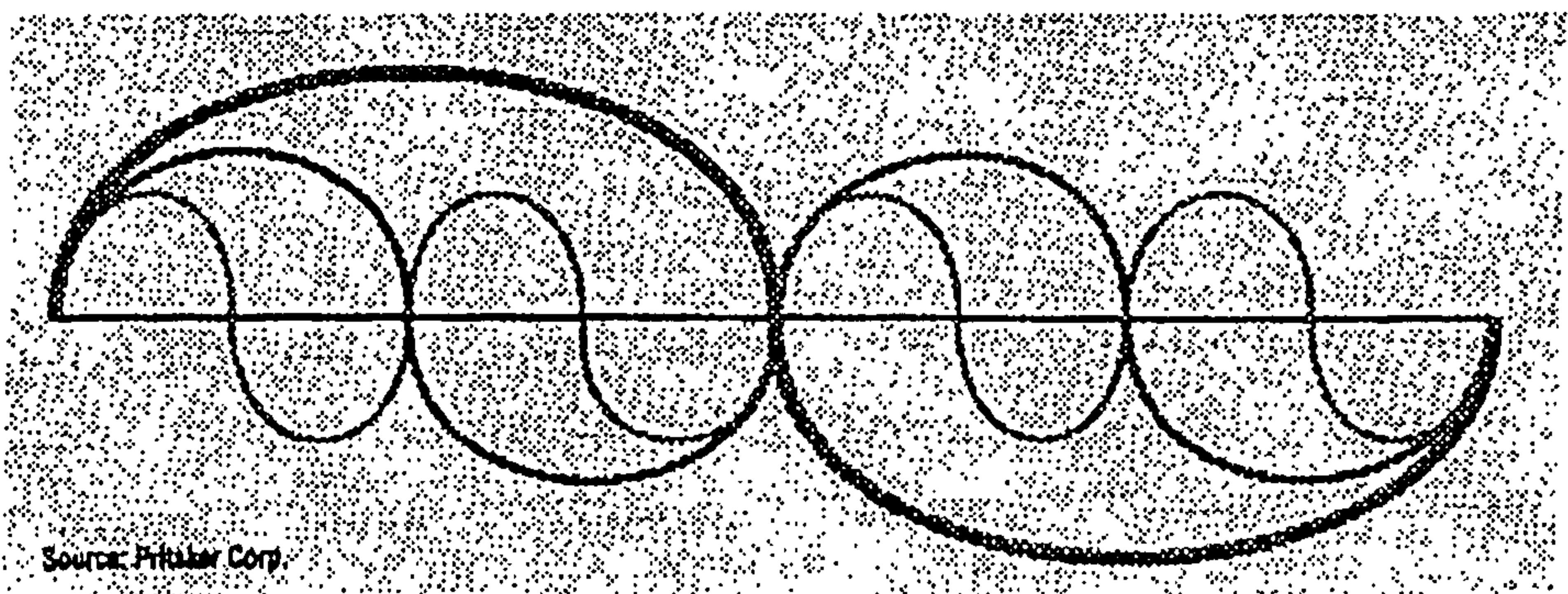
Although time delays in a sequential communication process are inevitable as the simple example in Figure 3.7 shows, when the delay time is halved, the amplitude of oscillations is also halved, whilst the frequency is doubled. The reduced amplitudes will reduce the oscillations in inventory levels and resource requirements and, therefore, improve a production plant's responsiveness to changes in demand. It is important to note here that the responsiveness of the factory, and not suppliers and distributors, dictates the amount of inventory needed in a supply chain. Hence the ability to reduce in-plant response time is a key to reducing the level of inventory required to support the customer delivery expectations (Blumenfeld, et. al., 1999; Layden, 1998; Souza, et. al., 2000; Stalk, 1988) within the supply chain. The factory dynamics will control the overall supply chain inventory situation, even though most of the inventory is elsewhere in supply chain.

To gain control over system dynamic behaviour new supply chain collaboration and integration approaches need to be developed to address these time delays in the



communication process. Zero-latency strategies have emerged (Enslow, 1999) in which latency represents the time taken for a system to respond to an input. Viewing the modern enterprise as a complex system, a zero-latency strategy implies that all parts of the enterprise can respond to events as soon as they become known to any one part of the enterprise. There is a variety of middle-ware and supply-chain technologies to implement zero-latency with most of these systems using some form of messaging middle-ware. In this respect, the Internet often plays an important role in distributing the information among participants. When deciding on a network structure, basic options exist (Layden, 1998; Souza, et. al., 2000), ie:

- a) eliminate the delays completely through broadcast communication, or
- b) reduce the time delays directly through faster communication.



Simple oscillation patterns illustrate the effect of changing time delays. Note that when the delay time is halved, the amplitude is halved while frequency is doubled.

Figure 3.7 - Effects of Reducing Time Delays

The broadcast communication method, illustrated in Figure 3.8 has been proven to be of more effectiveness (Souza, et. al., 2000).



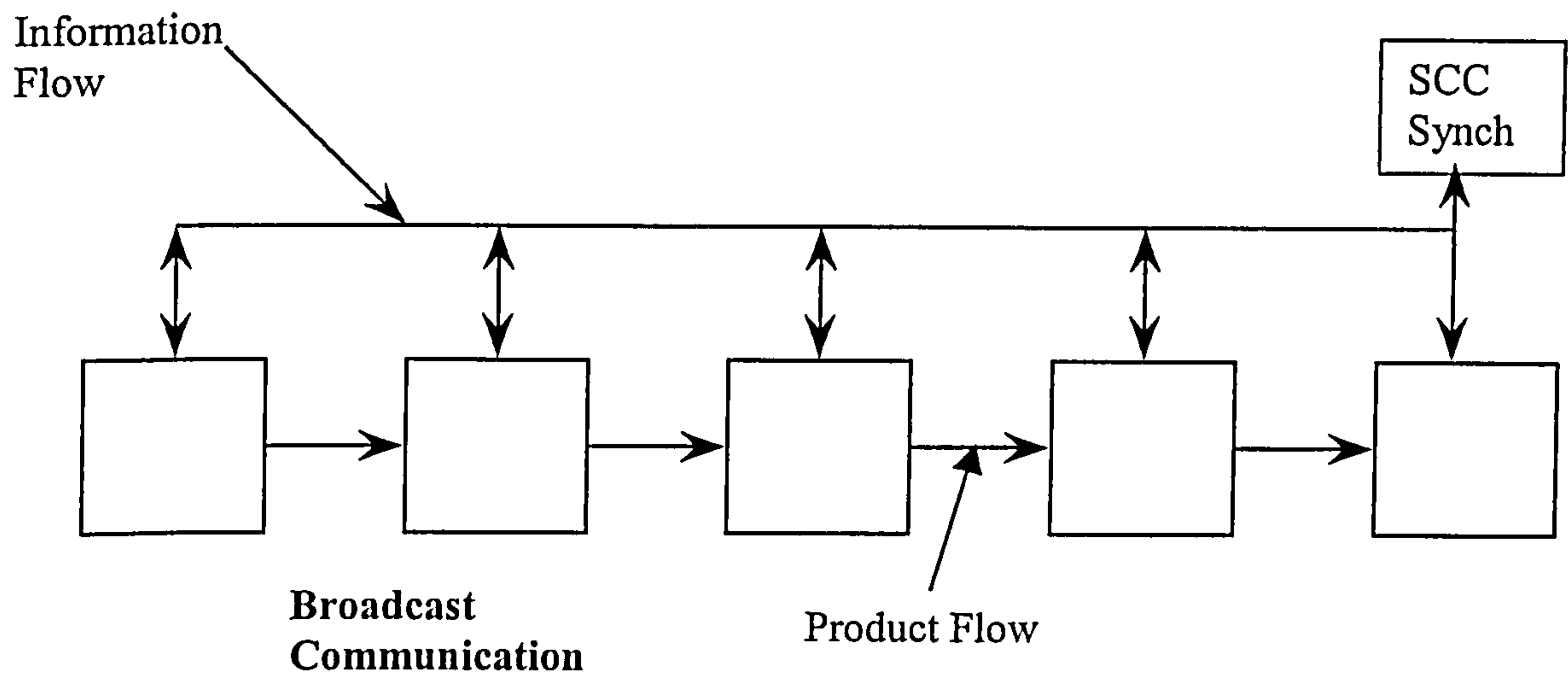
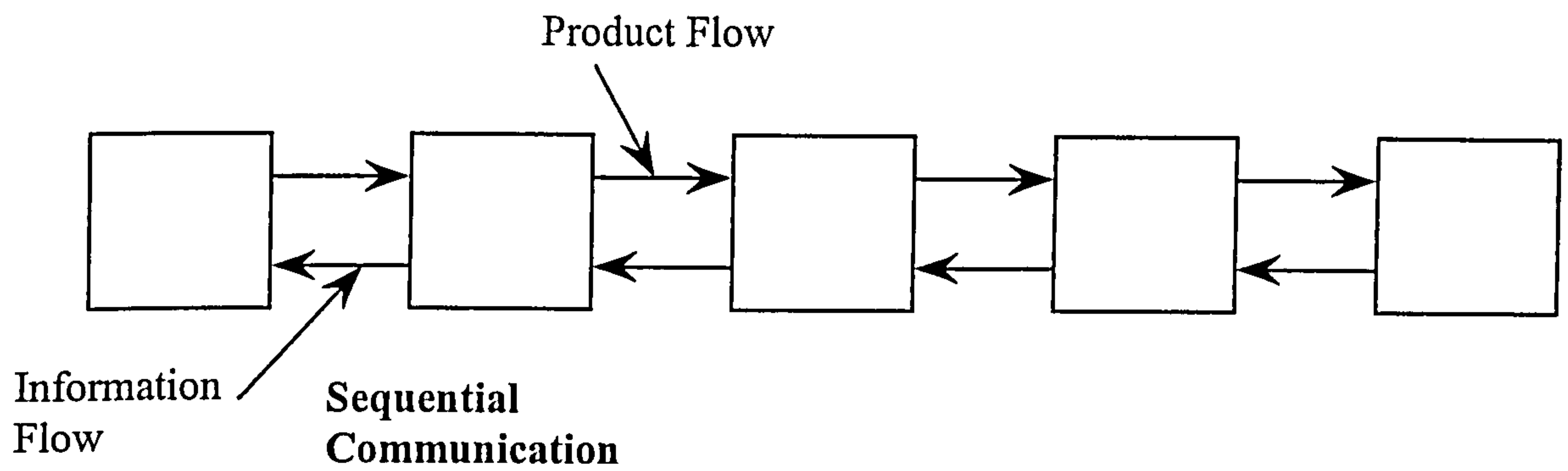


Figure 3.8 - Broadcast Communication (Layden, 1998)

Souza, et. al., (2000) point out that in terms of a system's dynamic performance improvement, eliminating information delays is more beneficial than shortening material supply delays.

### ***3.3 Effects of current information technologies***

There are fundamental factors of the business opportunities of the 21<sup>st</sup> century that set the guidelines for the future information systems in supporting business operations (Ross, 2000), ie:

- a) the unpredictability of how business will be conducted in the future with technology drastically changing the possibilities and scope of business rapidly,

- b) the increasing speed of change, where successful companies in the future can quickly address new possibilities and counter new threats in the marketplace, and
- c) the internationalisation of business, where the Internet, communications and transportation converts the marketplace from a closed national market to an open global market, although national culture and tradition in business on the same time has to be respected.

For efficient operations the information system supporting a company's logistics processes has to mirror the above fundamental demands effectively and economically. Since one cannot accurately predict how business will be conducted in the future, it must be simple and cost-efficient to change the way, a supply chain management system handles the information. Hence, as Allen, et. al. (1998) point out the core of future information systems has to be fundamentally structured around managing changing processes in a company.

It is becoming increasingly essential to provide the facilities for integrating previously heterogeneous systems into a single network characterised with seamless communication (Allen, et. al., 1998; Tan and Shaw, 1998). Such systems should be capable, of interfacing with external applications, addressing the future needs of business-to-business and business-to-consumer commerce on the Internet, and managing supply chains. Within this framework, it must be possible for users to quickly change the content and sequence of user-defined processes in the supply chain planning system, without the need for supplier intervention (Allen, et. al., 1998). For example, supply chain planning systems must, within the same structure, be able to abide to an individual country's language, culture, practices and legal requirements.

In order to generate facilities that are capable of rapid change the business component approach can be adopted. This approach consists of a large number of small building blocks of business application logic. These building blocks are capable of being grouped together and sequenced in terms of business processes according to the needs of the users. Hence such systems can mirror the processes within supply chains to facilitate seamless task and resource sharing between different network nodes (Tan and Shaw, 1998). Business components possess a standardised interface that enables

external components to be integrated and interfaced directly into a company s processes (Allen, et. al., 1998). Hence users are able, within the structure of the system, to change processes. To achieve this the design and implementation of supply chain systems needs to be process orientated, ie this allows users to ensure information systems support business processes.

A component is a physical encapsulation of one or more services that are made available through its interfaces (Allen, et. al., 1998). The services it provides and how it interacts with other components define a component. All that is known about a component externally is its interface. A consumer component can call upon the services of a supplier component without regard to how or where the supplier component is implemented. For example, a retailer could have a GUI (Graphical User Interface) component installed on its system. This GUI component could communicate with a capable-to-promise component that resides in a manufacturer s system in order to perform material and capacity availability tests.

The processes are divided into procedures that are, themselves, formed by business components as illustrated in Figure 3.9. The components can normally be shared amongst different procedures.

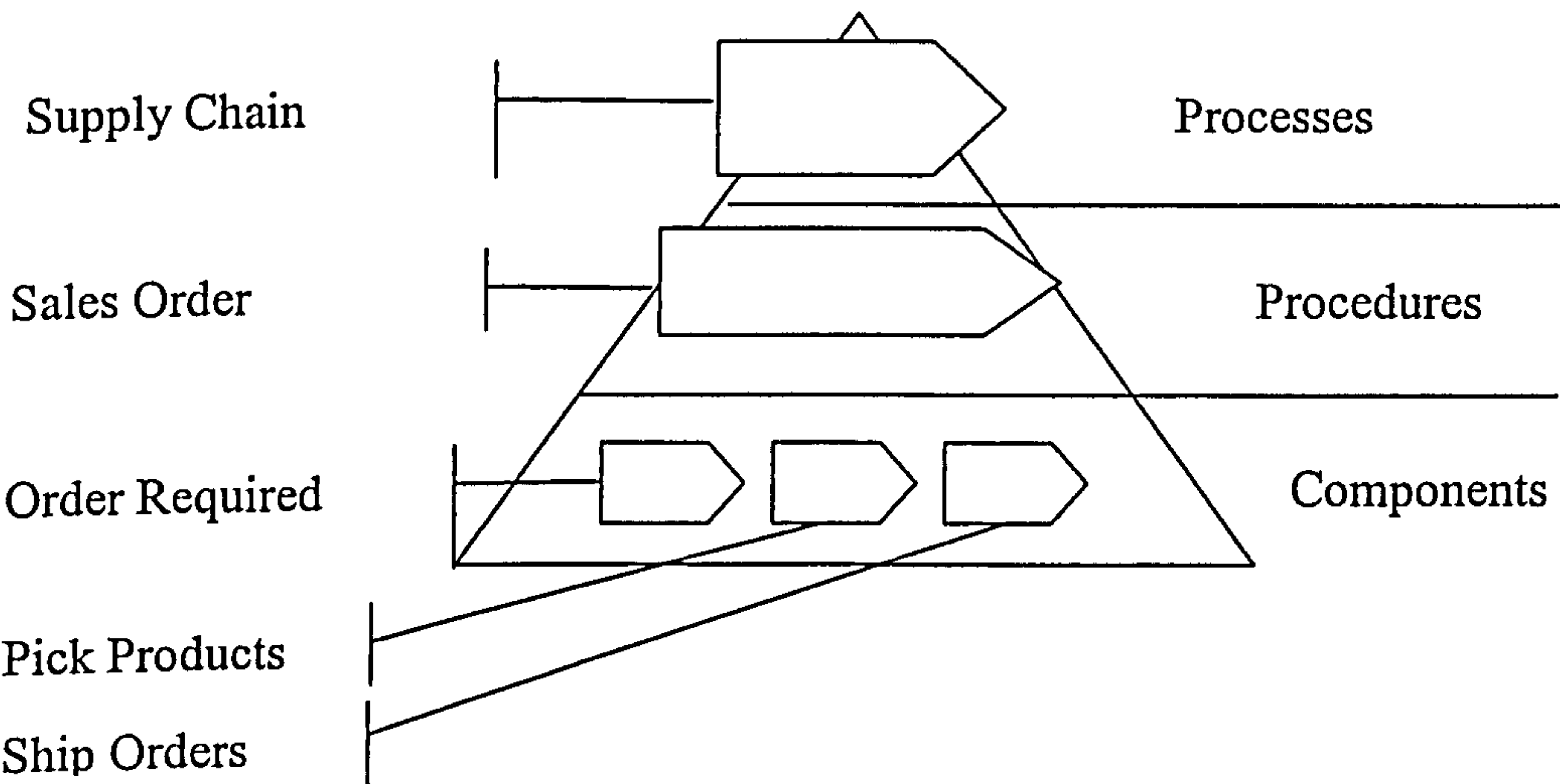


Figure 3.9 - Formation of processes from procedures and components (Allen, et. al., 1998)



The component based approach to building software offers a novel method of handling customer specific functionality. For functionality to be modified or replaced an appropriate approach is to simply replace an individual component. For example, a third party vendor can offer a component with identical interfaces as an ERP system warehouse component, but with additional functionality.

### ***3.4 Limitations of existing planning and operating concepts***

Supply chain optimisation techniques (Lapide, 1998c) have been developed that attempt to:

- a) determine a feasible plan that meets all demand needs and supply limitations, and
- b) optimise the plan in relation to corporate goals such as low cost and profitability.

Generally, optimisation problems seek a solution where decisions need to be made in a constrained or limited resource environment. Examples of constraints placed upon the supply plan include (Lapide, 1998c):

- a) a supplier s capacity to produce raw materials or components,
- b) a production line that can only run for a specified number of hours per day, and
- c) a customer s or distribution centre s capacity to handle and process receipts.

Optimisation procedures seek one or more of the following (Lapide, 1998c) objectives:

- a) maximising profits or margins,
- b) minimising supply chain costs or cycle times,
- c) maximising customer service,
- d) minimising tardiness,
- e) maximising production throughput, and/or
- f) satisfying all customer demand.

Models that adequately represent the reality and quality of data that exist within business environments are important elements in optimisation-based planning processes in order to ensure the development of meaningful and executable plans. In addition to this it is important to have the most appropriate solution technique for the problem size and type. In the area of supply chain optimisation, the basic types of solution techniques are as follows (Lapide, 1998c):

- a) mathematical programming, ie largely linear and mixed integer programming,
- b) heuristics that include scheduling methods such as the Theory of Constraints or Simulated Annealing,
- c) genetic algorithms, and
- d) full enumeration of all possible solutions.

Generally, mathematical programming methods are used for generating strategic and higher level tactical plans. These methods are restricted to solving linear and integer-based planning models that are commonly used in strategic levels of planning (Korpela and Lehmusvaara, 1999). Tactical and operational models are normally non-linear and are too complex to be solved using mathematical programming methods. For this reason, heuristic methods are generally used for making tactical and operational plans. Genetic algorithms are used primarily in operational planning to consider a large number of possible solutions (Disney, et. al., 1997). While not a formal optimisation technique, exhaustive enumeration is predicated on using the computer to find a solution by looking at all possible alternative plans. This method proves useful in simple supply chain situations (Lapide, 1998c). There are a variety of optimisation techniques available which makes it difficult to find the most appropriate tool for the planning situation under consideration.

From the perspective of supply chain dynamics the main disadvantage of using optimisation techniques is the need to develop plans for specific planning periods, ie the planning process is, therefore, inherently a batch process. Because batch processes cause time delays in the planning process the result is normally that by the time the plan



is optimised and ready for implementing the actual demand levels used to generate the plan have changed and hence the plan is no longer valid (Layden, 2000).

Furthermore, as depicted in Figure 3.10 period planning processes used on an operational level result in prolonged order launch periods needed for such activities as dispatching, sequencing, and printing of documents. Thus, the use of optimisation algorithms can be justified in longer-term strategic and tactical planning where calculations are performed on a weekly, monthly or yearly basis.

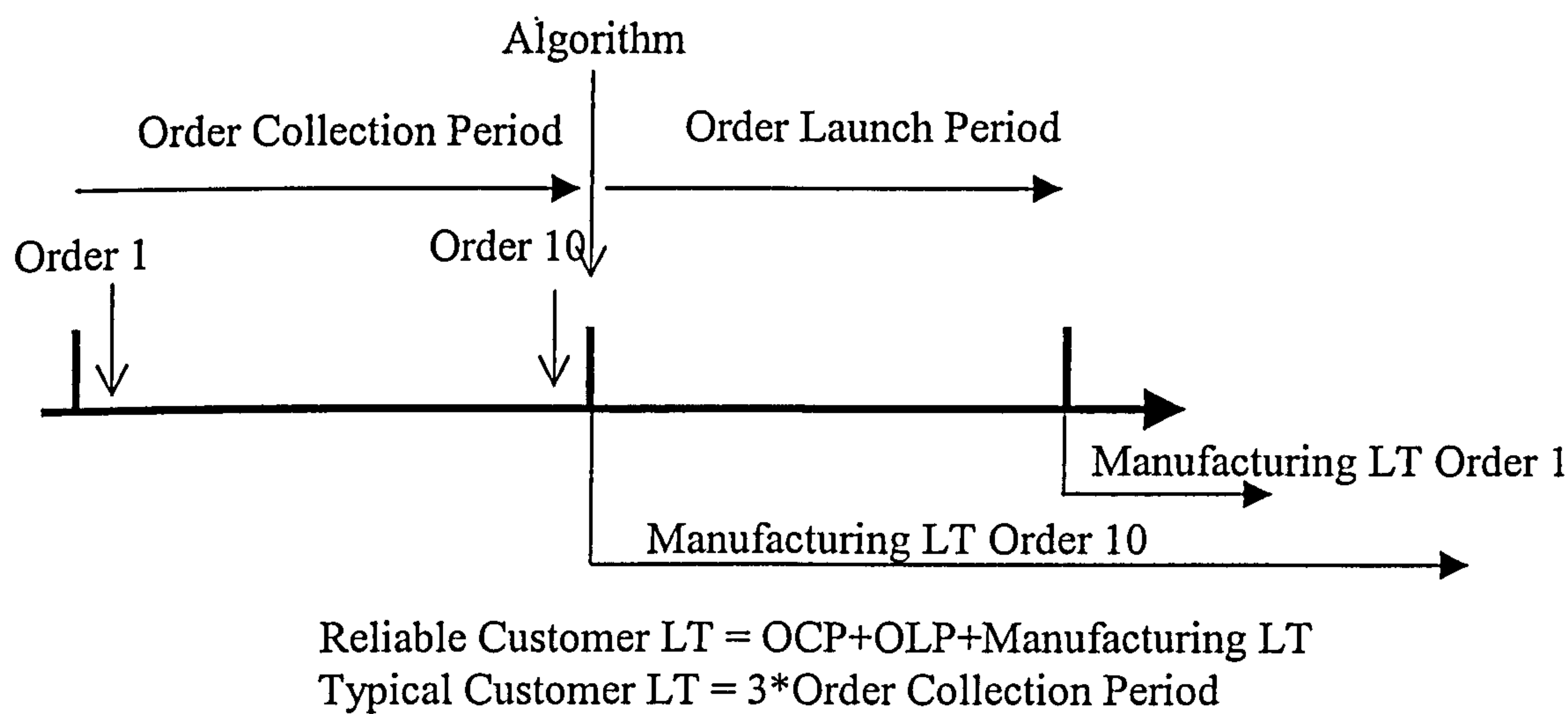


Figure 3.10    Prolonged order launch as a result of period process planning (Layden, 2000)

MRP, in essence, operates in a similar fashion, ie after inputting customer orders a simple calculation algorithm is applied and the manufacturing orders generated are then pushed to the shop floor. Hence, traditional MRP is seen, when used to cope with volatile customer demand and due to the periodic conduct of planning, to be one of the major contributors to increasing demand oscillations within supply chains (Layden, 2000).

In light of the limitations of existing MRP based push techniques, the use, during the past decade, of pull techniques, such as Just-in-Time (JIT) and CONWIP, has been steadily increasing amongst manufacturers. The basis of JIT inventory control is demand pull of products through the factory and/or through the supply pipeline.



However, from the point of view of operations, pull systems are no longer adequate (Layden, 2000; Ross, 2000) due to the turbulence that exists in increasingly crowded and competitive marketplaces. This effect coupled with the instant communications provided by the Internet can result in constant changes to supply chain plans. Conditions can, therefore, exist in which planning efforts in distribution or production are no longer effective. Under these conditions, for example, order cancellations must be communicated deep into the supply chain to prevent work continuing (Stalk and Hout, 1990).

The key limitations of existing planning tools and pull strategies are the following (Layden, 2000; Ross, 2000):

- i) Costly inventory is being used as information.
- ii) Planning tools are still in batch mode, causing inventory accumulations and scrap.
- iii) Information is best understood inside plant operations, poorly understood between plants and enterprises.
- iv) Changes to information that affect the replenishment or production plan do not travel fast enough to shift all work from unproductive to productive ends.
- v) Reservations for orders throughout the supply chain are not possible for better promise dates.
- vi) The disruption caused by engineering changes is difficult to minimise.

## 4 Supply Chain Planning

### 4.1 *Introduction*

The introduction of Advanced Planning and Scheduling (APS) has represented a significant change in manufacturing systems from that of the emergence and application of MRP over 20 years ago. With APS, many of the compromises and restrictions inherent in the MRP approach are removed and modern tools are applied to planning. This chapter examines the role of APS planning techniques in providing dynamic planning tools for supply chains.

### 4.2 *Material Requirements Planning*

Prior to the introduction of MRP material replenishment planning methods were based on variations of the re-order point concept. These methods with their focus on past usage of materials were backward-looking which MRP overcame by enabling replenishment based on future needs rather than past usage.

Despite its success the MRP process has significant restrictions in its use, particularly with respect to its use as a suitable planning system within dynamic supply chains, since it requires the following assumptions (Chizzo, 1998; Turbide, 1998a), ie:

- a) all customers, products, and materials are assumed of equal importance and hence MRP cannot deal with the complexity of component or supplier substitutions, ie this requires identifying alternatives and quickly evaluating and resolving conflicts,
- b) lead times are assumed fixed and known,
- c) resource capacity is assumed to be available,
- d) requirements calculation logic is a top-down, one-pass, sequential process that may optimise the requirements of individual components but does not necessarily optimise on a global bill-of-material basis,
- e) broad, simultaneous data sharing is not allowed hence the data sharing capabilities are not available for co-ordinating supply chain activities across multiple sites of multiple resource entities such as transportation, plant production and distribution,



- f) requirements processing can typically take hours to complete leading to many companies performing MRP processing only at night or at weekends, ie there is no opportunity to regenerate the plan during the normal workday to assess the impact of changes and MRP provides no simulation or decision support capability.
- g) may produce inaccurate views of the true costs associated with activities in the supply chain.

### ***4.3 Finite Capacity Scheduling***

When first introduced MRP was a significant advance and for more than two decades it has provided significant management information to many thousands of manufacturers. However, with advances in technology new techniques have evolved to take advantage of the increased processing speeds and memory capacity of computers. One such advance was the introduction of Finite Capacity Scheduling (FCS), to compensate for the infinite loading and fixed lead-time assumptions inherent in MRP.

In reality manufacturing and procurement lead-times are not constant but vary with such factors as level of shop loading, priorities, availability of equipment and personnel. The MRP approach cannot consider this information but uses standard lead times for components to determine the start date by back scheduling from the due date of a manufacturing order. Capacity Requirements Planning (CRP) was then used to identify under-load and overload situations and to resolve them. In this respect CRP is essentially a reporting function although often available with limited simulation capabilities that allowed users to test the affect of various solutions to capacity loading problems.

FCS is aimed at replacing the manual CRP process with program logic that follows user-entered rules to direct it to resolve load-to-capacity mismatches. That is, FCS adjusts the schedule and/or the capacity, as much as its rules will allow, ensuring all the work is realistically planned. Any planning situations that cannot be resolved by the FCS program are set aside for human attention. Besides needing time-consuming manual planning which inevitably leads to time delays in passing demand to a shop-floor, there are a number of other restrictions inherent in finite scheduling tools



(Layden, 1999), particularly with respect to the use of FCS tools as suitable planning systems within dynamic supply chains, ie:

- i) Primarily, FCS tools schedule orders released to the plant by sequencing them in work centre queues that load the plant based on available capacity and known constraints. FCS tools, therefore, do not access planned orders nor do they have the visibility to resolve constraints early in the planning process.
- ii) Many finite scheduling tools merely consider capacity and/or labour constraints and not constraints associated with the provision of materials. These tools are also not capable of launching a material requisition.
- iii) Finite schedulers consider the level of capacity available as finite and are not capable of identifying additional capacity that would be required to meet customer request dates.
- iv) Finite scheduling tools are generally based on MRP generated orders, which are often driven from forecasted demand rather than actual orders.

#### **4.4 *Fast MRP***

The further major advance in the manufacturing planning area was Fast MRP , a technological advancement rather than a conceptual one. A fast MRP system employs conventional MRP logic but exploits the processing speed and abundant memory of modern computers to accomplish the planning process in minutes rather than hours. Initially using UNIX Workstations and later high performance PCs, the Fast MRP systems were designed to load all program logic and the entire planning database into the computer system's memory where the calculation could proceed at the speed of the processor, uninhibited by slow read-write to and from disk drives. Fast MRP introduced the concept of using a separate processor strictly for planning calculations.

Fast MRP provided decision support by allowing users to examine alternative planning scenarios and what if cases and to compare, within a relatively short period of time, the results of alternative planning runs. Once an acceptable plan had been identified, through lack of integration, Fast MRP would then need to make the necessary changes to the operational database. This would involve the operational MRP system's planning files being down-loaded to the Fast MRP system where they would be processed in a

clone or shadow environment. Later versions of Fast MRP systems overcame this limitation and were designed to up-load the new plan to the main operating system. Processing was, however, still performed separately and only connected to the operational system on a batch load basis. With respect to the use of such a tool as a suitable planning system within dynamic supply chains this represents a major limitation.

#### *4.5 Advanced Planning and Scheduling (APS)*

During the late 1980s and early 1990s, manufacturers began viewing the forecasting and planning of production, distribution, and transportation as part of a total supply chain planning process. From this extended enterprise perspective, the limitations of MRP systems became more severe primarily due to their batch processing characteristics.

The development of APS systems began with the introduction of artificial intelligence, rules-based logic, and heuristics to the planning process. The APS planning philosophy combined with these developments the finite capacity approach, memory-resident fast planning, advanced planning logic and innovative planning ideas which allowed APS to consider a wider range of constraints including (Bermudez, 1998a; Symix, 2000):

- a) material availability,
- b) machine and labour capacity,
- c) customer service level requirements,
- d) due dates,
- e) inventory safety stock levels,
- f) cost,
- g) distribution requirements, and
- h) sequencing for set-up efficiency.

APS tools differ from traditional master production scheduling (MPS) and material requirements planning in distinct ways (Bermudez, 1998a), ie APS planning and scheduling tools:

- i) View capacity and materials simultaneously, not sequentially through a series of hierarchical steps.
- ii) View capacity as both infinite and finite and not solely as infinite.
- iii) Possess the processing speed and computational power to devise plans and recognise constraint exceptions within minutes, not days or hours.
- iv) Are capable of operating in real-time, ie immediately upon receipt of batch files, remote procedural calls or automated equipment updates.
- v) Are driven by a model of a given plant and a sophisticated calculation engine that uses algorithms based on multiple business objectives, costs and detailed scheduling heuristics. In comparison traditional MRP based planning uses the same gross to net requirements algorithm and an infinite loading feedback loop to address multiple objectives.
- vi) Do not aggregate demand into batches but deal with each order independently and can aggregate demand or break it down further into separate orders for individual operations.

In summary APS replaces the traditional MPS/MRP four-step planning process, illustrated in Figure 4.1, with a one-step planning process where all traditional MRP steps are conducted simultaneously and transparently.

The need to re-orientate businesses towards customers and the new enabling technologies such as APS have given rise to the Japanese concept of Seiban (Sei order), where a single customer order is directly connected to the operations on the factory floor (Layden, 1999). This makes it possible for different order fulfilment groups to monitor orders throughout the whole cycle, ie from order entry to delivery.



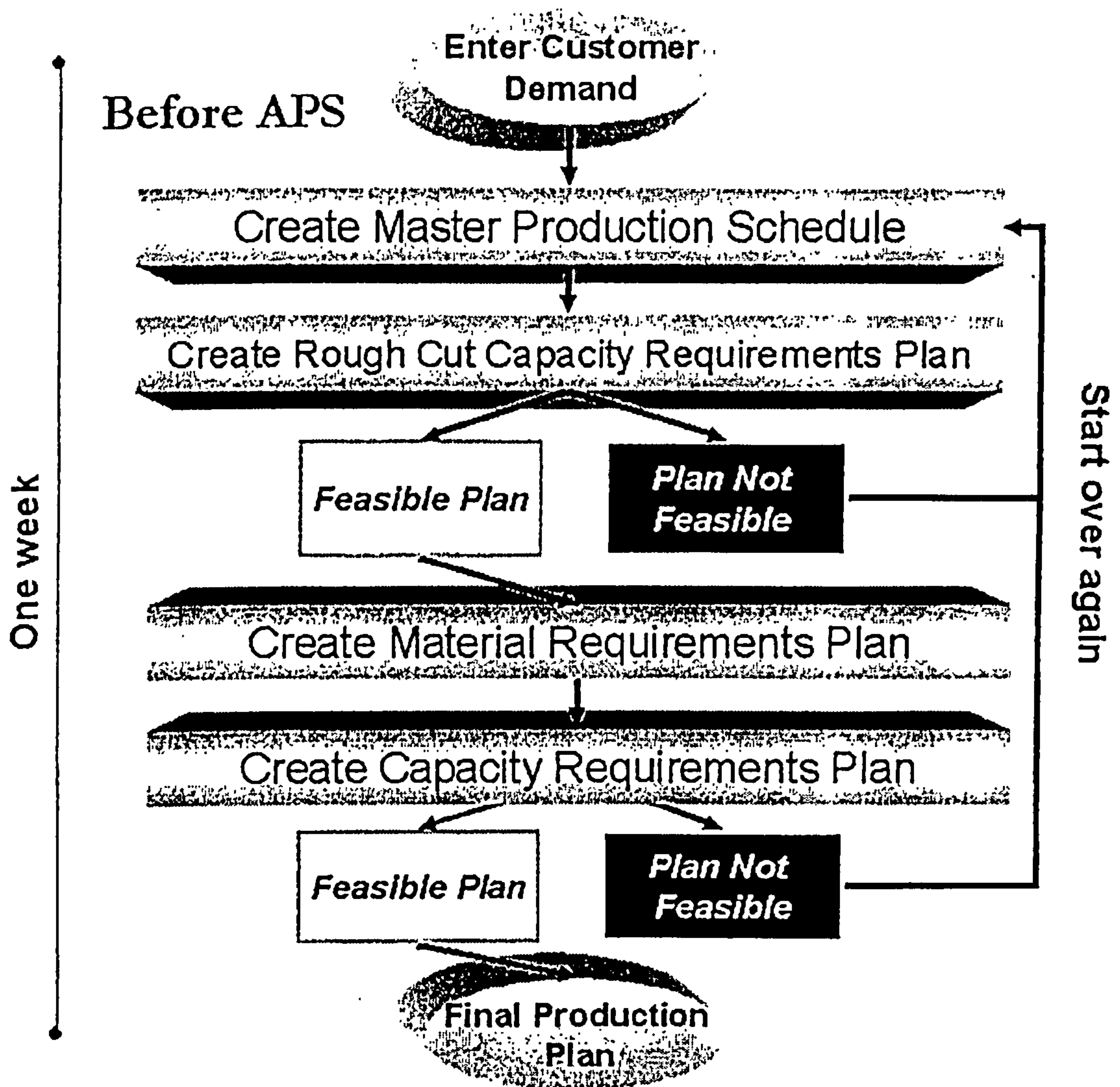


Figure 4.1 Traditional MRP (Turbide, 1998b)

APS is, therefore, recognised as a supply chain management (SCM) system (Chambers, 1996) since it is possible using APS tools to plan and schedule orders and resource constraints both across multiple business sites and along supply chains. Hence areas such as demand management, production planning, scheduling through to distribution and transportation planning all benefit from the APS methodology. Many of the new APS systems allow users to build virtual models of their supply chains and simulate various planning and scheduling scenarios.

APS has been identified as being most appropriate to companies whose business environments include (Turbide, 1998b):

- i) Extremely dynamic order activity.
- ii) Rapid response configure-to-order situations.
- iii) One or few resources controlling plant throughput.
- iv) Continuous run manufacturing with critical run sequencing.
- v) Campaign production situations in which products are scheduled together based on predetermined constraints.

A common application of APS is the promulgation of Capable-to-Promise (CTP) dates (Hill, 1999) across multiple business sites (ie nodes). Figure 4.2 illustrates this approach, ie each node, represented by a rectangular box, has its own APS system and nodes are connected by electronic means such as the Internet. After receiving a customer order a downstream node sends out requests concerning component availability to nodes upstream, ie requests are sent to alternative suppliers of ordered products. A request contains information about the product type, the quantity, and the date the product is requested. In response to such a request the production planning is performed at the node which received the request. If, as a result of this production planning, material or capacity shortages are identified, then requests are sent to the suppliers of this particular node (ie to upstream nodes).

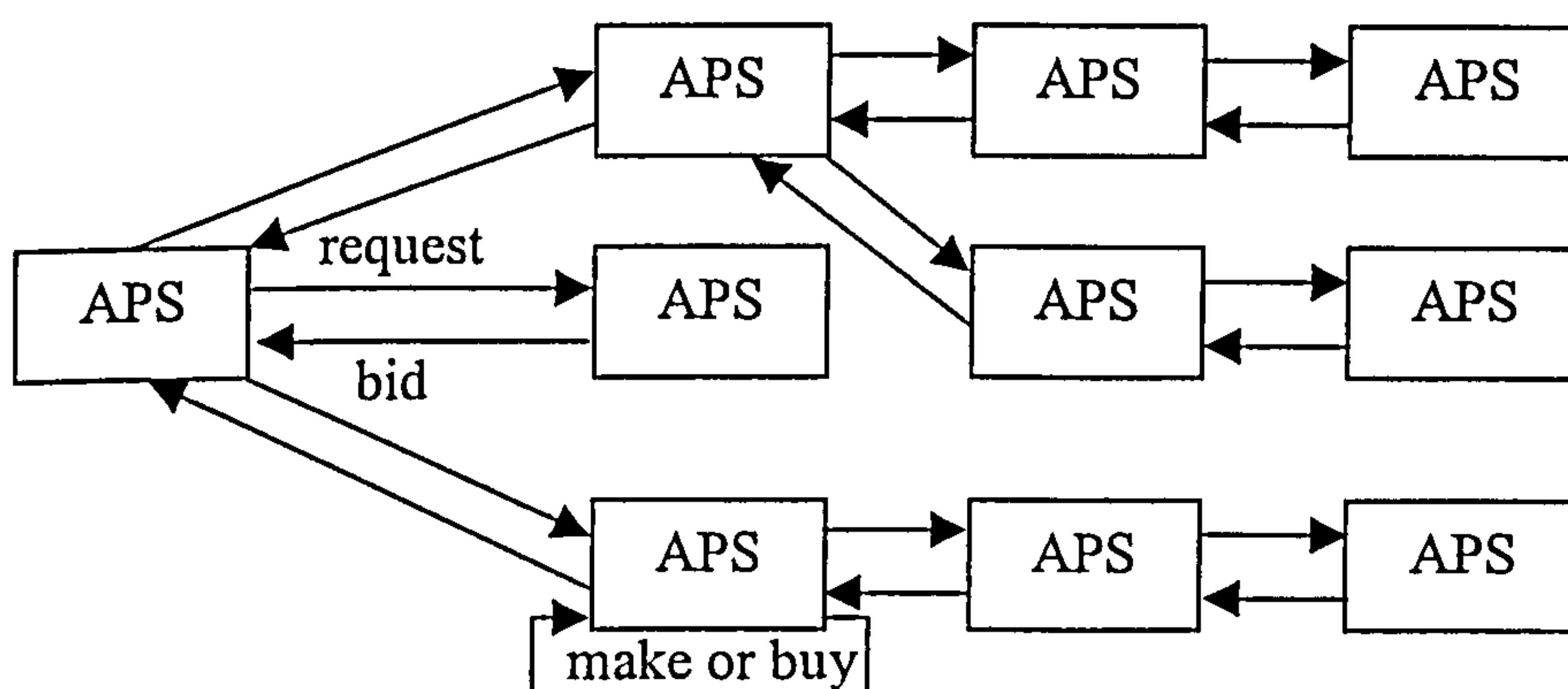


Figure 4.2 CTP across multiple sites

Therefore, an initial request sent by a downstream node can reach raw material suppliers, ie it depends on the material and capacity shortages at intermediate nodes. After performing the production planning bids are sent to respond to the received requests. Bids contain information about the actual delivery time when this request could be satisfied. After receiving bids they are evaluated to determine the best suppliers to source from. Hence, after receiving customer demand it is immediately broadcast to supplying nodes, which perform their planning functions and respond with delivery dates to promise, ie the supply routes are determined dynamically for each order.

Customer demand signals that are transmitted can be of a recursive nature in order to assist upstream companies in resolving complex make or buy decisions. Hence, purchase orders can be converted quickly into manufacturing orders and vice versa.

This flexible system is based on the use of distributed databases which provides a number of advantages (Layden, 2000) including:

- i) Information on inventory can be used instead of actual inventory to ensure reliability of delivery lead times.
- ii) Changes to an order or to logistics are instantly reflected in the work throughout the supply chain.
- iii) Logistics, production, and distribution capacity and inventory can be reserved throughout the supply chain network.
- iv) While one system is down other systems can remain operational.
- v) Support is provided for heterogeneous platforms that are easily configurable and extendable.

#### ***4.6 The need for ERP and APS integration***

APS is essentially a planning engine that does not include such functions as master file maintenance and control, and transaction entry and management to capture inventory movement, shop activity, customer orders and shipments (Michel, 2000). In order for APS to function, therefore, it is normally integrated with the operational parts



of a manufacturer s business system using an Enterprise Requirements Planning (ERP) package, as illustrated in Figure 4.3.

An essential aspect, in relation to its use within supply chains, of APS integration with ERP functions is the provision of on-line access to real-time information. Implementation based merely on batch updates would, when applied within a supply chain, be a self-defeating solution.

Of importance during this integration process is the provision of facilities for fast feedback both to and from the shop floor. In this respect demand data must be processed by APS and forwarded to a shop floor as quickly as possible. This two-way exchange of information must form a closed loop model similar to the planning structure provided by Manufacturing Resource Planning (MRPII) applications.

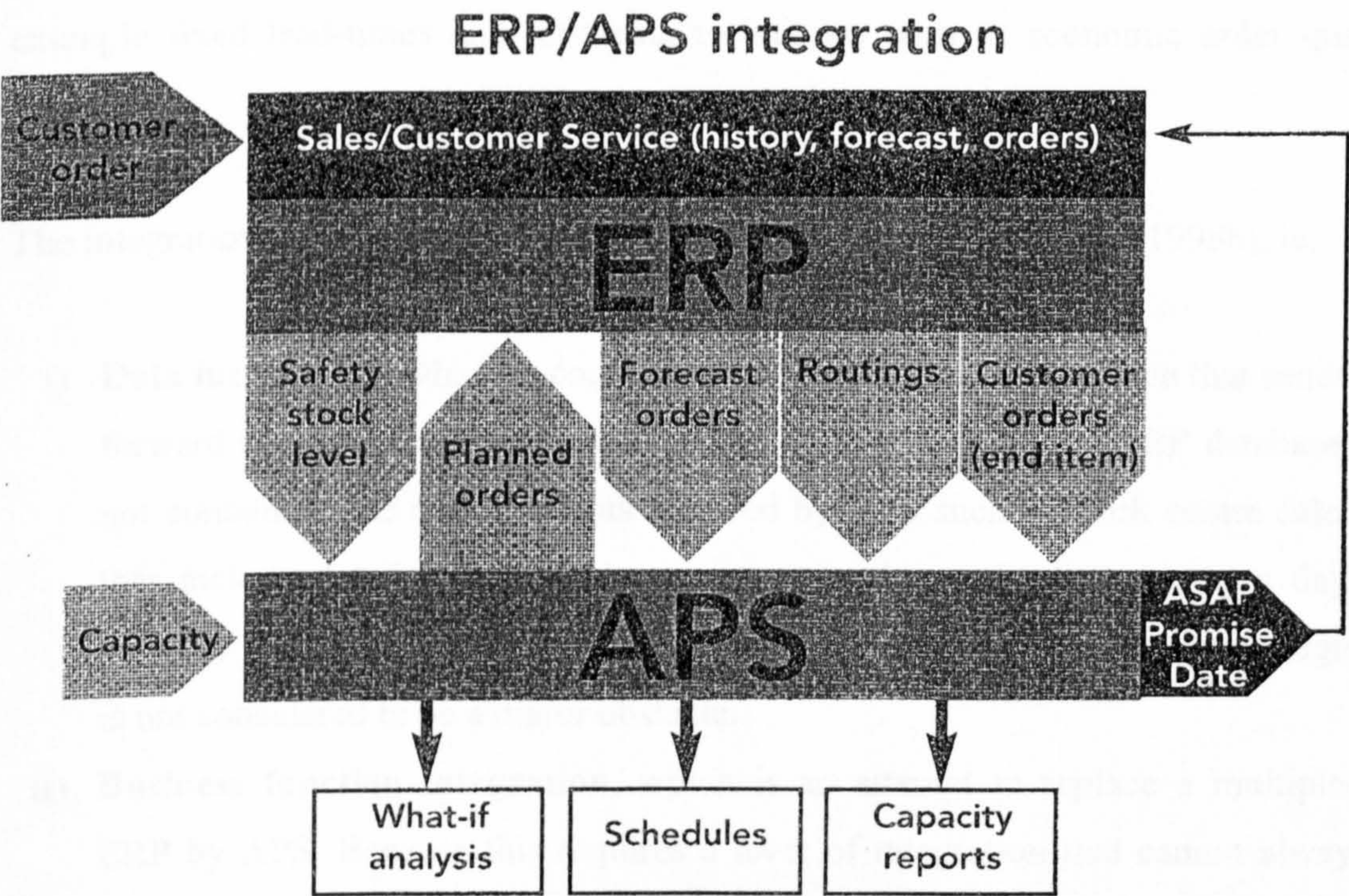


Figure 4.3 APS/ERP Integration (Turbide, 1998b)

Approaches that are employed by ERP vendors in obtaining APS functionality (Bermudez, 1998b, Turbide, 2000) include:



- i) Development of their own APS module.
- ii) Acquiring one or more APS suppliers and embedding those products into the their own ERP suite.
- iii) Forming a strategic alliance with a single APS vendor that allows for embedding the APS product into an ERP suite.
- iv) Developing marketing alliances with several APS vendors.

Integrating ERP with APS is a challenging task since these two types of systems were originally designed to operate in fundamentally different ways. For instance, ERP creates work orders from customer orders and explodes only through phantom items. APS on the other hand uses only customer order data, such as quantity and delivery date, and during planning calculations proceeds through the whole bill of manufacture. ERP planning calculations make use of information not required when using APS, for example fixed lead-times and lot-sizing techniques such as economic order quantity (EOQ).

The integration of APS and ERP requires two major steps (Bermudez, 1998b), ie:

- i) **Data integration**, which is concerned with setting up the interface that sends data forward and backward between ERP and APS. Generally, the ERP database does not contain all the data elements required by APS such as work centre calendars that include details of available capacity per day and when during a day this capacity is available, ie start and stop times. Despite these issues, data integration is not considered to be a major obstacle.
- ii) **Business function integration**, which is an attempt to replace a multiple-step ERP by APS. Because this requires a level of integration that cannot always be achieved, many companies produce plans partly using ERP and partly using APS. This requires maintaining duplicate records and ensuring that these records remain synchronised between the two systems. Achieving this level of integration is considered a challenge and hence it is anticipated that the preference to buy a system from a single vendor will force software developers to find ways for seamless APS and ERP integration.

4.7 Planning Levels and Scope of APS

APS systems perform a wide range of SCM functions and these functions are normally divided between three planning levels as illustrated in Figure 4.4. The challenge manufacturers face today is how to integrate and synchronise the planning activities between these three levels.

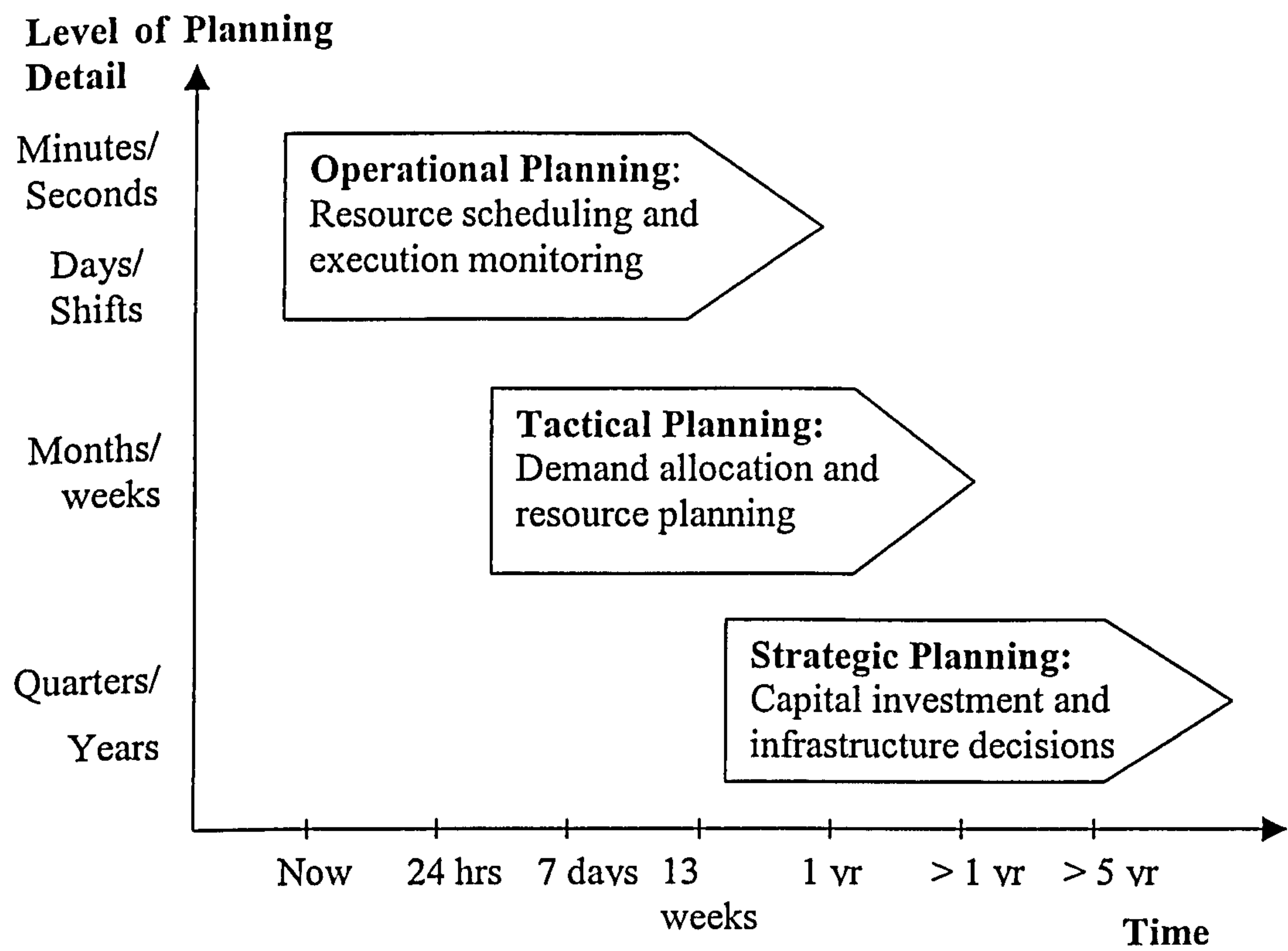


Figure 4.4 Three planning levels of SCM systems (Gumaer, 1998)

4.7.1 Strategic Planning

At the strategic level, the planning concern is with long-term decisions that often deal with problems of infrastructure such as the location of plants, warehouses, and distribution centres. These decisions typically have a one-to five-year planning horizon. However, the increased focus on out-sourcing manufacturing operations can result in shorter planning horizons. Strategic planning helps to determine how to compete successfully in any given market. Strategic planning can be used to structure material sourcing, production, and delivery of the target goods to the target market by providing



information on which markets to focus on, what competitive factors are important, and what product or product family is the leader in the product mix. At the strategic level, scheduling focuses on defining aggregate capacity, configuring a network of suppliers, warehouses, plants, and subcontractors, and planning the distribution channels required to satisfy demand (Dullin, 1998). At this planning level for specific environments eg chemical industry, mixed-integer programming has been found to be most suitable (Gumaer, 1998) since it considers constraints and costs as it determines low cost planning solutions. Although mixed-integer programming calculations are time consuming they are suitable for a strategic planning environment where planning occurs periodically, such as quarterly or annually, and run-time, therefore, is not a major consideration.

#### 4.7.2 Tactical Planning

At the tactical level, planning decisions normally revolve around the allocation of demand to the various plants, logistics facilities, and transportation links within the supply chain. Interdependence between tactical and strategic planning levels results in the effectiveness of tactical planning solutions being determined by the strategic plan (Gumaer, 1998). For example, a global manufacturer could increase the efficiency of its regional warehouses through a tactical planning tool that generates higher inventory turns. However, the potential at the strategic level for eliminating the warehouse, by optimal design of the supply chain, may not have been considered and therefore the final outcome may not further the company's financial performance.

While tightly linked to strategic planning, tactical planning embraces different supply chain challenges. Essentially tactical planning depends on demand forecasts since a primary objective is the optimal allocation of demand to appropriate plants, warehouses, and modes of transportation. Different routings and resources, such as equipment and personnel, are considered at an aggregate component level. APS systems that focus mainly on aggregate planning use time buckets, primarily of weeks or months, and employ static lead-times between operations (Dullin, 1998).

The time frame for tactical decision making is normally quarterly or monthly, with weekly or daily reviews. In the tactical planning phase, businesses still have adequate

time to plan, hence mixed-integer and linear programming are normally sufficient (Gumaer, 1998).

#### 4.7.3 Operational Planning

At an operational level companies have less time to make decisions since planning decisions occur in narrow time frames, eg planning periods can be less than a minute. The operational level, therefore, requires rapid calculations in response to real-time events and time-intensive planning calculations are not normally applicable. For example, if a machine breaks down or a part is scrapped, it is not normally feasible to address such a granular problem by re-optimising the master supply chain plan. At this level, plant managers need to be provided with the facilities for fine-tuning the local schedule to meet the real-time demands of this constantly changing operations environment. However, when making planning changes in the mid-term it is still necessary to consider firm orders committed to execution. Since this is particularly true in planning environments having short lead-times it underlines a need for bottom-up integration between operational and tactical levels.

The planning tools applied at this operational level make use of deterministic networks that are implemented using a memory-based database to receive fast and accurate planning solutions rather than optimal solutions that require longer planning times.

### 4.8 *Overview of Functionality*

ERP systems primarily focus on planning and scheduling within an enterprise whereas APS systems on the other hand, attempt to tackle the full spectrum of enterprise and inter-enterprise planning and scheduling problems (see Figure 4.5).

The following sections provide a brief overview of the planning functions identified in Figure 4.5.

#### 4.8.1 Supply chain network design

The output from this planning function provides an accurate, time-phased supply chain view to support optimal supply chain design and policy decision-making. By modelling

end-to-end supply chain implications, it is possible to determine the most profitable supply chain strategy, from amongst the alternatives (Parker, 2000b), ie:

- a) optimal inventory levels,
- b) appropriate product mix across the network,
- c) optimal production, storage, and distribution locations,
- d) optimal lane volumes, or
- e) appropriate seasonal pre-builds.

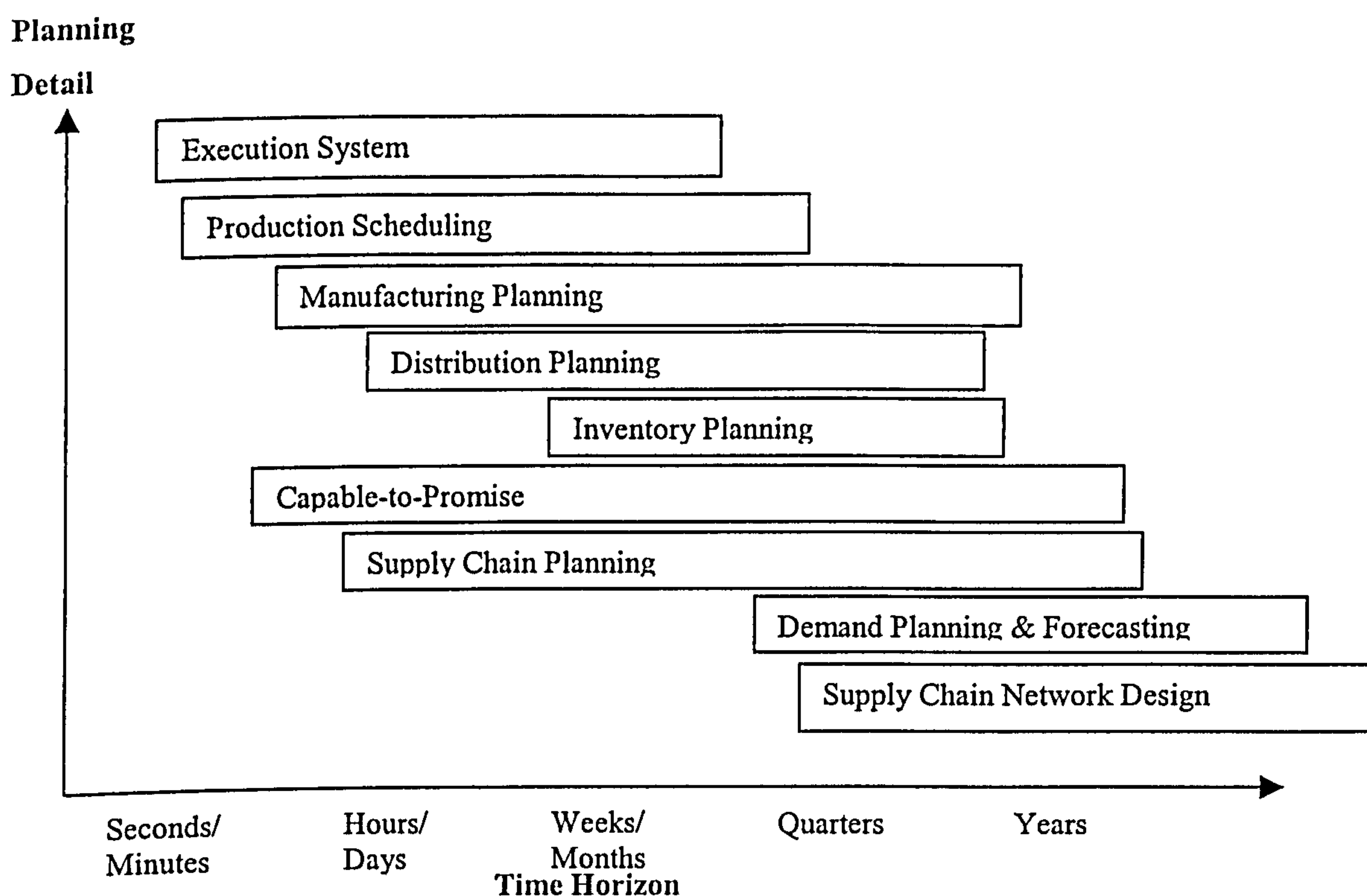


Figure 4.5 Supply chain planning time horizon (Bermudez, 1998a)

What-if analysis can be performed to test the impact of closing or moving facilities on profits and customer service levels.

Supply chain network design tools are often applied to optimise the balance between the location of inventory and transportation costs (Bermudez, 1998a). More advanced Supply Chain Network Design tools are able to recognise the multiple dimensions of time, location, product, customer, cost, and profit. Optimisation techniques can be



included that simultaneously balance profits, time-phased demand and supply, fixed and variable costs, varying transportation and manufacturing lead-times, and factors stemming from international trade logistics such as tariffs and value-added taxes.

#### 4.7.2 Demand Planning and Forecasting

Manufacturers are moving from a production push environment, which is largely focused on production efficiency, to a consumer pull environment, which is focused on meeting expected consumer demand. This has led to an increased interest in demand forecasting processes and systems as a means to better understand future consumer demand (Lapide, 1998b). Demand management tools offer a greater variety of forecasting algorithms that are able to identify the critical factors that drive demand. Under these circumstances it is essential to select the right forecasting tool for the job (Pancucci, 1998).

Demand planning addresses the creation of demand through promotions and external events. Demand forecasting uses statistical and time-series mathematics to forecast future demand from sales history. Demand forecasts are often considered as unconstrained as they reflect what customers want, not necessarily what can be produced. Accurate prediction of customer demand means simply achieving the balance between minimal stock versus suitable service levels.

Demand management systems, ie demand planning and forecasting systems, act as early warning systems that can accurately predict future customer demand, provide alerts to potential supply problems, and find demand patterns overlooked by traditional forecasting solutions (Weil, 2000). These systems enable demand to be tracked simultaneously across multiple functions including sales, marketing, and logistics. State of the art demand management tools improve the ease with which human expertise and opinion can be input into the forecasting and planning processes.

Despite the benefits of using demand management applications the level of support provided to marketing and sales decisions, ie in relation to the product, price, promotion, and placement decisions (Lapide, 1998b) is in need of improvement.

## 4.8.2 Inventory Management

Inventory planning and control is an essential part of successful supply chain management. For example, distribution-intensive supply chains use inventory management systems (IMS) to buffer the impact of supply and demand variability and the problems caused by long lead-times. Such systems must enable on time delivery of goods to customers who expect products primarily to be available either off-the-shelf or to be delivered within several days. Hence, distribution-intensive enterprises can gain many benefits from IMS (Girard, 1998) including:

- i) Improved management of the relative levels of customer service and inventory cost, this objective is currently of great interest to such business types.
- ii) Because of recent improvements the potential for further cost savings through reducing manufacturing inventories and lowering interest rates is limited. However, in general *distribution* inventory remains high and opportunities for savings in this area are considered of greater possibility.
- iii) As technology reduces the cost of extending the range of inventory management, more companies will be expected to actively manage many more inventory locations for larger numbers of customers.
- iv) Regardless of which product strategy chosen, companies will need improved inventory management systems to implement a supply chain that is sufficiently responsive for mass customisation and/or that can cope with the efficiency of the supply chain necessary for global product management.

### 4.8.2.1 Vendor Managed Inventory/Continuous Replenishment Planning

Vendor Managed Inventory/Continuous Replenishment Planning (VMI/CRP) (Smith, 2000) is a continuous replenishment strategy which is illustrated in Figure 4.6. Here the manufacturer owns the inventory, takes responsibility for replenishment, and provides direct shipments to the retailer. All manufacturers, whether engaged in VMI/CRP or not, are asked to ship smaller lots, to more sites, more frequently.



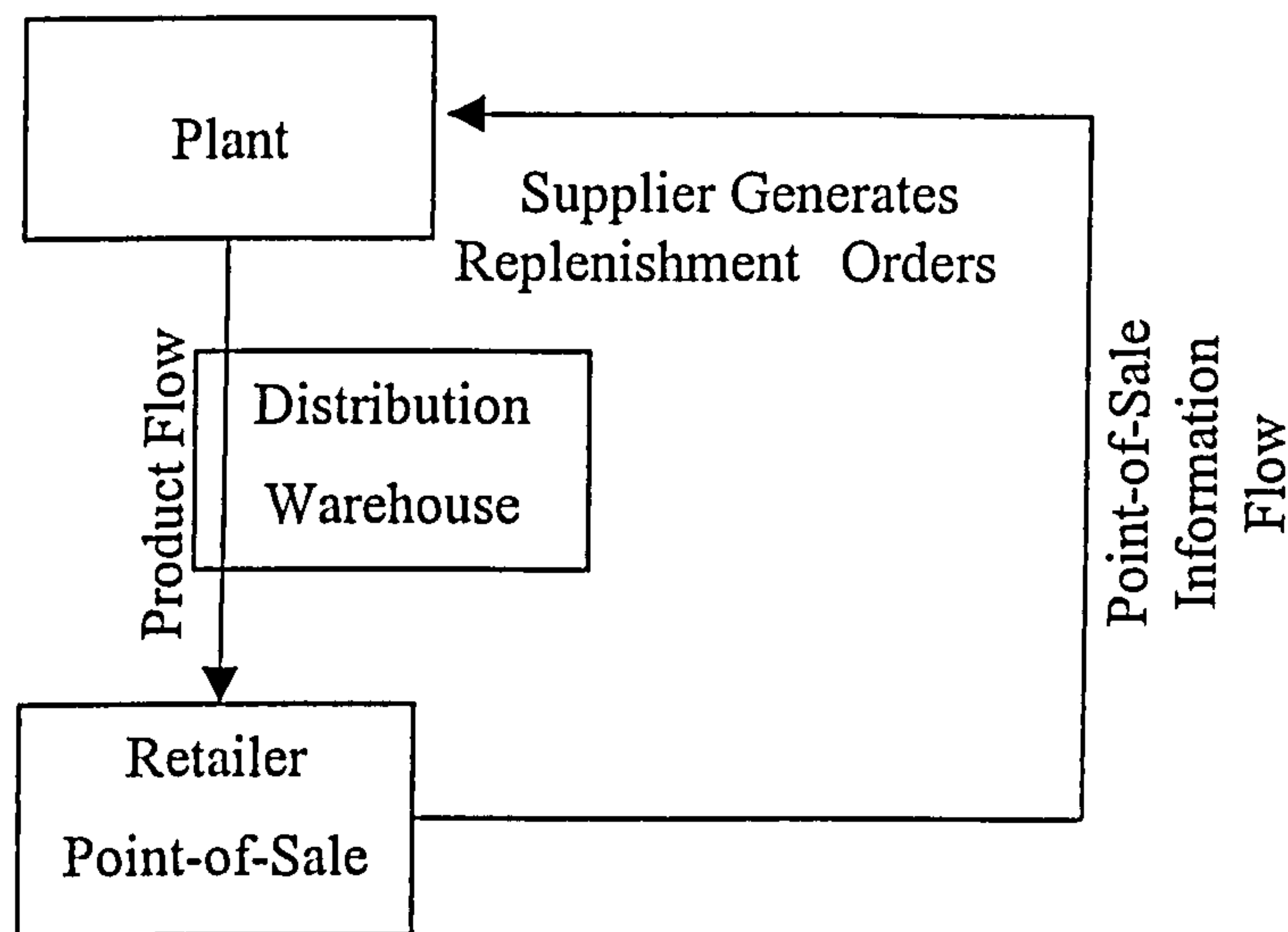


Figure 4.6 - VMI/CRP

#### 4.8.3 Available-to-Promise and Capable-to-Promise

Traditional Available-to-Promise (ATP) methods determine whether a customer's order request date can be met or proposes the next best date from analysis of existing inventory and production orders (Vollmann, et. al., 1997).

A subset of such ATP functionality often, ie capable-to-promise, analyses available plant capacity and determines whether an order can be inserted into the schedule to meet the customer's request date (Bermudez, 1998a). However, the fact that a product is scheduled for manufacture does not necessarily ensure that a customer's request date can be achieved since the time required for distribution is not taken into account. More advanced ATP solutions, therefore, resolve these issues since they can allocate transportation resources hence ensuring a carrier can deliver in a specified delivery window (Manugistics, 1998). ATP can take place at various planning levels, ie at the manufacturing planning and production scheduling levels.

#### 4.8.4 Distribution Planning

Distribution planning is the point of convergence between manufacturing, supply and demand planning. To determine the optimal balance between customer service levels and inventory, distribution planning takes into account manufacturing constraints, inventory investment, desired service levels, customer delivery windows, and current orders and/or commitments. This requires distribution planning applications to support



extensive communications capabilities, ie companies must be linked via the Internet ensuring real-time communication and hence more timely orders and deliveries. In addition, most applications also provide electronic data interchange (EDI) support for automatic ordering, replenishment, invoicing, and shipping (Bagnell, 2000).

The planning capabilities of distribution planning include detailed item planning to balance loads and orders, extensive simulation that can be used to determine the effect of planning changes that can range from detailed policy changes to new supply chain behaviour, and constrained Distribution Resource Planning (DRP) (Ross, 1996). As a result of this later capability distribution planning systems are suitable tools for implementing continuous replenishment strategies such as VMI/CRP (Ross, 1996).

When companies need to maintain both complex distribution networks and in addition close links with customers, distribution planning tools provide the ability to view inventory from several perspectives, including actual demand data, future distribution needs and replenishment commitments (Dilger, 2000).

More advanced distribution planning applications provide the functionality to dynamically search for available product inventory throughout a network hence minimising lost revenue by ensuring customer requirements are met despite unanticipated delays in production, cross-border shipments, or transportation. In addition, through the use of user-controlled allocation strategies, in times of prolonged product shortage, customers can continue to receive appropriate supply allocations (Manugistics, 1998).

At the first sign of excess, obsolete, or expiring inventory or when product distributions are in danger of falling short unexpectedly, distribution planning tools can launch proactive alerts to distribution planners. Through this early intervention process, push logic, and customer specific date sensitivity tracking, potentially unusable inventory can be appropriately re-deployed within the network (Manugistics, 1998).

#### 4.8.5 Supply chain planning

The supply chain planning (SCP) activity simultaneously optimises the use of manufacturing and distribution resources to meet forecast and actual demand. The forecast is often supplied to the SCP function by a demand forecasting application particularly in CPG industries. The consideration of transportation requirements is more common in CPG and chemical industries (Bermudez, 1998a). The output of SCP is an optimised production plan (see Figure 4.7), where limited resources are allocated and co-ordinated based on a company's user-defined strategies. These strategies take into consideration customer, item, and location prioritisation, and the optimisation of pre-determined business goals such as increased revenue and improved services.

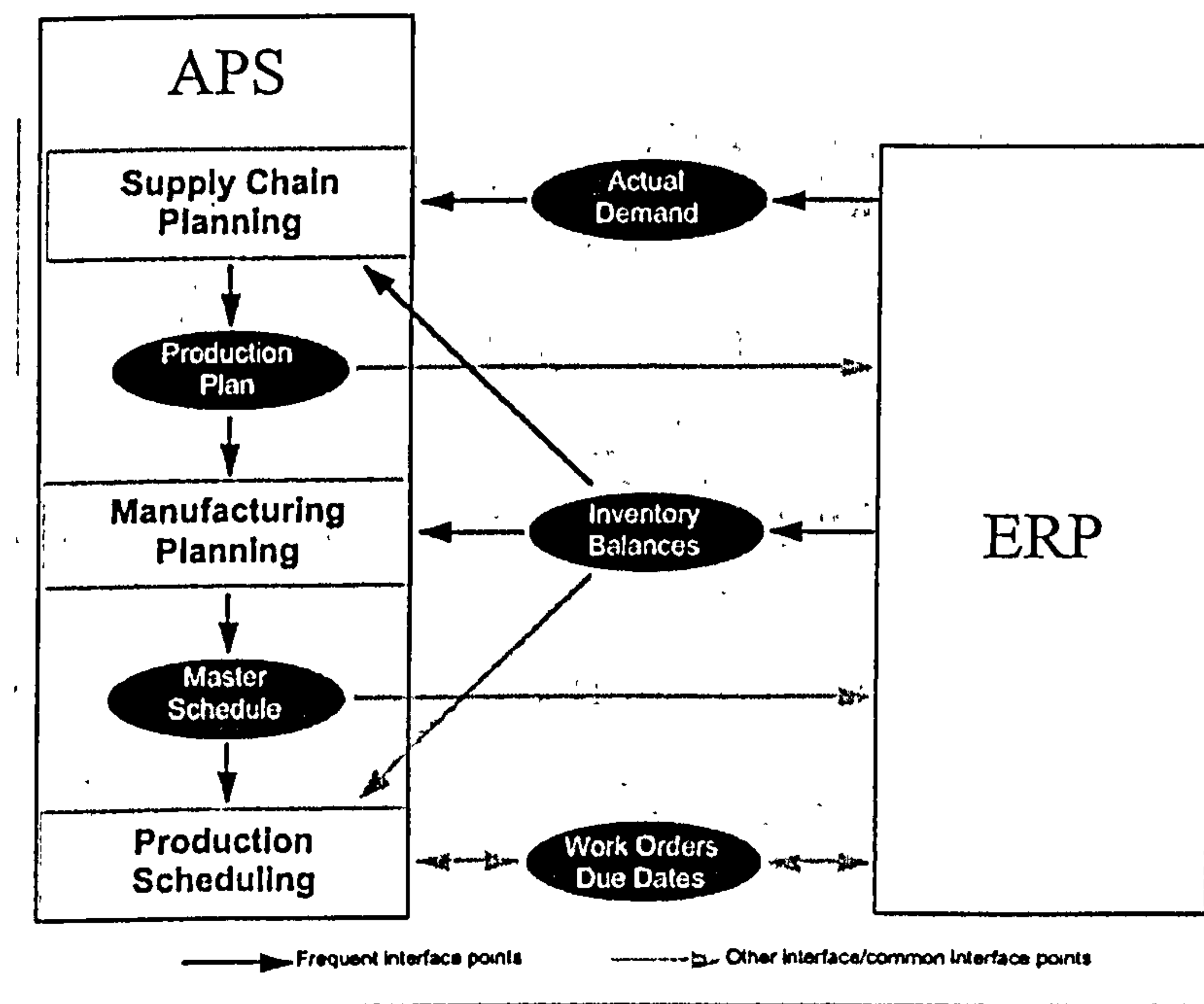


Figure 4.7 Relationship of major planning functions with typical data (Bermudez, 1998a)

Generally, SCP plans use aggregate-level resources and critical materials to develop constrained multiple-plant master production schedules. Since SCP generally spans multiple manufacturing and distribution sites it, therefore, utilises network design and sourcing policies generated during the design phase of a supply chain network to provide seamless integration between strategic business goals and operational activities (Manugistics, 1998). Run times for regenerating plans, which take place on a net change



basis, are less than 20 minutes hence enabling the SCP to function on a daily basis to react to changes in demand immediately (Bermudez, 1998b).

In many cases master schedules are sent directly to the manufacturing plant to serve as weekly or monthly production schedules. The level of material planning performed during SCP generally varies depending on the product being manufactured. Products with shallow BOMs may incorporate procurement planning, normally MRP based, into the SCP process. Products with deep BOM-s must rely on a separate MRP process for procurement planning because of run time performance issues. The solution to unsatisfactory performance issues in environments with complex process and material planning is to create aggregated resource models that capture the critical constraints (Bermudez, 1998b).

The need for aggregation will decrease as the CPU speeds and memory sizes increase. Conceptually, most APS vendors have designed the SCP planning application to feed its output, ie the constrained master schedule, to the ERP system as input for detailed MRP or more detailed manufacturing planning and scheduling applications. Several vendors with larger APS suites have designed their SCP applications to produce multiple-plant plans that are passed to manufacturing planning applications that produce more detailed, constrained master schedule, with or without MRP. APS vendors that focus on CPG and chemicals often combine the manufacturing planning step with SCP and pass the output to a production scheduling application (Bermudez, 1998a).

#### 4.8.6 Manufacturing Planning

Manufacturing planning develops a master schedule that is constrained by material availability and plant capacity. This is generally undertaken for a single plant or for a group of similar plants. Manufacturing planning can be integrated with SCP to follow enterprise-wide planning guidelines. The difference between multiple-plant manufacturing planning and SCP is often a matter of semantics. Generally, SCP is used by centralised planning functions to balance a supply chain, especially where distribution plays a critical role. While manufacturing planning can be implemented as a centralised function across multiple plants, it generally focuses on developing the detailed master schedule for a single plant. According to Bermudez, (1998b) SCP



determines what should be made given the available resources to achieve business goals and manufacturing planning determines how and when it should be made based on material and resource constraints to meet customer demand.

Existing manufacturing planning tools generally consider more detailed capacity constraints and provide a variety of planning and scheduling capabilities ranging from complete MRP explosions to critical materials, regenerative or net change scheduling. A net change rescheduling capability is particularly valuable as it allows schedules to evolve as conditions change on a day-to-day basis. This evolving schedule enables schedules to remain stable hence such schedules can be quickly revised to meet new conditions (Hatcher, 2000). The depth of material planning often depends on the complexity of BOMs and the desired recalculation time. Manufacturers with less complex BOMs may generate a full procurement plan during the process of generating master schedules (Bermudez, 1998a).

#### 4.8.7 Production Scheduling

Production scheduling receives as input a master schedule, which is generated either by SCP or the manufacturing planning function. Thereafter production scheduling determines the optimal sequencing and routing of orders on the plant floor based on detailed product attributes, work centre capabilities, and material flow. Output from the production scheduling function is sent to the plant floor as a daily, weekly, or monthly production schedule. This plan is not normally output to an ERP system, but it is often maintained separately (Bermudez, 1998b).

Manufacturers that benefit from production scheduling fall roughly into two groups, ie:

1. Discrete manufacturers with complex processes. Here manufacturers tend to select APS solutions capable of supporting a mixture of short-term material planning and detailed routings.
2. Process manufacturers with complex sequencing requirements. Here manufacturers, often producers of semiconductors, chemicals, or food and beverages, frequently pass the output of the SCP process directly to production scheduling solutions designed for process manufacturing.

## 5 Experimentation

### 5.1 *Problem specification and objectives*

As identified in Section 4.7.2 forecasting is normally used to estimate demand at each stage within a supply chain. This information determines the inventory levels that need to be held between network stages in order to provide protection against fluctuations in supply and demand that may occur across the network. Such fluctuations arise due to diverse reasons such as machine breakdowns and unusually large demand requests. Increasingly the trends identified in Section 2.3, which include shortening of product life cycles and increasing variability in customer demand, could result in the use of inventory as protection against such variability. It is becoming a poor strategy to adopt since it results in high costs and reductions in supply flexibility.

Where possible, therefore, inventory should be replaced by information. This could be achieved by making use of the material lead-time information from suppliers to plan, as illustrated in Figure 4.2, material arrivals. Actual customer demand information should, therefore, be the only information that provides signals for initiating manufacturing processes. This would allow the decentralised control property of supply chain networks to be maintained by providing planning co-ordination between entities in performing their tasks. In order to achieve this, however, actual customer demand information would need to be broadcast to all the supply chain network nodes on a timely basis as depicted in Figure 3.8.

To guarantee timely deliveries production cycle times have to be predictable, ie cycle time variability has to be reduced. As indicated in Section 3.1, reduced variability results in lower WIP levels, higher throughput, and shorter cycle times. In facilitating such variability reduction, the operating policies of up-stream and down-stream supply chain entities need to be co-ordinated.

Due to the complexity of supply chain planning processes, the algorithmic approach to planning appears infeasible in situations where the number of variables and possible



alternatives to evaluate is large. Therefore, a simulation model has been developed in order to examine the possible performance changes that could arise from the use of new operating policies enabled by faster planning and information sharing. The simulation model has been designed to examine the influence of a core business process, ie the order fulfilment process. The main goal of the order fulfilment process is to guarantee timely deliveries of goods despite the variability in external, (eg customer order arrival times and quantities), and internal, (eg breakdown intervals and repair times) environments.

To summarise, the objectives of the simulation are:

- a) to imitate the bid and response activity based order planning approach and examine a novel batch sizing and release approach where the delivery time of a customer order can be based on the projected delivery time of a particular batch that moves in the network,
- b) to evaluate the proposed batch sizing and release approach in a moderately dynamic environment examining the connections between the order planning, release control, and cycle times, and
- c) to establish that the correct timing of manufacturing order releases and batch sizing of variable customer order arrivals reduces cycle time variability and thus minimises tardiness.

## ***5.2 Description of the simulation model***

A simulation model has, therefore, been developed to simulate the order fulfilment process within the type II supply chain network described in Figure 2.4. In contrast to a type II network, within the simulation model developed there are no suppliers delivering directly to distribution sites. This modification would not have an appreciable effect on supply chain performance since, as discussed in Section 3.2, it is manufacturing responsiveness that primarily determines the responsiveness of a supply chain. The simulation modelling software tool, Simul8, provided by Visual Thinking Ltd. (SIMUL8 Corp, 1999) has been used to develop the model.



The manufacturing processes for two finished products, P1 and P2, have been simulated. The bill of materials (BOMs) for these products are depicted in Figure 5.1, which also indicates in brackets the BOM quantities of each item.

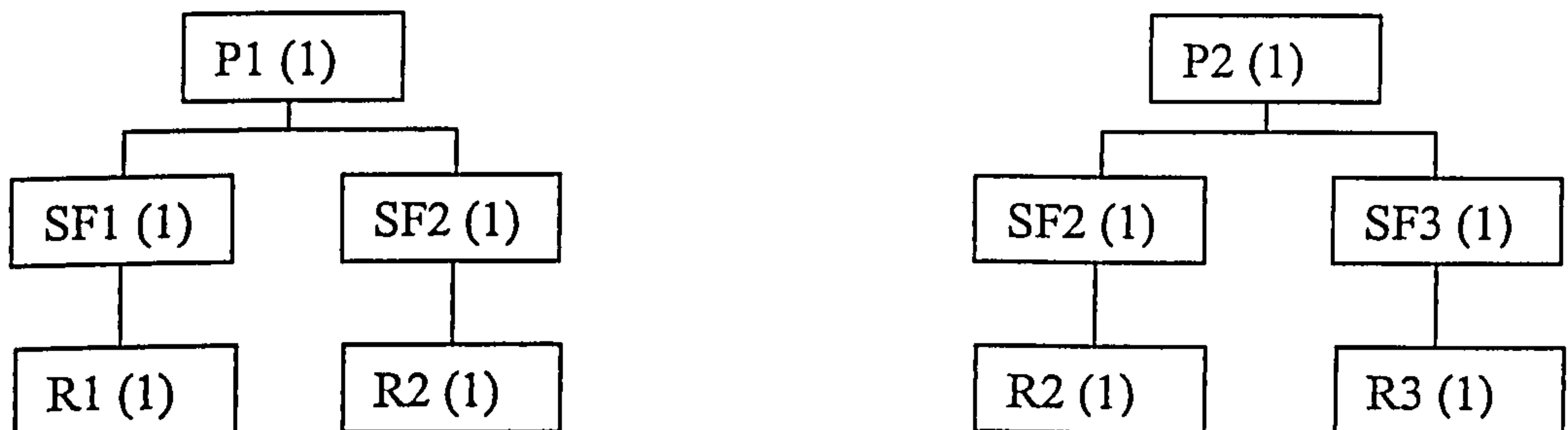


Figure 5.1 Product BOMs

Process and transfer batches are assumed to be the same.

The simulation model consists of the following sections, ie as shown in Figure 5.2:

- a) clients,
- b) planning,
- c) release control, and
- d) a 3 tiered supply chain network.

The *clients* section is responsible for:

- a) release of customer orders to the model, and
- b) acceptance of finished products.

Orders for P1 enter through the object IN1 and orders for P2 enter through IN2. After traversing the supply chain, products P1 are accepted through the object OUT1 and products P2 are accepted through OUT2.



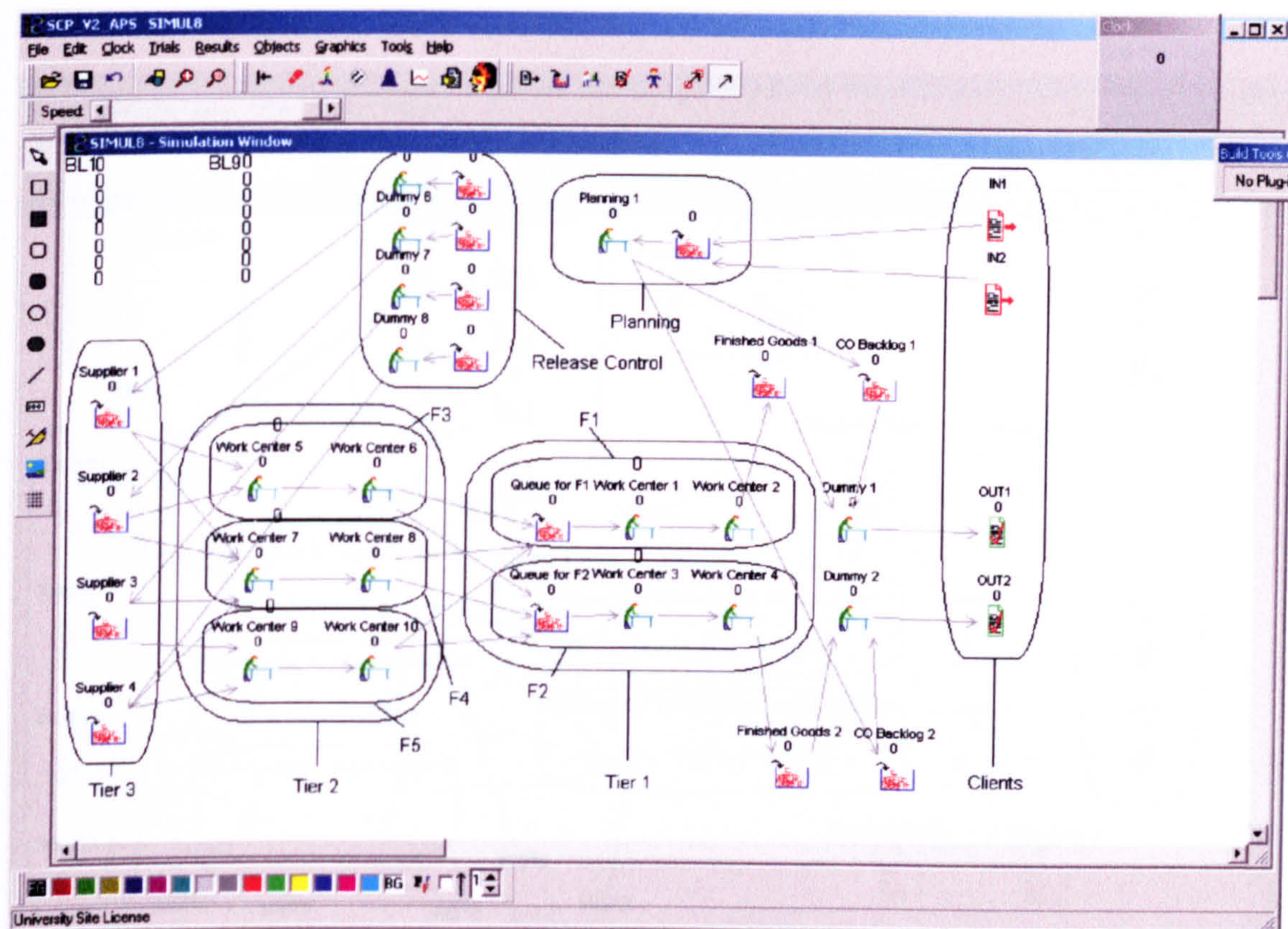


Figure 5.2 – Simulation model

In the *Planning* section the following sequence of tasks takes place:

- acceptance of orders from clients,
- determination of the best route for each manufacturing order to take,
- allocation of customer orders to manufacturing orders, ie batch allocation, and planning of new manufacturing orders,
- calculation of the lead time and delivery date to promise.

Orders from IN1 and IN2 are accepted by the object Planning 1 (see Figure 5.2 and Appendix 12.1), which then determines the best route for each job to take. The best route is that which results in the earliest delivery time. In determining routes, use is made of both planned order backlogs and WIP levels. As illustrated in Figure 5.3, the required WIP levels at each node and planned order backlog information is identified for each route.



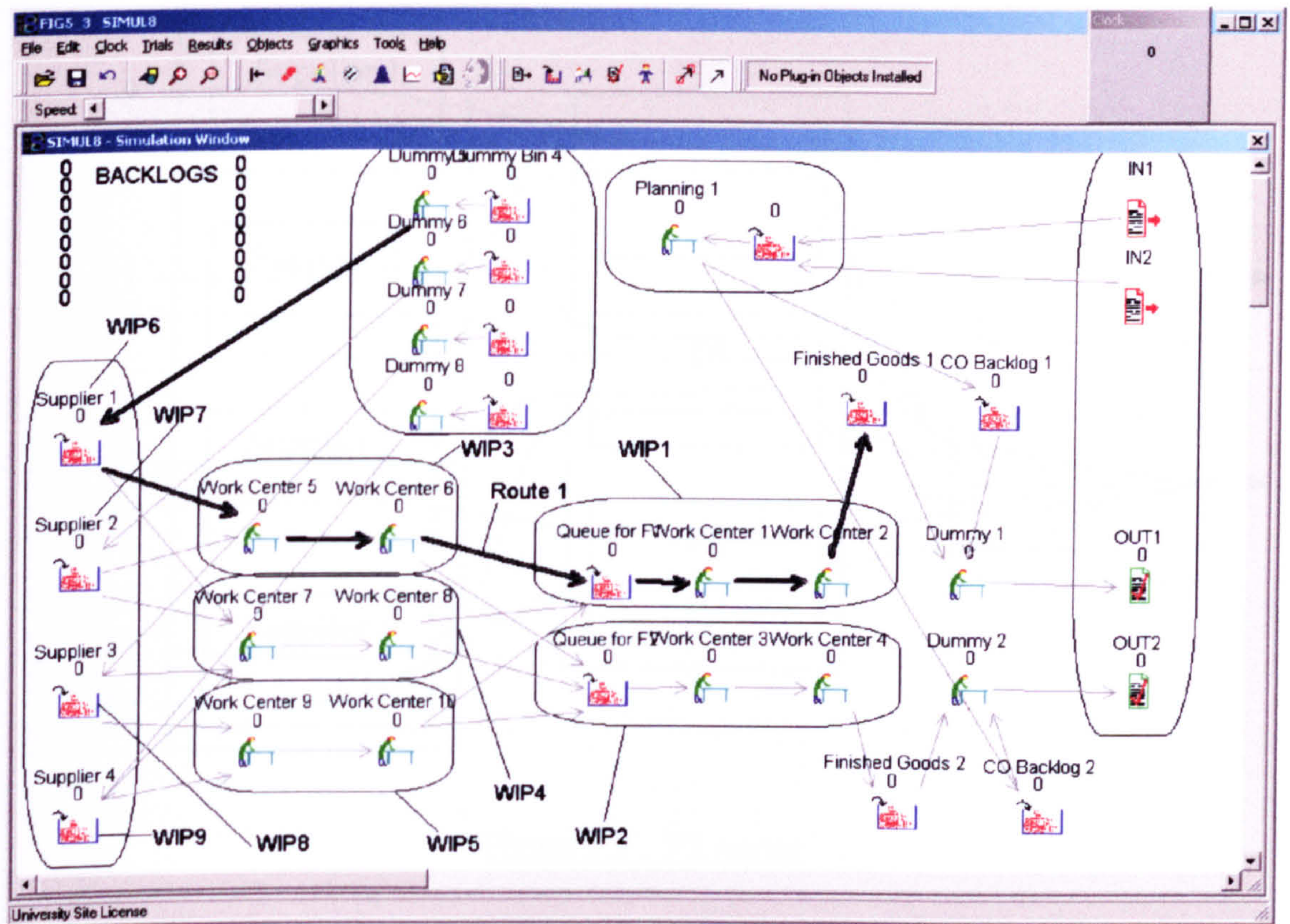


Figure 5.3 – Routes and WIP tracking within simulation

All routes for item P1 are depicted in Figure 5.4 and for item P2 in Figure 5.5.

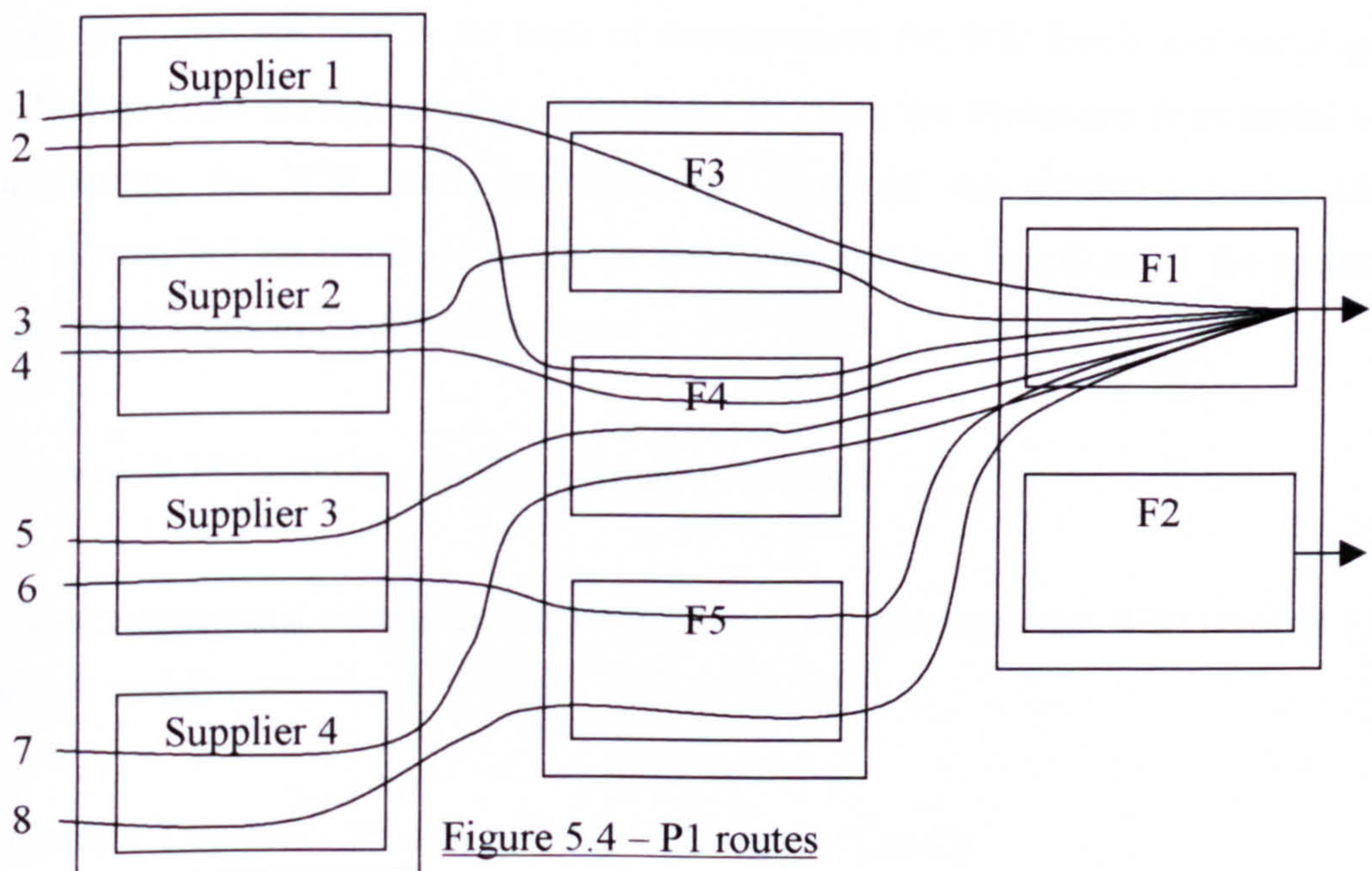


Figure 5.4 – P1 routes



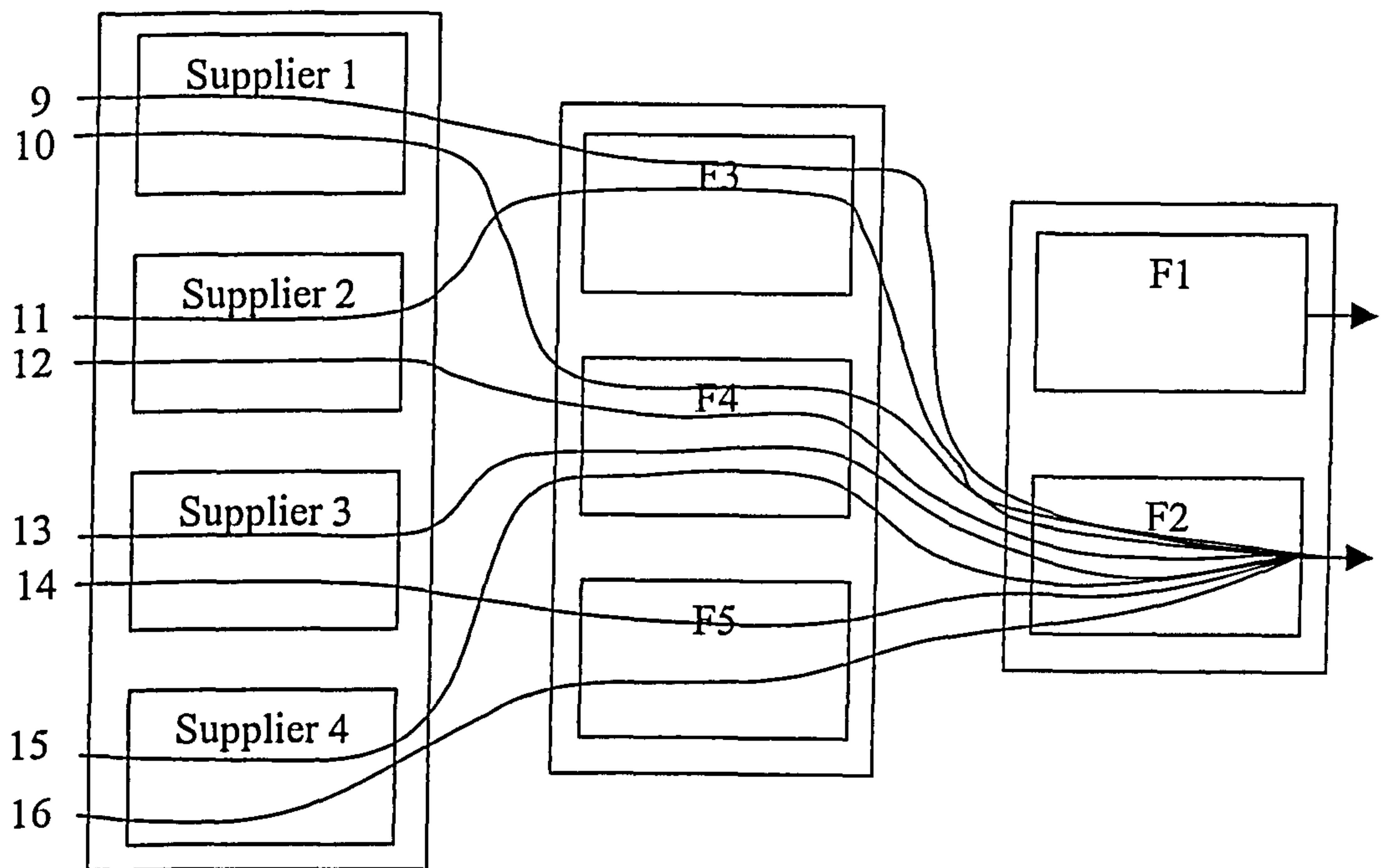


Figure 5.5 P2 routes

Backlog levels for a particular route are represented by a set of planned manufacturing orders residing in release control. Essentially, the backlog for a route is a sum of the lead times of all batches planned for manufacture along that route.

Simulation time units are used as the units of measurement for WIP levels and backlogs. Hence, when an order is received, for example for P1, then the routes are determined by first summarising the WIP levels and backlogs along all the available routes and thereafter, comparing the results to select the least loaded route. For Route 1 the system would determine loads in the following way:

Route 1 Load = WIP1 + WIP2 + WIP6 + Route 1 Backlog.

WIP levels are calculated using run and set-up times. For example, the WIP level at F1 is determined as follows:

$$\text{WIP1} = (\text{Setup} + \text{Quantity} \times \text{Time1}) + (\text{Setup} + \text{Quantity} \times \text{Time2}) .$$



Where:

- Set-up = variable used define set-up time in the Work Centre objects,
- Quantity = manufacturing order quantity (ie batch size),
- Time1, Time2 = variables used to define run times in objects Work Centre 1 and Work Centre 2.

The negative affects of highly variable customer order quantities and arrivals can be mitigated through the batching of manufacturing orders. As described in Sections 3.4 and 4.2, when using period planning processes such as MRP, customer orders are stored after receipt since planning occurs normally during the weekend or during the night. Consequently, as illustrated in Figure 5.6, the quantities despatched to manufacturing can vary considerably.

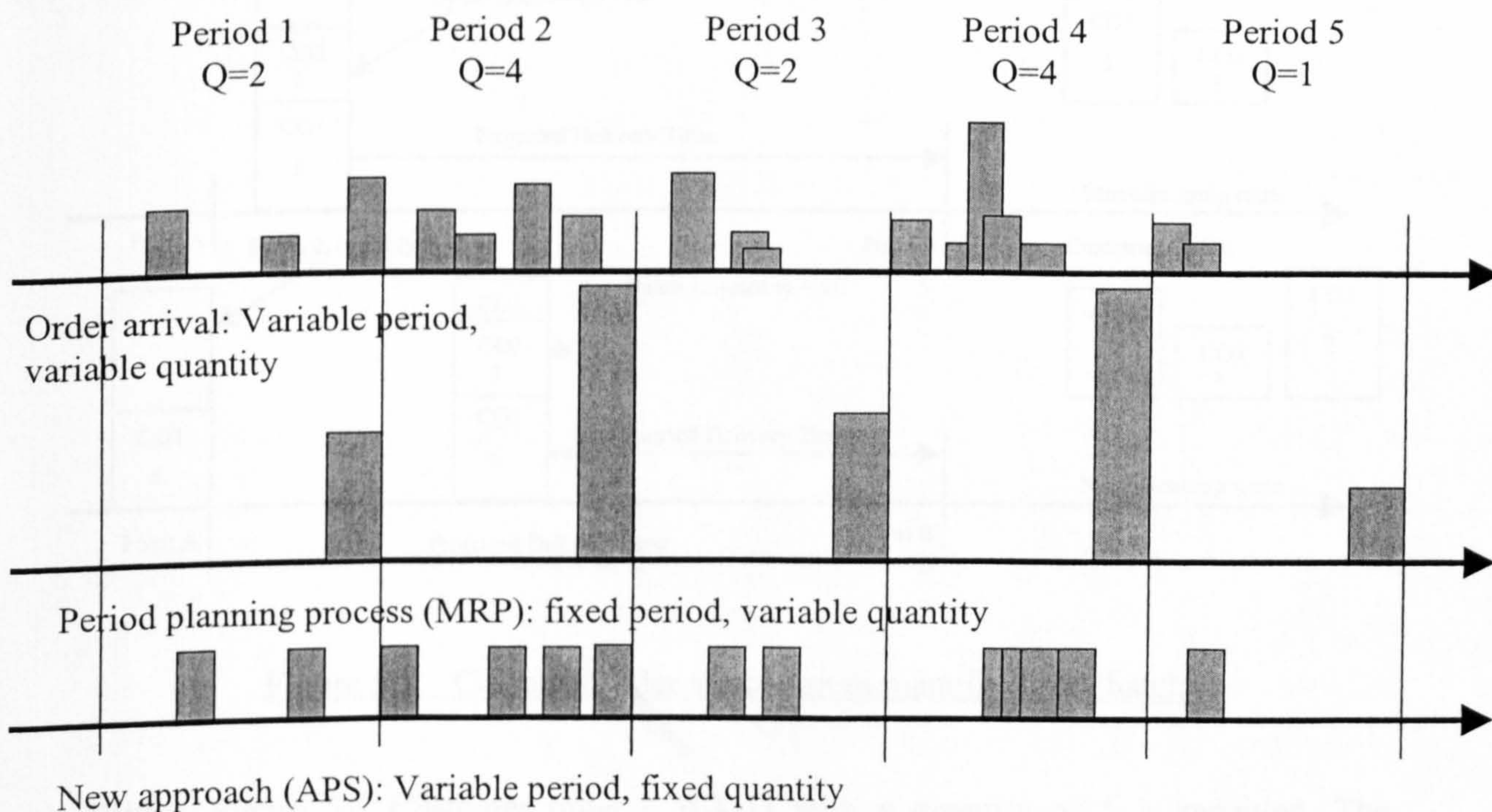


Figure 5.6 Manufacturing order releases and batching



As described in Sections 4.5 and 4.7, planning engines such as APS, are able to plan orders immediately upon receipt. In an attempt to utilise the computing power of APS engines and at the same time, reduce the effects of inter-arrival variability, the current work has imitated an approach depicted in Figure 4.2, where a customer order acts merely as a trigger for starting the planning process. During this planning phase an order release schedule for manufacturing batches of a fixed quantity, is determined. The movement of these fixed size batches in the supply chain network is constantly monitored. The delivery time for the next customer order, as illustrated in Figure 5.7, can then be promised using the projected delivery time of a particular batch moving through the network.

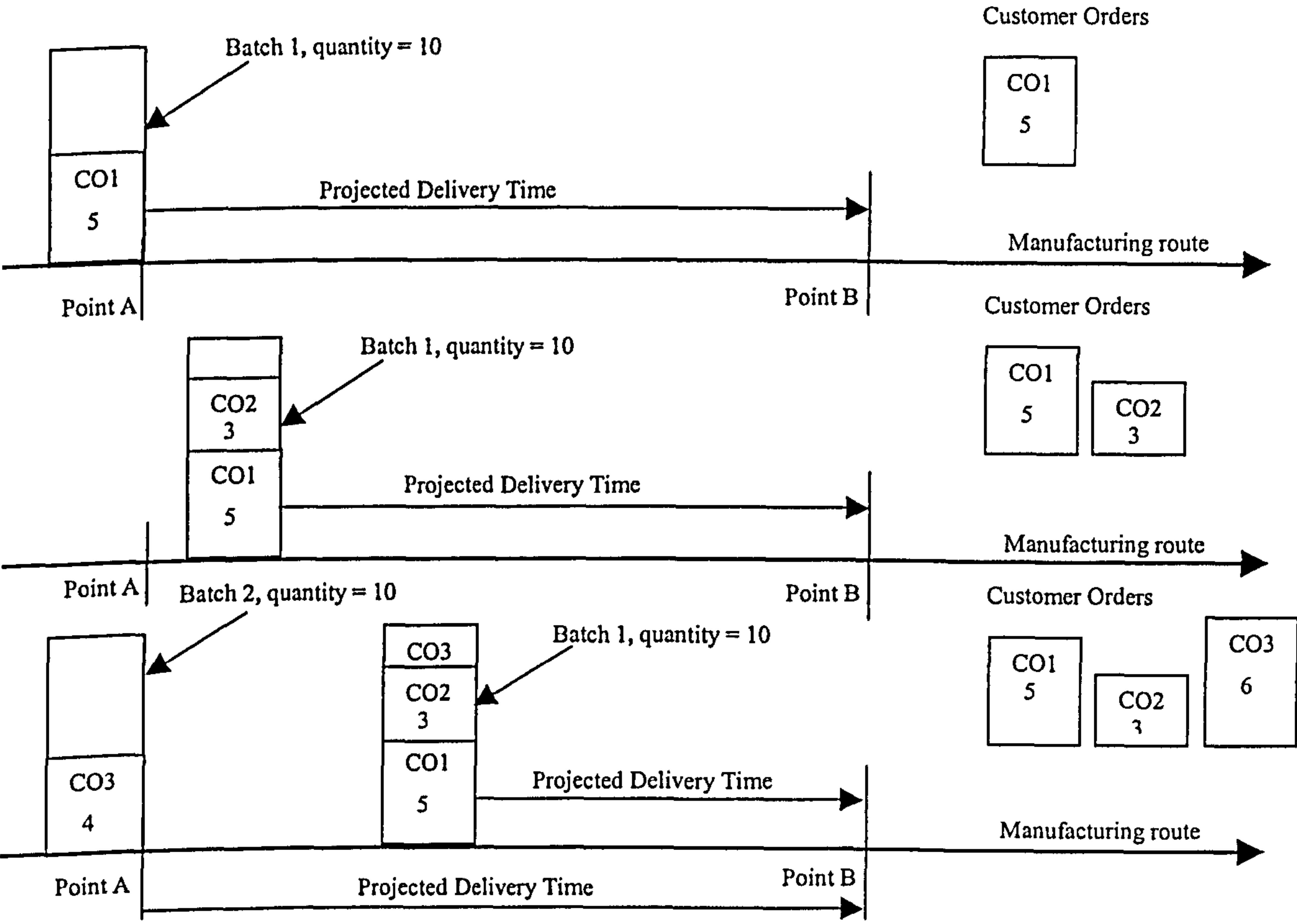


Figure 5.7 Customer order allocation to manufacturing batches

Within Figure 5.7 Customer order 1 (CO1) with a quantity of 5 is received. The production of Batch 1 is then planned assuming that the minimum optimal batch size is 10. In Batch 1, 5 pieces out of 10 are allocated to CO1. The delivery time of CO1 is



determined according to the projected delivery time of Batch 1. The projected delivery time is based on the run and set-up times of all the operations along the route.

At some point in time, CO2 with a quantity of 3 is received. The quantity is allocated from Batch 1 and the CO2 delivery time is set using the projected delivery time for this batch, ie this is recalculated considering the run and set-up times of all the remaining operations.

When customer s order CO3 is received 2 items are allocated to be delivered from Batch 1. In order to ensure delivery of the whole order, production of a Batch 2 needs to be planned and thus the CO3 delivery time is set according to the projected delivery time for Batch 2.

Within the simulation model, the batching process occurs in the object Planning 1 after the determination of the best route. A Visual Basic (VB) programme displayed in Section 12.4 has been developed for allocating customers orders to batches. This programme is initiated using the simulation tool s programme code. When the simulation model starts the batching process, at first the VB programme goes through all the nodes starting from the downstream nodes and looks for unallocated quantities within existing batches. Thereafter, based on the quantities of demand remaining, the release of new batches is planned.

Figure 5.8 describes this customer order allocation process. Assuming that a customer s order for 100 units of P1 is received, the VB programme initially examines nodes F1 and F2. 10 units of P1 available at F1 and these are allocated to the customer s order. The VB programme then continues to review tier 2 nodes, where it finds there are no quantities to allocate. The VB programme then moves to tier 3 nodes, ie node Supplier 1, where the VB programme finds 20 units of R1 available in three batches and then to node Supplier 3 where 20 units of R2 are available in three batches. Once these quantities have been allocated, the backlog of planned and unreleased batches is reviewed. This results in 50 additional units being allocated in each of the two batches. For the remaining 20 units of P1 the release of two batches is planned.

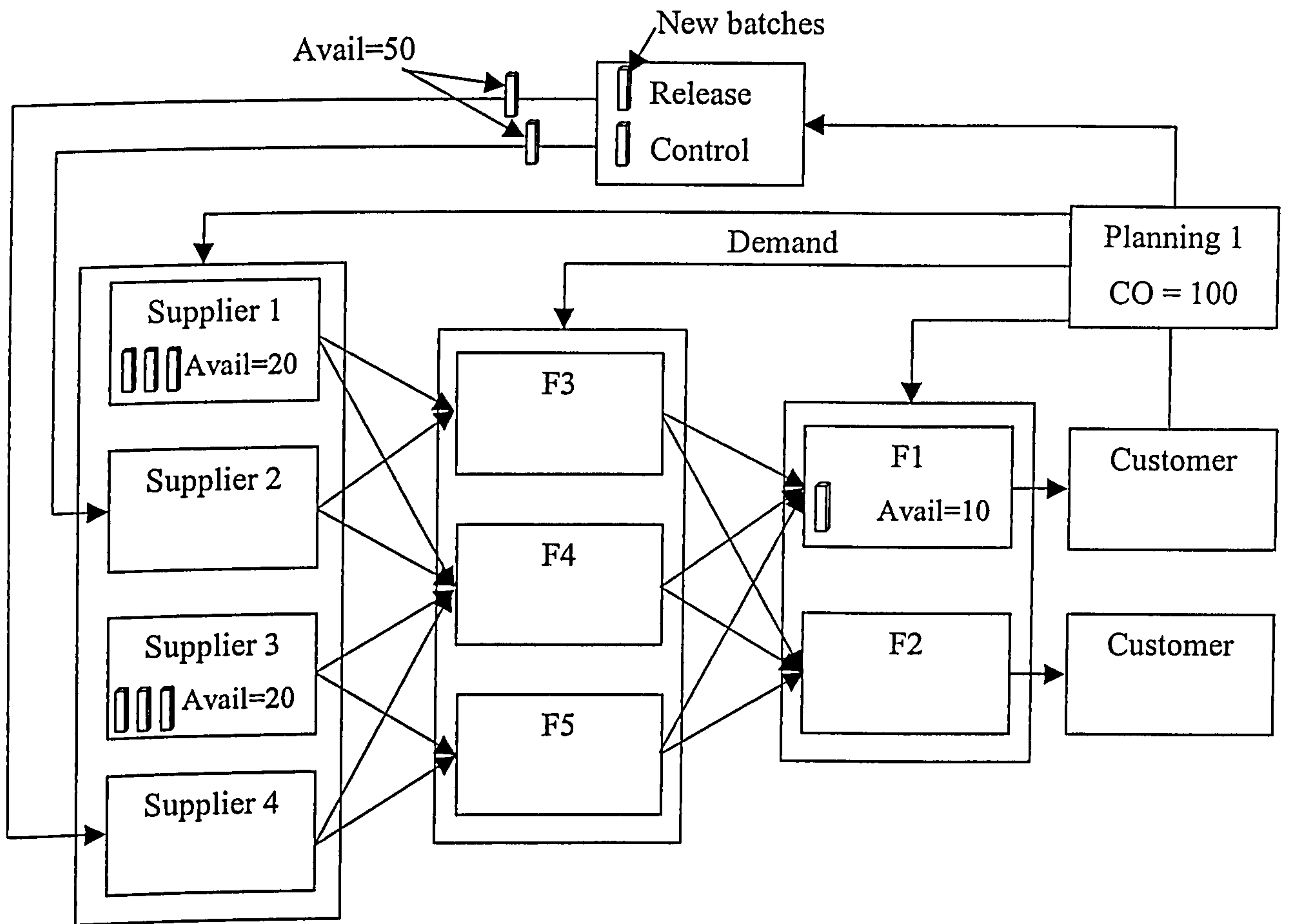


Figure 5.8 Batching Process

After determining the best route, the planned lead time for the order is calculated using the run and set-up times at each node. This lead time is added to the end of the backlog of the selected route. The order is then considered to be planned and will reside in the backlog waiting to be released by release control.

Planning has, therefore, generated the following information:

- the route number for each batch, and
- the lead time and projected delivery time of each batch.

The aim of release control is to protect the production environment from overloading. As described in Section 3.1, due to congestion cycle time, WIP and throughput increase delivery due date violations become frequent. In essence release control monitors the



WIP levels of each planned order to decide when to release the order from planning to manufacturing (ie release to WIP). In some circumstances release of an order could happen later than planned in which case the VB code calculates a projected delivery time.

After the release the order follows the route that was selected by a planning function. The routes pass through three tiers of the supply chain network as seen in Figure 5.2, where tier 3 represents raw material suppliers and tier 2 represents manufacturers where semi-finished items are produced in parallel. The variation of cycle times at those stages results in one semi-finished item arriving earlier than the other. Therefore, a proportion of semi-finished items may need to wait in queues before assembly in F1 and F2. The Visual Basic programme code for the selection and merging of batches of semi-finished item is included in Section 12.3. At the beginning of tier 1 the factories F1 and F2 assemble semi-finished items.

The projected delivery time is constantly recalculated at each node based on the WIP, and run and set-up times for the remaining downstream nodes. The projected delivery time at the last node in the route is the actual delivery time for an order. For example, the projected delivery time in the simulation object Work Centre 6 for movement along Route 1 is calculated as follows:

$$\text{Projected Delivery Time} = \text{Simulation Time} + (\text{Setup} + \text{Quantity} \times \text{Time1}) + (\text{Setup} + \text{Quantity} \times \text{Time2}) + \text{WIP1}$$

Where:

Simulation Time = the current value of the time within the model

### ***5.3 Verification of the simulation model***

Customer orders enter the model through objects IN1 and IN2. The movement of simulation work items from IN1 and IN2 to Planning 1 was observed visually. To impose more variable conditions and to validate the model, customised distributions of order inter-arrival times and quantities were created (see Table 5.1). According to the distribution the average level of the exponential distribution was set to change from 200



to 1000 every 12-simulation hours. Similarly, the level of normal distribution of order quantities was set to change every 12 hours from an average of 20 with a standard deviation 1 to an average of 200 with a standard deviation 50.

Using distributions FreqUp and QtyUp for both products P1 and P2, order inter-arrival times and order quantities for the first 200 items are depicted respectively in Figure 5.9 and Figure 5.10.

Distribution name	From 00:00 hours to 12:00 hours	From 12:00 hours to 00:00 hours
FreqUp	Exponential 200	Exponential 1000
FreqDown	Exponential 1000	Exponential 200
QtyUp	Normal 200, standard deviation 50	Normal 20, standard deviation 1
QtyDown	Normal 20, standard deviation 1	Normal 200, standard deviation 50

Table 5.1 Distributions of order inter-arrival times and quantities

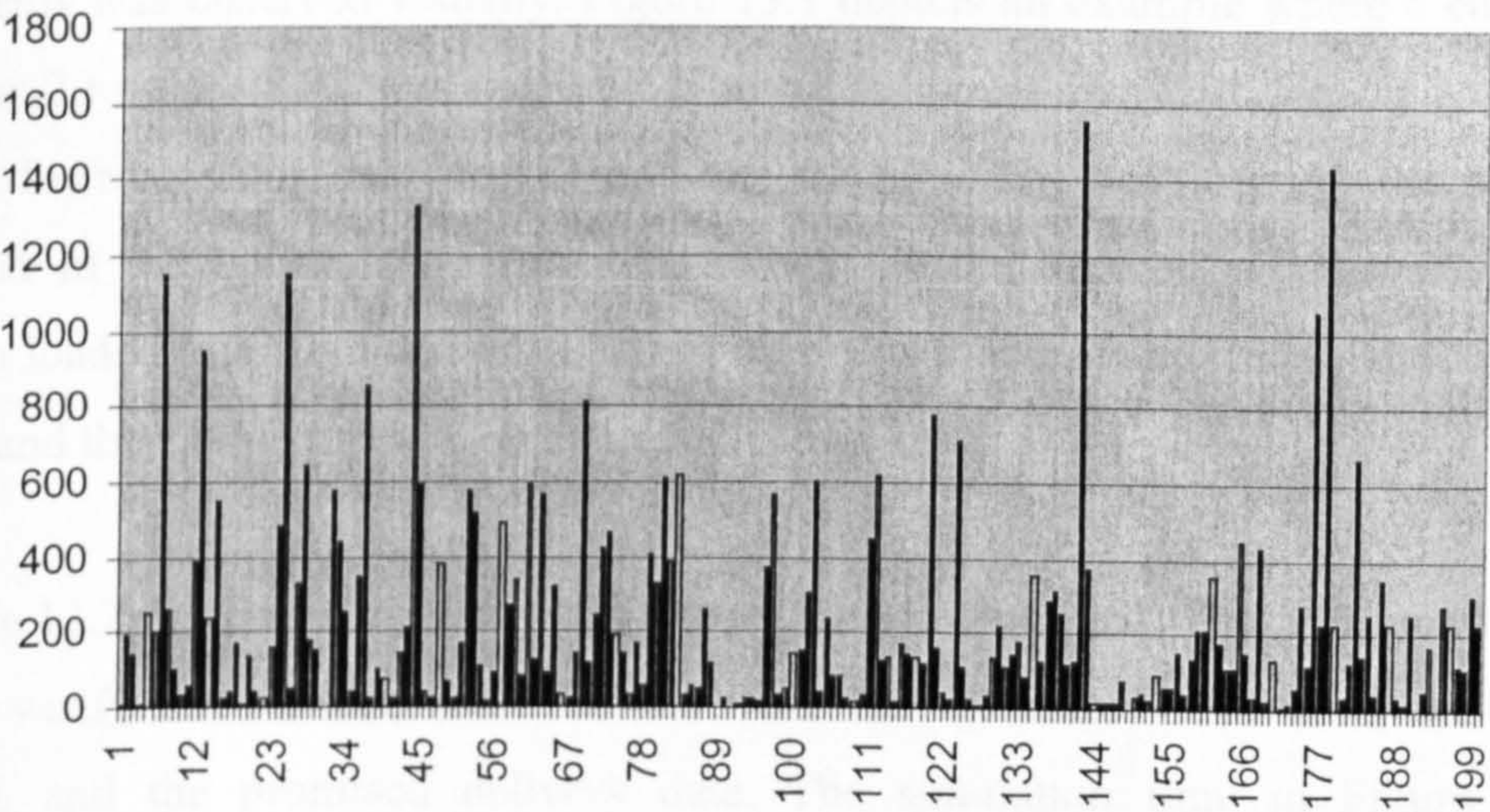


Figure 5.9 Order inter-arrival times



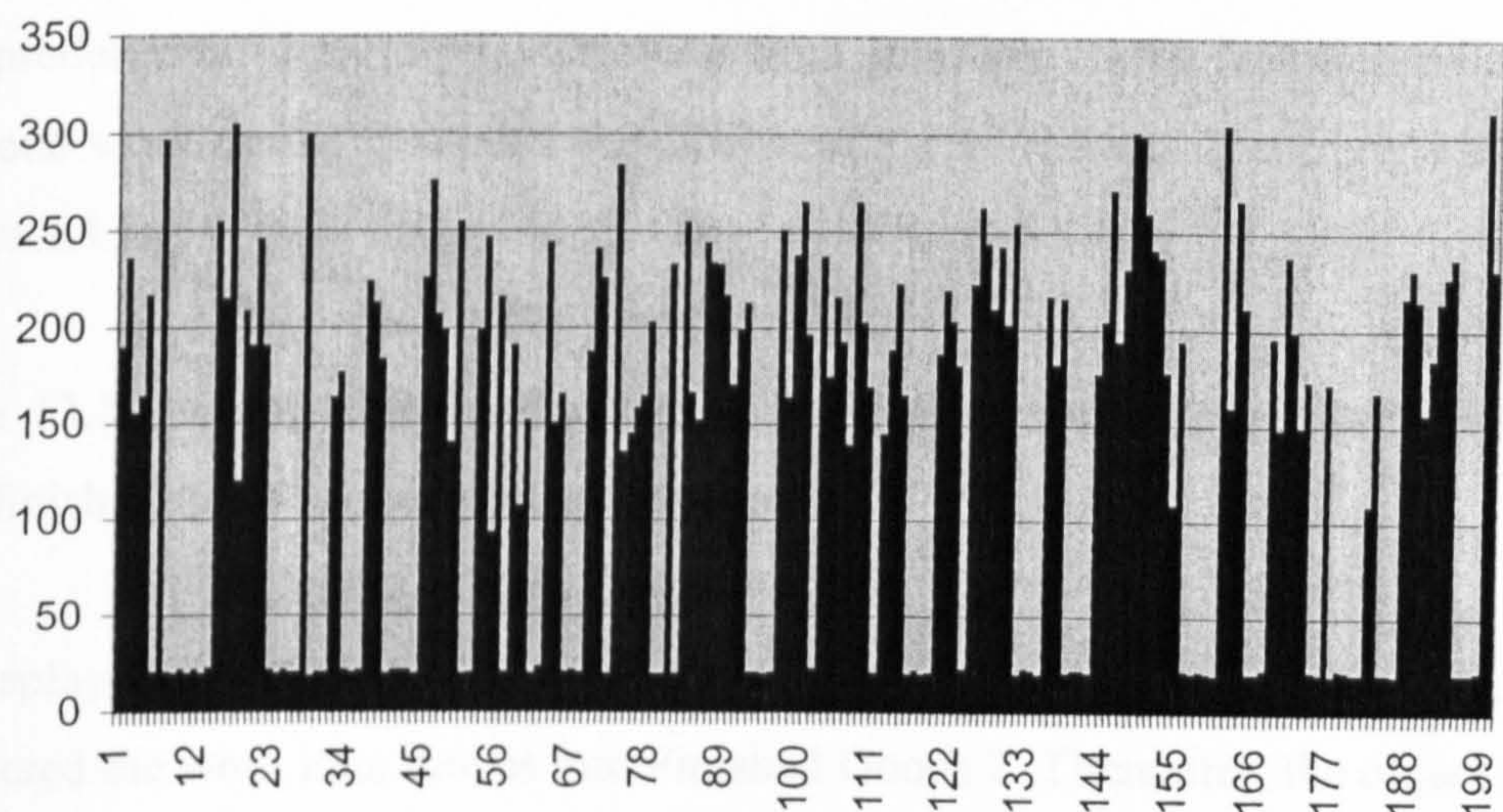


Figure 5.10 Order quantities

After work items arrive at Planning 1 the best route for the items to take is determined. The debugging features of the source code were used to evaluate the route planning validity of the VB programmes included in Section 12.1. In addition, the movement of work items was observed visually. Figure 13.1 depicts an example where a customer's order for 20 units of P2 was received. The batch size is 20. Therefore, 2 batches are planned for release, ie one for SF1 and one for SF2. The backlogs for the routes are displayed in the upper left corner. As shown for the ordered product P2, the VB program loaded routes 13 and 16. The run time was 2 and set-up time 1 at all the work centres and therefore, the backlog equals 164 time units.

In Figure 13.2 detailed information for a work item is displayed. The information can be used to verify the planned route for the item, the calculated lead time, the planned quantity, and the promised delivery date. The simulation time in Figure 13.1 is displayed in the upper right corner and is rounded to 33. Considering that the lead time was 164 time units, the promised delivery time of approximately 197 was, therefore, considered to be correct.

After orders are moved from release control to the network, the backlogs for the two routings were reduced by the planned lead times and WIP levels were increased as



displayed in Figure 13.3. It was also visually confirmed that orders were routed along their predetermined paths when moving from suppliers to the factories. When moving from one work centre to another the WIP levels were reduced accordingly as displayed in Figure 13.4.

Figure 13.5 demonstrates that the Visual Basic programme for selecting and merging semi-finished items is operating as intended.

As displayed in Figure 13.6 once the manufacturing and assembly processes are completed the work item moves into Finished Goods 2. Thereafter, the object Dummy 2 merges manufacturing and customer orders and sends them to object OUT2.

Figure 13.7 displays a situation, where a customer's order for 20 units of P2 has been received and two batches of 100 units of SF2 and SF3 are already being produced.

Figure 13.8 displays detailed information for SF2 batch. The label name Customer Order indicates the customer order numbers that are allocated to this batch. In this instance customer order 1 has been allocated and consequently, as the label named Rest indicates, only 80 units of SF2 remain unallocated.

As seen in Figure 13.7 a new customer order has been received to the Planning 1 object. After the planning operation, shown in Figure 13.9, customer orders 1 and 2 are now allocated to the same batch and the remaining unallocated quantity has been reduced to 59. The projected delivery time is approximately 810.

As displayed in Figure 13.10, the quantity in CO Backlog 2 has increased to 41 indicating that there are now two customer orders waiting to be delivered.

In Figure 13.11 the detailed work item information for customer order 2 has been displayed. As shown, CO Order Delivery time is equal to the Projected Delivery Time of the allocated manufacturing batch (ie see Figure 13.9). Consequently, batching has been confirmed to function as intended.



In Figure 13.12 a situation is displayed where the simulation model has already been running for some time. The release control has been activated and, as a result, orders have accumulated into backlogs.

Figure 13.13 illustrates having exactly the same customer order patterns the manufacturing orders have accumulated in supplier nodes instead of staying in release control. Release control is achieved by setting the run times in objects Dummy 5, Dummy 6, Dummy 7, and Dummy 8 equal to the current WIP levels in objects Supplier 1, Supplier 2, Supplier 3, and Supplier 4. Settings of object Dummy 6 have been illustrated in Figure 13.14.

To analyse the data from the experiments, a Visual Basic program was written to extract the data from the simulation model and insert it into a MS Excel sheets. The Excel sheets then contained the following information:

- a) order number,
- b) product id,
- c) promised delivery time,
- d) projected delivery time (only manufacturing orders),
- e) actual delivery time,
- f) quantity,
- g) cycle time, and
- h) lateness, where lateness equals actual delivery time less promised delivery time.

The tardiness is calculated manually considering that orders with negative lateness have tardiness equal to 0. An example is included in Section 12.5.

#### **5.4 Model validation**

In Figure 3.2 average cycle time is illustrated as a function of batch size. Since, the batching and release control are two main constructs in the developed simulation model, then, in an attempt to validate the model, it was necessary to refer to this defined cycle time and batch size relationship.

Varying only the batch size, 20 experiments were run in which the model parameters were set at:

- a) P1 order inter-arrival time distribution = FreqUp,
- b) P2 order inter-arrival time distribution = FreqUp,
- c) P1 order quantities distribution = QtyUp,
- d) P2 order quantities distribution = QtyUp,
- e) work centre run times = 2,
- f) work centre set-up times = 10,
- g) distribution of the time between breakdowns at work centres = Exponential, average 200,
- h) distribution of the time to repair the work centres = Normal average 15, standard deviation 1,
- i) batch allocation = Yes, and
- j) release control = Yes.



The results of the experiments are displayed in Table 5.2. The graphical plot of the results is displayed in Figure 5.11.

Batch size	Average Cycle Time with
40	2664.2
50	2137.8
60	1378.4
70	1578.9
80	1762.7
90	2014.0
100	2055.5
110	2116.3
120	2357.0
130	2452.6
140	2277.9
150	2756.7
200	3619.7
250	3982.9
300	4778.6
350	5117.2
400	6063.5
450	7371.4
500	7014.0
550	8265.6

Table 5.2 Results of the model validation experiment

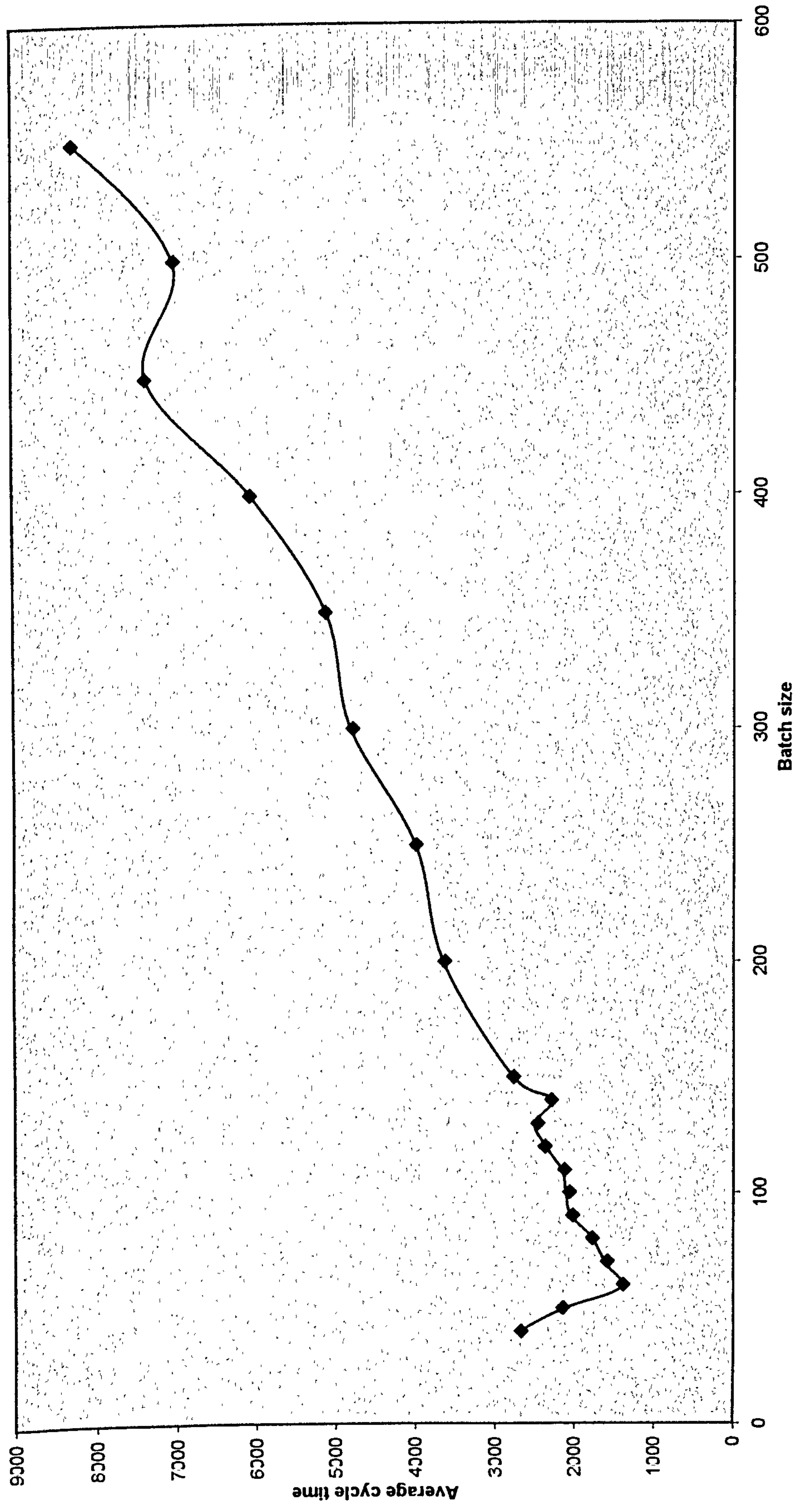


Figure 5.11 – Result of the model validation experiment



Karmarkar (1993) defined the relationship between cycle times and batches, displayed in Figure 3.2, using M/M/1 queueing model. The simulation model developed in this work is a representative of type II supply chain network discussed in Section 2.4. Despite complexity of supply chain networks compared to single machine queueing models, the curve, depicted in Figure 5.11, resembles that produced by Karmarkar (1993) which confirms the importance of batching decisions in achieving greater order movement velocity throughout the network. The minimum optimal batch size is near 60. Having batch sizes greater than 60, results in a longer cycle time, ie cycle time increases steadily with a batch size increase. Reduction of the batch sizes from 60 leads to a steeper average cycle time increase.

The simulated system performed as expected. The simulation model is representative of real world because it encompasses all of the major components of the supply chain planning process, and it involves a view of the detailed planning procedures that are not provided in high level analytical models. Validity beyond this level is difficult and would require implementation of a specific real-world supply chain.

### *5.5 Design of the experimentation*

The Taguchi approach (Fowlkes and Creveling, 1995) to the design of the experimentation was chosen to minimise the number of experiments that had to be undertaken.

The first set of Taguchi experiments was designed to assess the affect of various noise (eg breakdown intervals, repair times, etc.) and control factors (eg set-up times). It is important to identify the levels of the noise and control factors that induce significant variability in the data. Noise factors are used in the experiment to force variability, rather than depending on the random variation and sources of variability that may be intermittent. Set-up time was the control factor that was included in the experiments. Having defined the breakdown and repair time distributions, which lead to variable run times, the run times were fixed at 2 during all the experiments.

Thus, the factors evaluated in the first set of the experiments were:

- a) distributions of ordering frequencies of P1 and P2,
- b) distributions of order quantities of P1 and P2,
- c) exponential distributions of times between breakdowns at work centres,
- d) normal distributions of times to repair the work centres, and
- e) set-up time.

To induce high levels of response variability the control factors for the noise experiment were set at the following:

- a) Batch allocation = No,
- b) Release control = No.

The L12 orthogonal array was used to define the experimental runs. L12 is a special array in which all columns have their interactions evenly distributed between them (Fowlkes and Creveling, 1995). The WinRobust software package provided by Abacus Digital, Int. (Abacus Digital, Int. , 1995) was used to perform the calculations and display the results. In Table 5.3 the factor settings are defined.

	1	2	3	4	5	6	7
Run	Order quantities P1	Order quantities P2	Inter-arrival times P1	Inter-arrival times P2	Time to repair	Time between breakdowns	Set-up time
1	FreqUp	QtyUp	FreqUp	QtyUp	5	200	1
2	FreqUp	QtyUp	FreqUp	QtyUp	15	1000	10
3	FreqUp	QtyUp	FreqDown	QtyDown	5	200	10
4	FreqUp	QtyDown	FreqUp	QtyDown	15	1000	1
5	FreqUp	QtyDown	FreqDown	QtyUp	5	1000	10
6	FreqUp	QtyDown	FreqDown	QtyDown	15	200	1
7	FreqDown	QtyUp	FreqDown	QtyDown	15	1000	10
8	FreqDown	QtyUp	FreqDown	QtyUp	15	200	1
9	FreqDown	QtyUp	FreqUp	QtyDown	5	1000	1
10	FreqDown	QtyDown	FreqDown	QtyUp	5	1000	1
11	FreqDown	QtyDown	FreqUp	QtyDown	5	200	10
12	FreqDown	QtyDown	FreqUp	QtyUp	15	200	10

Table 5.3 – Noise and control factor settings defined using L12 array



The columns from 8 to 11 were left empty.

To identify the factor levels that cause maximum noise in the system, the data from the experiments was decomposed using analysis of means (ANOM). ANOM identifies both the magnitude and directionality of the factor effects.

The measured responses to analyse using ANOM are:

- a) standard deviation of the cycle time,
- b) mean of the cycle time, and
- c) order tardiness.

The analysed factors are combined and used in the main experiment to test the performance of batching and release control in the process described in Figure 5.8. The factors are combined depending on the directionality of their effects. The factors that cause an increase in the response are grouped together into CNF<sub>+</sub> (Compound Noise Factor), and those that cause a reduction in the response are grouped together into CNF<sub>-</sub>. These two groups, CNF<sub>+</sub> and CNF<sub>-</sub>, are used within the main experiment for each combination of the control factor array.

The results of the compounding are verified by using the same nominal system as for L12 experiment at the compound noise factor combinations. Usually, the verification test is expected to produce data where the quality characteristic level for CNF<sub>+</sub> is significantly higher than for CNF<sub>-</sub>. That result alone is adequate, but the values should be checked against the predictive equation. Although, the comparisons need not be exact to be valid.

The L4 orthogonal array was chosen for the main experiment. In Table 5.4 the factors settings for this experiment are defined.

	1	2	3
Run	Release Control	Batching	
1	Yes	Yes	
2	Yes	No	
3	No	Yes	
4	No	No	

Table 5.4 – Control factors setting of the main experiment defined using L4 array

The responses of the main experiment were analysed using ANOM. The responses analysed were the same as for the previous set of experiments.

It was decided to set the results collection period in simulation tool equal to 50000 simulation time units. The decision was based on several test runs. They showed no significant changes in results obtained after simulation runs that had the results collection period greater than 50000.

The main experiment will attempt to define the affect of the two model constructs (ie release control and batching) on the average cycle time and tardiness. To attain a more detailed understanding of batching and release control effects an additional 40 experiments have been conducted. During the experimentation all the noise and signal factors will be set to CNF+. Similarly to the validation experiments the batch size will vary. 20 experiments will be conducted having release control activated and during the other 20 experiments the release control will be deactivated.



## 6 Analysis of results

The results of the noise experiment described in Section 5.5 are displayed in Table 6.1.

Run	Standard deviation of cycle time	Mean cycle time	Tardiness
1	4706.7	7247.0	4724.6
2	4752.4	7137.5	4303.8
3	4398.5	5781.9	2810.3
4	3763.8	4926.0	2788.6
5	3199.5	4871.6	2608.6
6	3889.1	4775.4	2915.6
7	3791.9	4881.9	2823.3
8	3500.3	4782.8	2827.2
9	3168.9	4915.9	2735.6
10	3158.8	5049.4	2924.2
11	3651.0	4793.8	2751.4
12	4455.0	6641.6	3715.4

Table 6.1 – Results of noise experiments

The ANOM results of the noise experiment were interpreted by inspection of the factor effect plots in relation to their effects on the standard deviation of cycle time, mean cycle time, and tardiness, shown in Figure 6.1, Figure 6.2, and Figure 6.3.

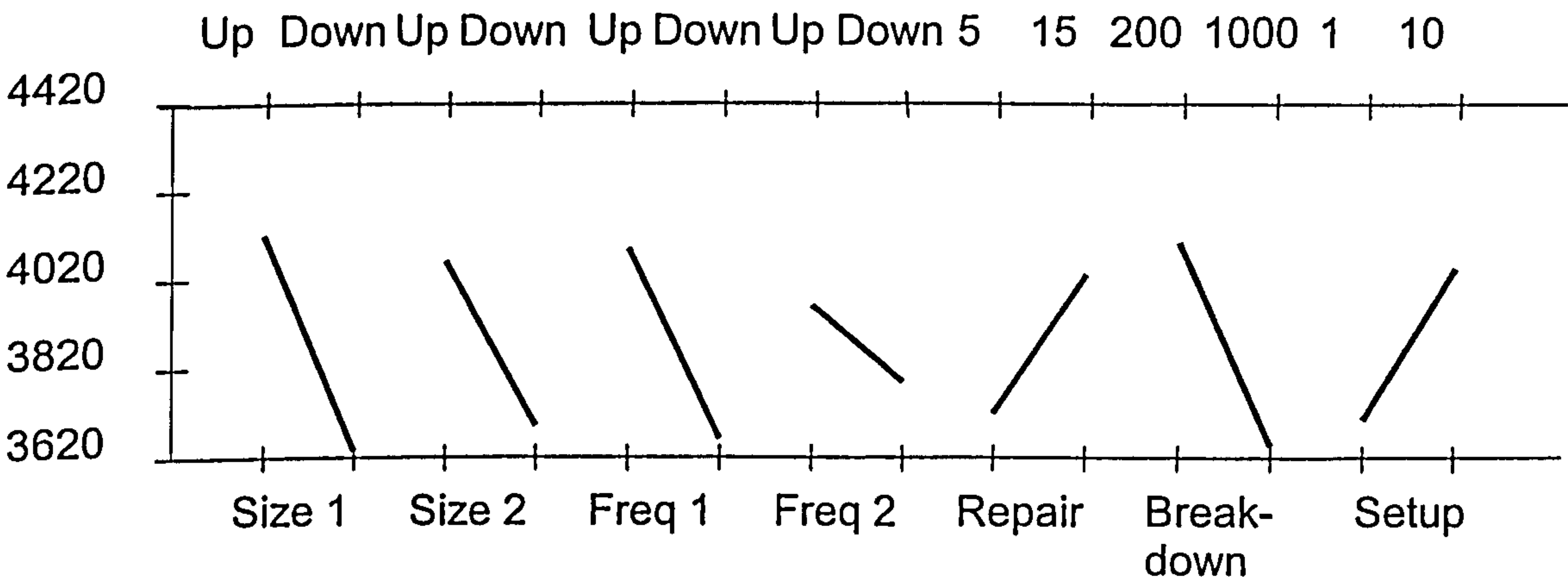


Figure 6.1 – ANOM plot of the noise experiment factor effects on the standard deviation of cycle time

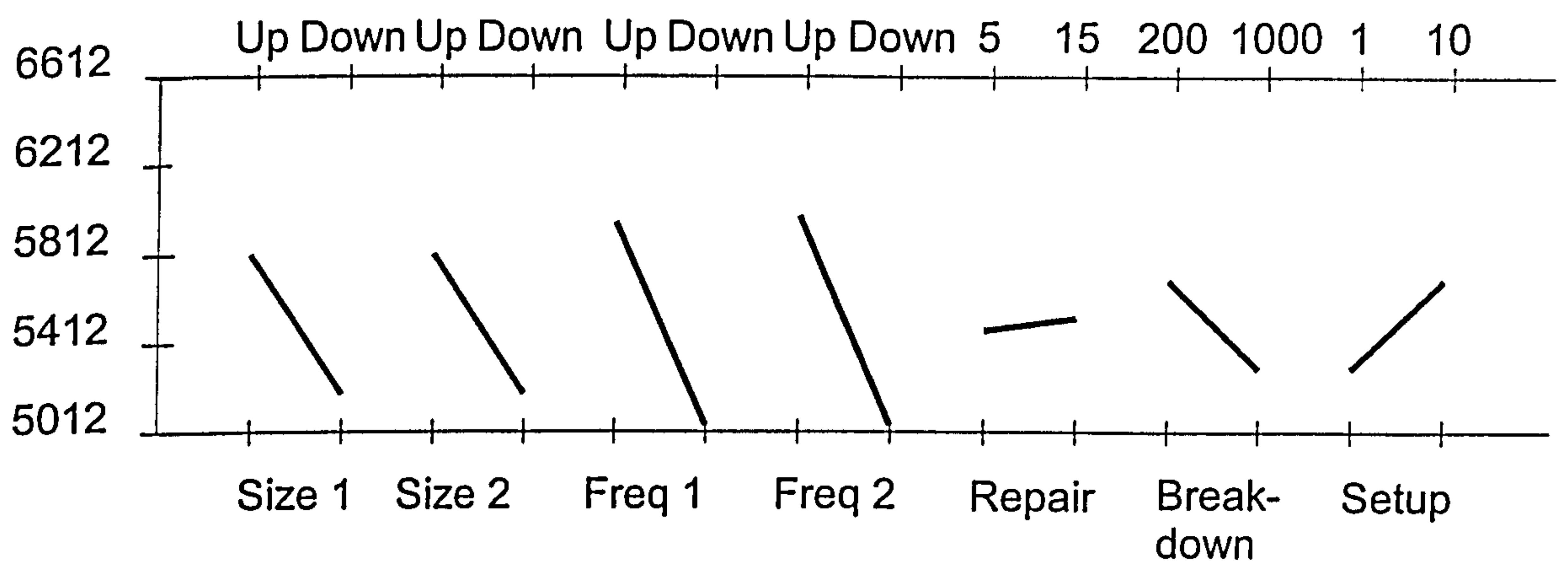


Figure 6.2 – ANOM plot of the noise experiment factor effects on the cycle time mean

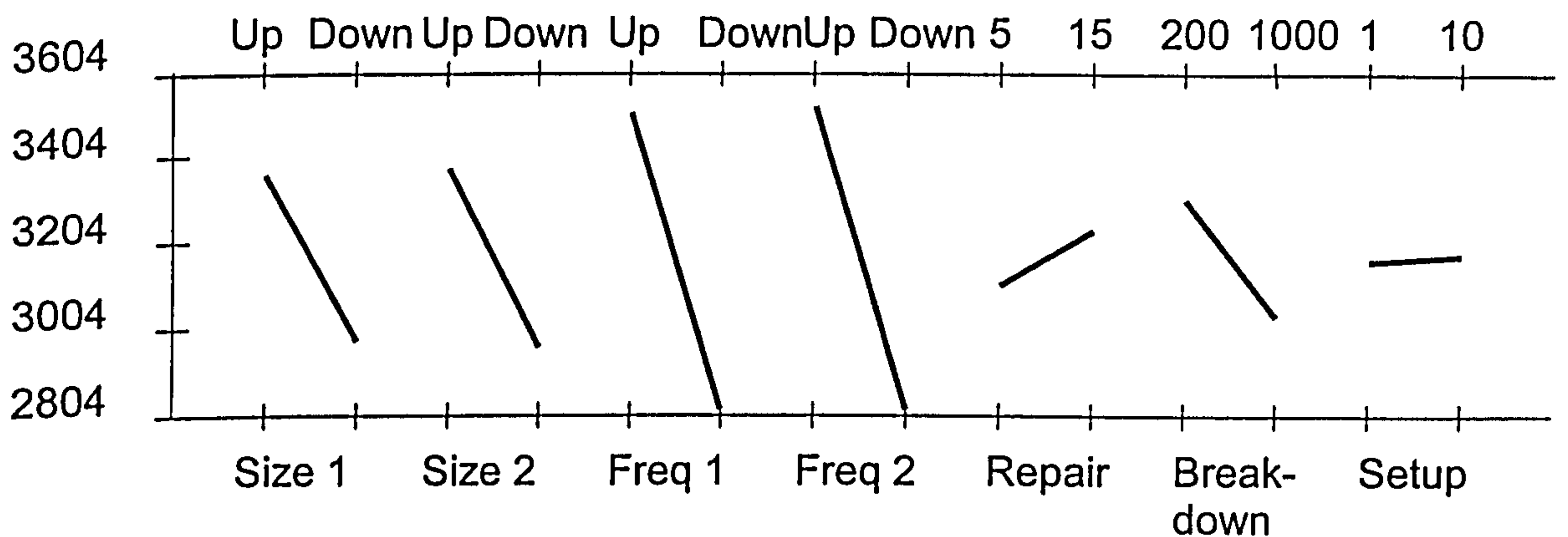


Figure 6.3 - ANOM plot of the noise experiment factor effects on the tardiness

The lower slopes of curves for the factors Repair and Setup effects on the cycle time mean and tardiness indicate that they are less significant contributors to the compound noise factors. Factors Size 1, Size 2, Freq 1, Freq 2, and Breakdown, however, appear to be important.

The compounding of these individual effects is determined by the direction of the factor effect slopes. Thus, for CNF<sub>+</sub> the following factor levels all act together to cause the mean and the standard deviation of the cycle time and the tardiness to increase:

- a) Size 1 = QtyUp,



- b) Size 2 = QtyUp,
- c) Freq 1 = FreqUp,
- d) Freq 2 = FreqUp,
- e) Repair = 15,
- f) Breakdown = 200, and
- g) Set-up = 10.

Similarly, for CNF. the following factor levels all act together to cause the mean and the standard deviation of the cycle time and the tardiness to decrease:

- a) Size 1 = QtyDown,
- b) Size 2 = QtyDown,
- c) Freq 1 = FreqDown,
- d) Freq 2 = FreqDown,
- e) Repair = 5,
- f) Breakdown = 1000, and
- g) Set-up = 1.

The means of the noise experiments, the predicted means of the measured responses and the results of the verification tests run using compound noise factors CNF<sub>+</sub> and CNF<sub>-</sub> are displayed in Table 6.2:

Responses	Means	Prediction CNF <sub>+</sub>	Verification CNF <sub>+</sub>	Prediction CNF <sub>-</sub>	Verification CNF <sub>-</sub>
Standard deviation of cycle time	3869.7	5165.5	4836.0	2573.8	3102.1
Mean of cycle time	5483.7	7456.6	7413.1	3510.9	4746.2
Tardiness	3160.7	4474.2	4775.7	1847.3	2579.2

Table 6.2 – The results of the verification experiments

The differences between predicted and verified values are minimal. This provides strong confirmation of satisfactory level of robustness and repeatability of results, and hence confidence in the design of the model and set-up of the experiments.

The results of the main experiment described in Section 5.5 are displayed in Table 6.3.

Run	Cycle time standard deviation		Mean cycle time		Tardiness	
	CNF.	CNF <sub>+</sub>	CNF.	CNF <sub>+</sub>	CNF.	CNF <sub>+</sub>
1	640.8	821.1	2216.1	2756.7	1382.5	2046.3
2	1323.4	1872.6	2700.6	3834.0	1723.7	3879.1
3	3522.3	3663.1	4692.7	5372.0	2345.5	2825.5
4	3102.1	4836.0	4746.2	7413.1	2579.9	4775.7

Table 6.3 – The results of the main experiment

The ANOM results of the main experiment are plotted in Figure 6.4, Figure 6.5, and Figure 6.6.

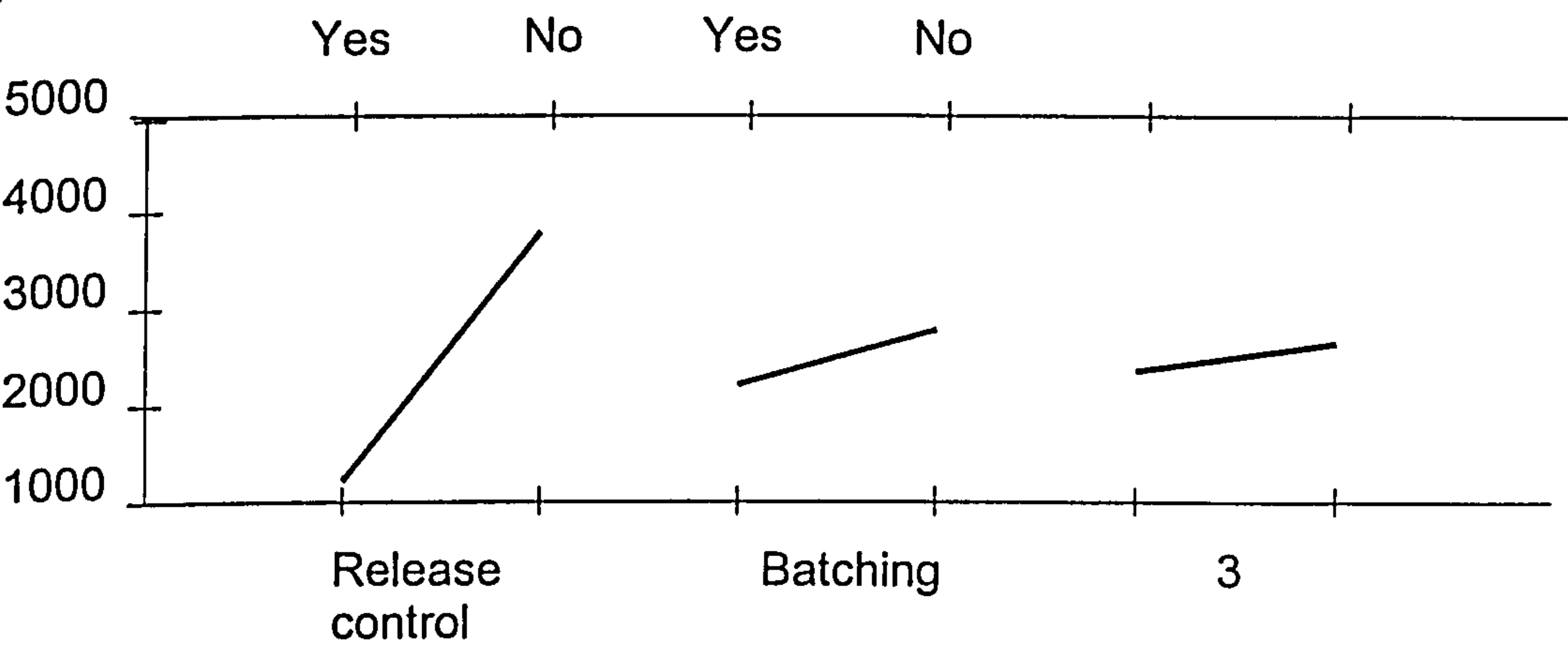


Figure 6.4 - ANOM plot of the main experiment factor effects on the standard deviation of cycle time

These results suggest that when order release control and batching are operating, order tardiness, and the mean and standard deviation of cycle time are reduced. Release control has greater affect on the standard deviation and mean of the cycle time than batching whereas batching has greater affect on the tardiness.



Since the third column in the L4 array remained empty it can now be used to analyse the interactions between release control and batching. The slope of the release control and cycle time curves are in the same direction and the third interaction plot is almost horizontal. These interactions are therefore minor which suggests that a specific level of performance could be achieved by merely implementing either release control or batching.

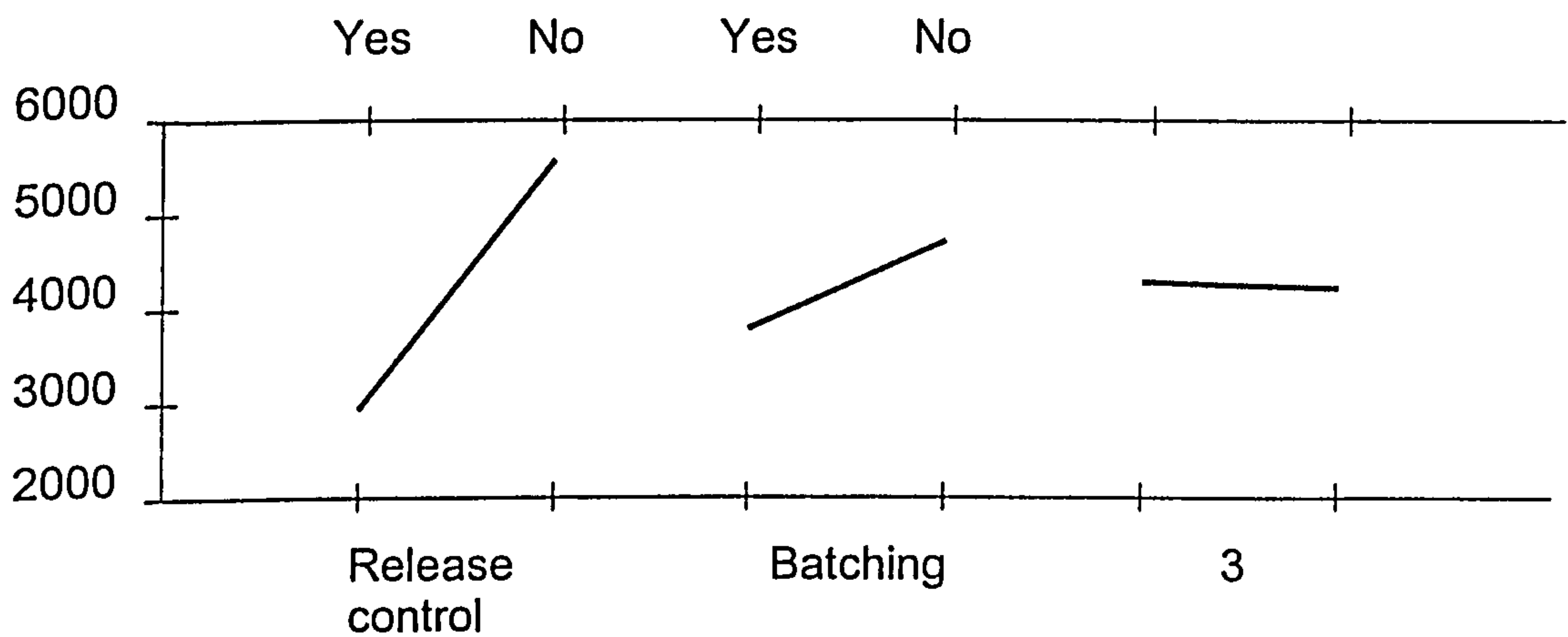


Figure 6.5 - ANOM plot of the main experiment factor effects on the cycle time mean

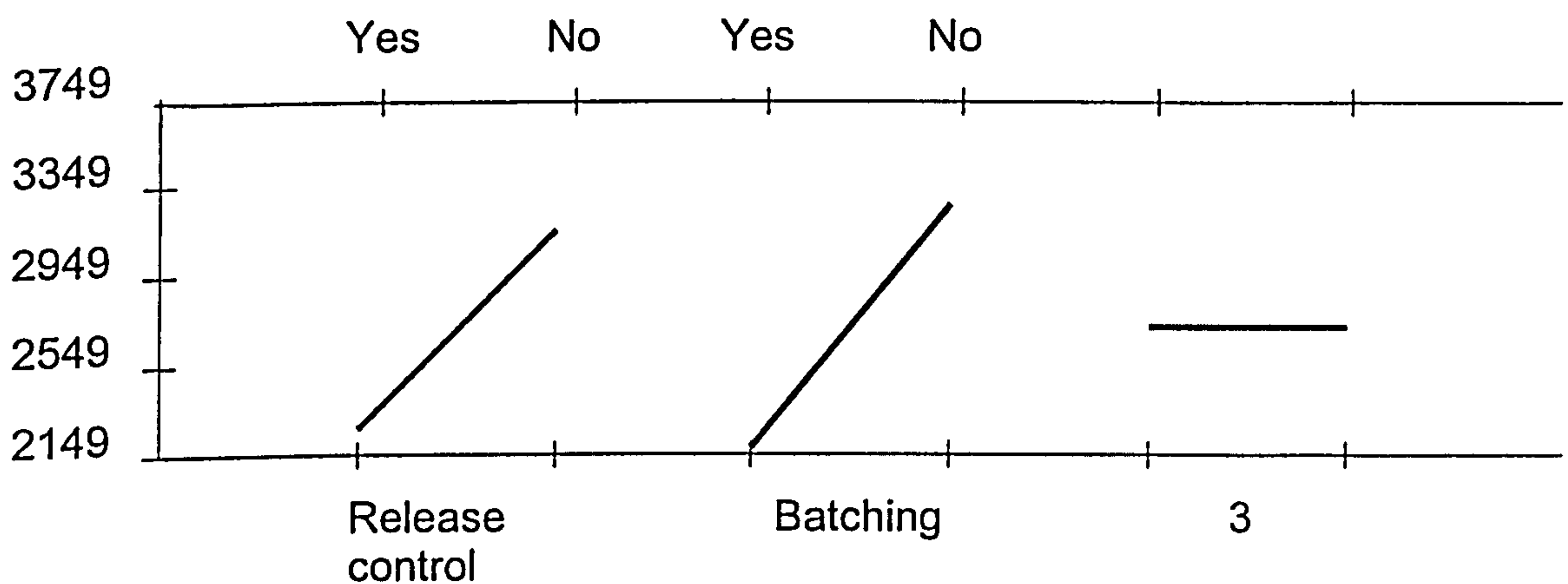


Figure 6.6 - ANOM plot of the main experiment factor effects on the tardiness

In an attempt to more fully understand the affect of batching and release control on the cycle time additional experiments were undertaken. Varying only the batch size, these experiments involved selecting two sets of model parameters, ie:

Model parameters – first set:

- a) P1 order inter-arrival time distribution = FreqUp,
- b) P2 order inter-arrival time distribution = FreqUp,
- c) P1 order quantities distribution = QtyUp,
- d) P2 order quantities distribution = QtyUp,
- e) work centre run times = 2,
- f) work centre set-up times = 10,
- g) distribution of the time between breakdowns at work centres = Exponential, average 200,
- h) distribution of the time to repair the work centres = Normal 15, standard deviation 1,
- i) batch allocation = Yes, and
- j) release control = No.

Model parameters – second set:

- a) P1 order inter-arrival time distribution = FreqUp,
- b) P2 order inter-arrival time distribution = FreqUp,
- c) P1 order quantities distribution = QtyUp,
- d) P2 order quantities distribution = QtyUp,
- e) work centre run times = 2,
- f) work centre set-up times = 10,
- g) distribution of the time between breakdowns at work centres = Exponential, average 200,
- h) distribution of the time to repair the work centres = Normal 15, standard deviation 1.
- i) batch allocation = Yes, and
- j) release control = Yes.

The results of the experiments are displayed in Table 6.4. The graphical plots of the results are displayed in Figure 6.7, Figure 6.8, Figure 6.9, and Figure 6.10.



Batch size	Average Cycle Time with release control	Average Cycle Time without release control	Number of items produced with release control	Number of items produced without release control	Order Backlog with release control	Average manufacturing order tardiness with release control	Average customer order tardiness with release control	Average manufacturing order tardiness without release control	Average customer order tardiness without release control
40	2664.2	5931.9	18200	18601	99.5	3070.5	3219.7	5160.5	4068.6
50	2137.8	5268.9	18700	19797	63.1	2510.4	2786.2	4026.7	3893.1
60	1378.4	5574.7	19657	21097	90.1	2935.4	2352.4	4122.3	3615.2
70	1578.9	5596.3	21207	22400	112.3	2831.4	2092.8	3827.1	4147.6
80	1762.7	5692.1	21017	21377	74.0	2886.3	2000.5	4064.7	3383.9
90	2014.0	5898.0	21897	22500	82.8	3095.1	1958.7	3906.8	3160.2
100	2055.5	5291.7	21300	21800	61.9	2276.2	1579.9	3334.2	2747.7
110	2116.3	5809.2	21450	21890	56.0	2328.7	1605.9	3811.9	3128.4
120	2357.0	5350.4	21360	21240	56.6	2680.1	1350.5	3177.5	2783.3
130	2452.6	7185.9	21320	21190	46.5	2320.1	1395.9	2948.7	2993.2
140	2277.9	5472.9	21000	23240	35.0	2054.4	1229.5	2830.0	2198.5
150	2756.7	5372.0	22200	21900	32.6	2046.3	1186	2825.5	2478.2
200	3619.7	7955.4	21800	22800	30.3	2366.1	1488.3	3520.0	2970.8
250	3982.9	7203.7	22250	22250	17.6	1429.3	807.1	3030.5	2612.0
300	4778.6	10481.2	22500	23100	31.5	1811.3	1116.5	4040.4	2945.2
350	5117.2	7564.7	22400	21350	14.0	886.7	337.5	1937.1	2500.3
400	6063.5	8413.0	20800	22800	11.0	448.7	166.5	1965.7	2289.9
450	7371.4	8456.3	22050	23450	9.6	1978.9	925.7	1875.5	2045.1
500	7014.0	8597.3	20000	22000	8.0	1231.9	720.4	1159.3	1118.2
550	8265.6	9365.1	19800	23100	9.6	2220.5	954.2	1617.4	1519.3

Table 6.4 – Results of the experiments to analyse release control affect on the cycle time - batch function



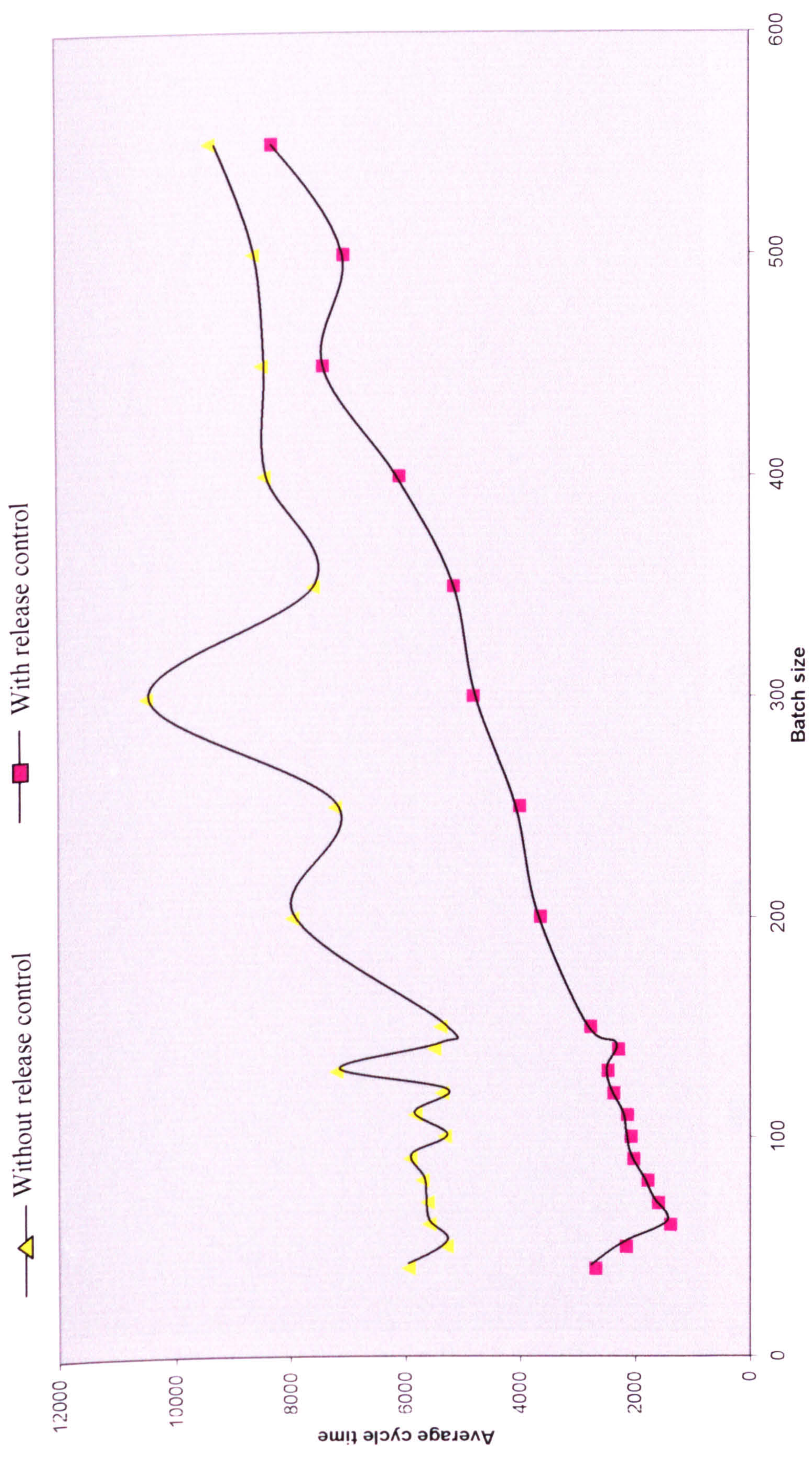


Figure 6.7 – Cycle time as a function of batch size with and without release control



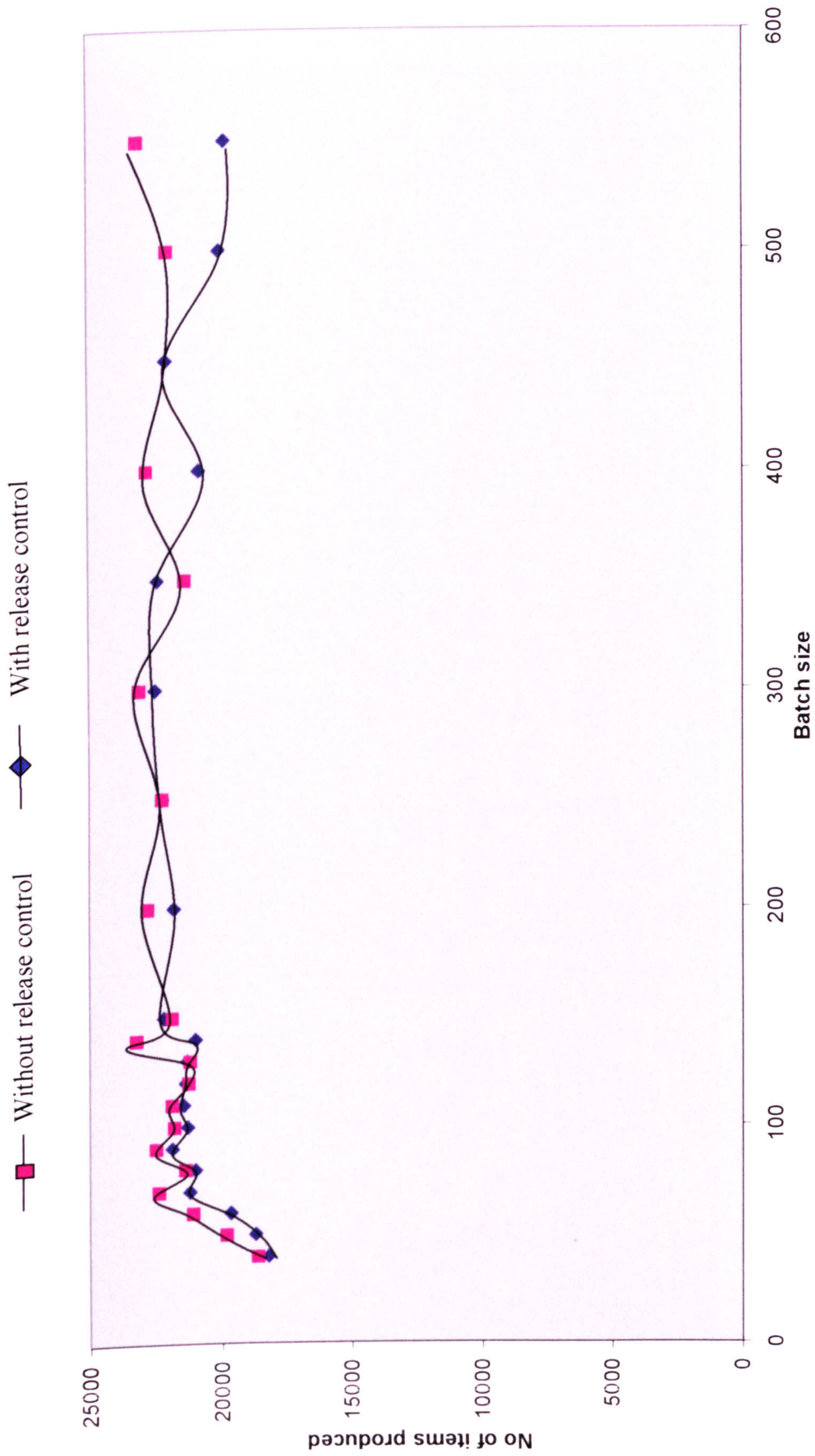


Figure 6.8 – Number of items produced as a function of batch size with and without release control



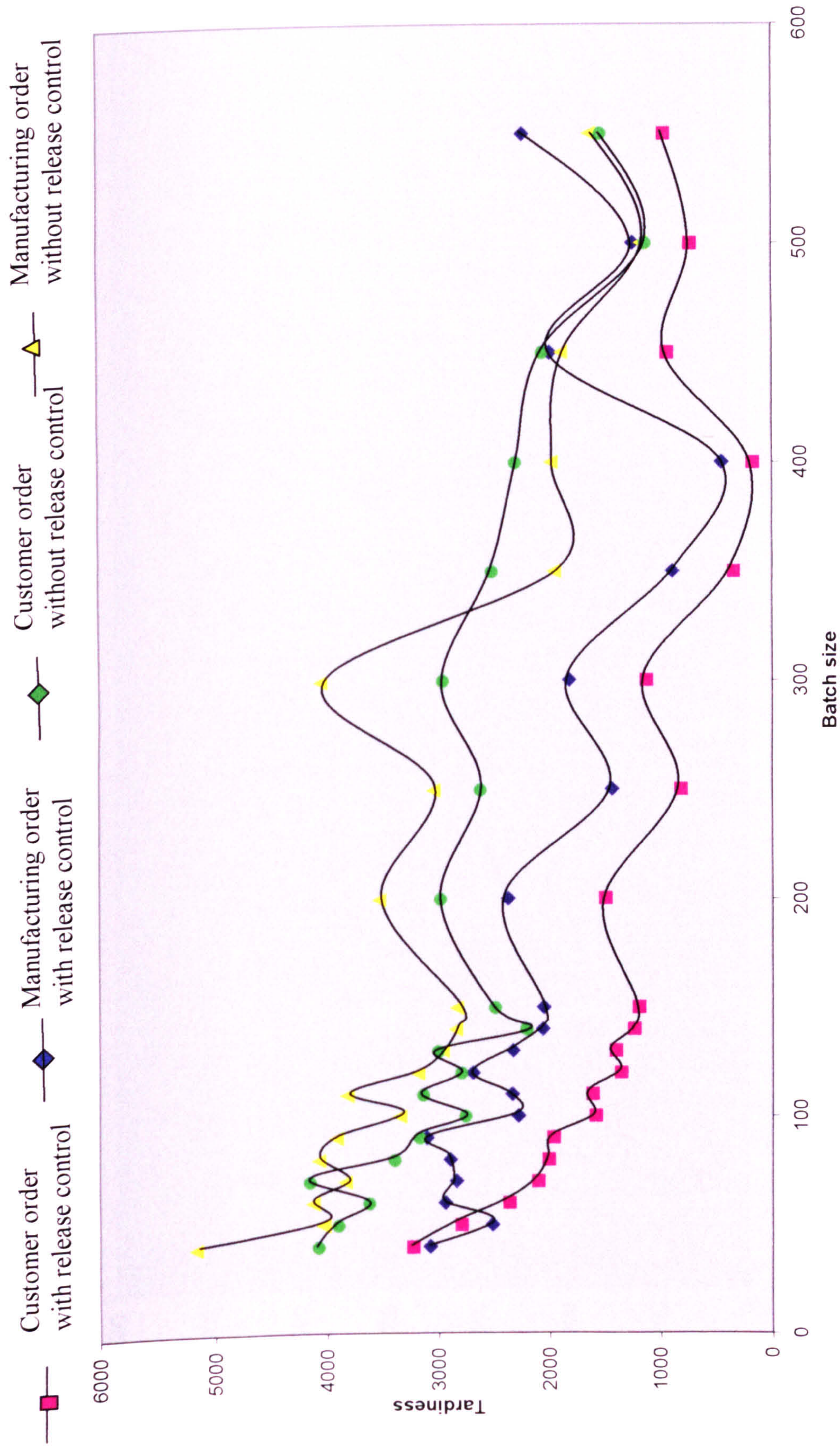


Figure 6.9 –Tardiness as a function of batch size with and without release control



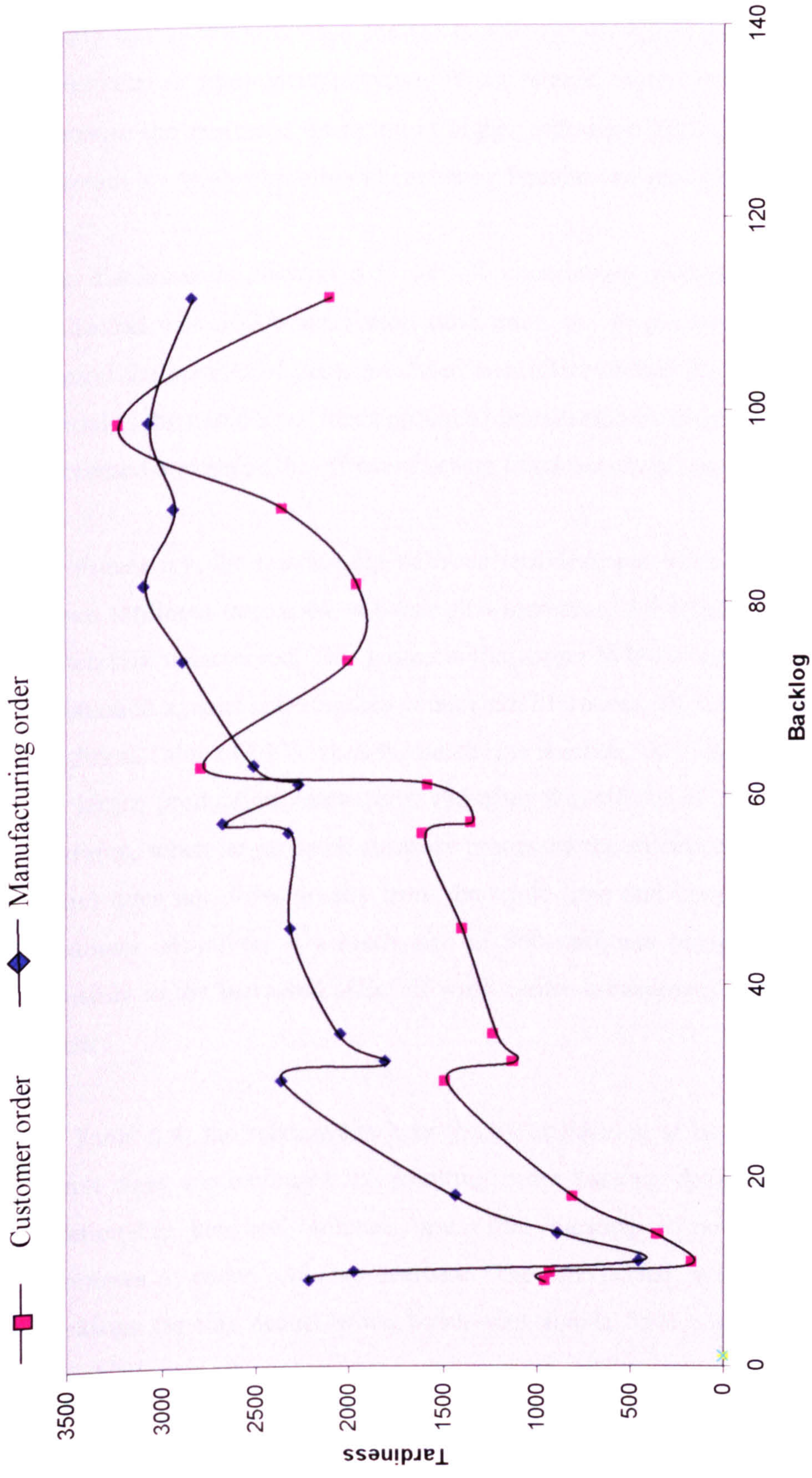


Figure 6.10 – Tardiness as a function of planned order backlog



As seen in Figure 6.7, without release control there are considerably higher average cycle times. When release control is active cycle times are more stable and increase gradually as batch sizes increase. When release control is not active instability arises because the system is operating at higher utilisation levels, and, hence as discussed in Section 3.1, high variability in customer demand can easily lead to congestion.

As discussed in Section 5.5, for all experiments period over which results were collected was 50000 simulation time units. As displayed in Figure 6.8, during this period the number of items produced is similar whether release control is 'on' or 'off'. Initially, the numbers of items produced increases in both these cases as the batch size is increased and hence the effects of set-up times becomes less dominant.

In Figure 6.9, the relationship between tardiness and batch size is displayed, ie in all cases tardiness decreases as batch size increases. All slopes of curves decline as the batch size is increased. This indicates that larger WIP (ie inventory) provides improved protection against uncertainties in demand. Moreover, all slopes appear to converge at a tardiness value of 1000 when the batch size reaches 500 units. This effect may arise due to larger production batch sizes reducing the effects of queue and set-up time. In addition, when larger batch sizes are processed the calculated processing time (ie lead-time) does not differ greatly from the cycle time and hence this results in decreased tardiness. However, at a batch size of 550 tardiness begins to increase slightly due possibly to the increased affect of work centre breakdowns and their associated repair times.

In Table 6.4, the relationship between order backlog at batch size is displayed, ie as batch sizes are increased the resulting order backlog decreases. In Figure 6.10, the relationship between tardiness and order backlog is now displayed, ie tardiness decreases as order backlogs decrease. The unexpected increase in tardiness at small backlogs (ie this occurs when batch size equals 550) could arise due to increased variability at work centres.



By comparing Figure 6.9 and Figure 6.10 it can be concluded that larger batch sizes result in larger backlogs. Larger backlogs, however, do not adequately reflect actual supply chain network (ie work centre) conditions. Since the lead-times of orders are not recalculated, the actual and promised delivery times begin to differ. Hence, lead-times and promised delivery times of newly arrived orders are also inaccurate. The larger the increase in order backlog the greater number of errors will accumulate. Resolving this situation requires frequent recalculation of these delivery times within the whole backlog.

As illustrated in Figures 6.7 to 6.10 the approach proposed within the current research to batching of customer orders into manufacturing orders and control of their release leads to greater stability of the production system, ie it results in shorter average cycle time and lower average tardiness.

Although, the lowest tardiness was obtained at a batch size of 400, using the release control, the shortest cycle time was obtained at a batch size of 60. However, as discussed in Section 3.1, larger batch sizes lead to higher WIP levels and longer cycle times, ie the throughput remains unchanged. Higher WIP levels lead to higher inventory carrying costs as demonstrated by the traditional EOQ formula (Vollman, et. al., 1997). Moreover, high inventory levels reduce the responsiveness of the supply chain to demand fluctuations as discussed in Section 3.2. Therefore, smaller batch sizes are desirable. Understanding the relationship between tardiness and the frequency with which order backlogs are recalculated could assist in attaining smaller tardiness and having simultaneously smaller batches.

## 7 Discussion

### 7.1 *Introduction*

Today a number of trends are combining to render the area of production planning rather more active than it has been for several decades. Increasing competitive pressures have forced companies to forego the expensive luxury of large amounts of excess capacity and high inventories, making effective allocation of manufacturing capacity and coordination of production activities throughout the supply chain a critical component of market success.

Several factors combine to make supply chain planning a difficult task. Particularly, since companies must respond to quickly changing market conditions and technological developments. As discussed in Section 2.3, a number of different, often conflicting objectives, such as fulfilling customer orders and maintaining low inventory levels and lead times, must be traded off against each other. Different amounts of variability in the production processes (discussed in Section 3.1) and customer demand (discussed in Section 3.2) must be managed. However, as described in Sections 2.5.1 and 2.5.2, there is considerable evidence from various industries that effective execution of this task can provide a significant competitive advantage.

In this chapter the discussion centres on developments in the area of the production planning and focusses on environments where multiple plants are considered. However, no attempt has been made to provide a comprehensive overview of the whole complexity of large supply chains, which should include such aspects such as strategic supply chain network design, transportation planning, demand management, etc (an overview of supply chain planning issues is provided in Section 4.8).

The discussion will involve reviewing the relationship between the production planning and scheduling functions, and their importance within a manufacturing company. In this context the effects of congestion on the shop floor will be examined and the relationship between workload and lead times which is fundamental to the relationship between



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protect themselves against uncertainties in supplier deliveries. In essence, this lack of information contributes to the 'Forrester effect' discussed in Section 3.2.

To minimise the 'Forrester effect' responsive and frequent communications are required within supply chains. A two-way communication should be established in which customer demand needs to be broadcast to all nodes to enable supply chain wide material and capacity reservations and where the shop-floor information such as WIP status should be known to the planning engine such as APS in order to make correct decisions.

However, customer demand can fluctuate considerably, ie the order quantities and the ordering frequency can change. Such demand fluctuations will result in fluctuations in requirements of resources on the shop floor, hence making it difficult to achieve synchronised plans. As depicted in Figure 3.10, the fluctuations in resource requirements can occur due to the use of traditional batch process based planning algorithms. These planning algorithms also contribute to the 'Forrester effect'.

To protect manufacturing from demand uncertainties, ie to reduce manufacturing cycle time variability, and at the same time to obtain an element of agile responsiveness a specific level of inventory is always required. As discussed in Section 3.4, pull systems such as Kanban and CONWIP use inventory not only to protect against demand uncertainties, but also to trigger upstream manufacturing processes, ie inventory is being used as information. However, inventory moves relatively slowly and is costly to maintain. Hence, it is more efficient and less costly to trigger production by the use of information as opposed to using inventory, ie demand information should be the trigger for starting production and this information should be communicated upstream through the manufacturing route as quickly as possible, ideally simultaneously to all nodes.

By using up-to-date batch movements information (ie inventory and WIP status), by having a demand as a single point to trigger (ie pull) manufacturing, by broadcasting this demand rapidly throughout a supply chain, by making the release of planned batches into manufacturing dependant upon the WIP levels (ie preventing congestion):



- a) reliable delivery dates can be quoted,
- b) manufacturing can be protected against demand uncertainties,
- c) cycle time variability and cycle times themselves can be reduced, and
- d) due to the reduced cycle times, systems can maintain lower inventory and WIP levels whilst maintaining the same level of throughput.

Based on these processes a novel operational level planning framework has been proposed, an example of which is depicted in Figure 7.1.

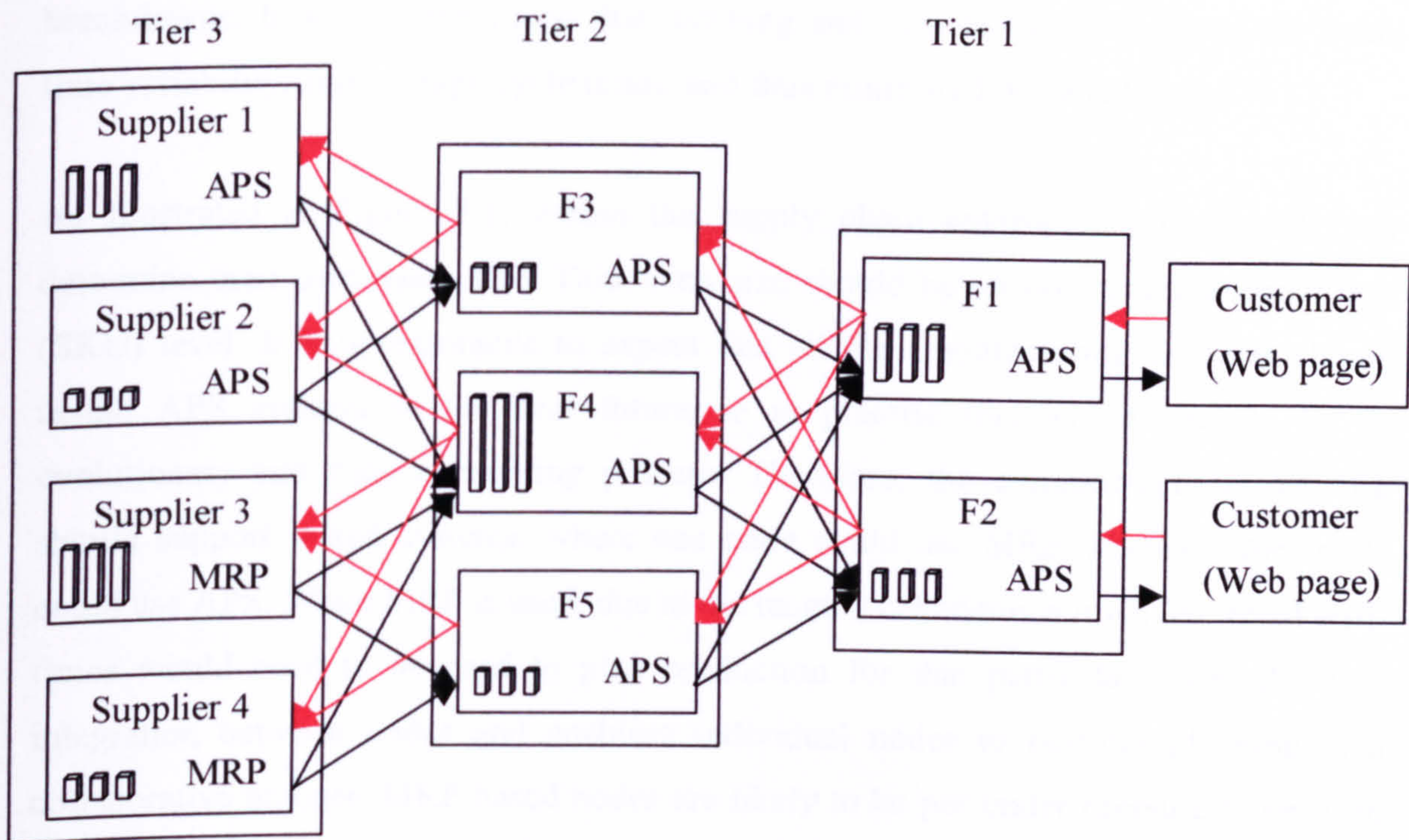


Figure 7.1 - Manufacturing batches across the network

The red arrows represent the connections within an Internet enabled communications network. Within this network, customer would have the facilities to place orders through a web page. Thereafter, the factories upstream of the customers, F1 and F2, would perform their capacity and material planning calculations. If material supplies are needed a bid would be sent to several alternative suppliers in tier 2. The bid would contain information about the product type, the quantity and date the product is needed. After performing planning calculations, should a mid-tier supplier identify material or



capacity shortages, then this supplier would send bids to its suppliers in tier 3. After performing order planning, moving upstream, the nodes send responses to the bids received. Thus, triggered by a single customer demand signal, each node within a network would perform planning calculations considering the responses of its suppliers. Eventually, the downstream nodes would propose a delivery date to the customer.

A simplified version of this planning approach was analysed in Chapter 5. In particular, the focus centred on analysing the effects of batching and release control in an attempt to minimise noise factors arising from such factors as volatile demand and machine breakdowns. It was demonstrated that batching and release control reduced the cycle time variability, and average cycle times, and thus minimised order tardiness.

As illustrated in Figure 7.1, within the supply chain environment each node can determine their own batch size. This batch size should be set on a stock keeping unit (SKU) level. It is unreasonable to expect that all the manufacturing facilities should install APS systems in the near future, ie in practise this would tend to be an evolutionary and time consuming process. Therefore, the communications network should support mixed systems, where one node could use MRP whereas other node could use APS. When MRP is used, due to the lengthy calculations involved, fixed lead-times would need to be used to plan production for that particular node. By tight integration between nodes and enabling individual nodes to perform planning in a collaborative manner, MRP based nodes are likely to be put under pressure to perform better and eventually, therefore to transfer planning into APS. Similarly, companies who experience high levels of competition will constantly be under pressure to reduce their batch sizes and hence to improve manufacturing efficiency.



## 8 Conclusions

This work has developed novel supply chain planning and control processes and examined their impact in enabling manufacturing businesses to take greater advantage of emerging Internet information technologies. The principal benefits of these planning and control processes are:

- a) they enable information to control the levels of inventory within a supply chain, ie inventory moves in response to information, and therefore improve supply chain stability in terms of reducing cycle time variability and reducing WIP levels whilst maintaining throughput rates,
- b) they offer the potential of improving the responsiveness of supply chains to unexpected events through faster demand communication and order planning,
- c) they offer the potential of reducing the amplitude of oscillations in material and resource requirements, through faster demand communication and order planning, and
- d) they improve delivery reliability since shorter and more stable cycle times result from more frequent, and synchronised material and capacity planning.

The above benefits are obtained through use of the novel planning and control features developed during this research, ie:

- a) The function of the *planning* processes developed is to improve order fulfilment planning within supply chain networks. The novel features of the order fulfilment planning processes are based on the use of information to ‘pull’ material through individual nodes within a supply chain using the following methods.
  - i) Customer demand information is continuously broadcast throughout the network using ‘bid and response’ rules, ie to all nodes, and is used to initiate planning. During this process supply chain routes are dynamically established each time a new order arrives from a customer.

- ii) Upon receipt of a demand request by a node, the planning function for this node generates capacity and material requirements schedules. These schedules are generated using real-time WIP and work centre loading information from the shop floor. During this scheduling process, customers orders are allocated either to released manufacturing batches or new manufacturing batches are planned for future release. When a customer's order is allocated to a released manufacturing batch then the delivery date promised to that customer is the projected completion date of the batch.
  - iii) Order backlog information is then used to provide customers with 'promised' delivery dates for future orders.
- b) During order planning, the function of the *control* processes developed is to monitor the utilisation levels of production facilities at individual nodes in order to ensure that congestion of facilities does not occur. At the point of release of a planned order to production, in addition to the 'promised' delivery date a 'projected' delivery date is calculated.

These planning processes have been modelled using a discrete-event simulation models. The analysis of the experimentation performed using these models indicated that:

- a) the 'bid and response' rules reduce demand oscillations within supply chain networks and hence lead to reduced oscillations in both inventory and manufacturing resource requirements,
- b) the proposed approach to batching of customer orders into manufacturing orders leads to greater stability in measured responses and results in shorter average cycle time and lower average tardiness,
- c) the order release procedures enable the correct timing of manufacturing order releases such that congestion does not arise and therefore leads to both reduced cycle time variability and reduced levels of tardiness,



- d) the procedures for batching customers orders reduces the adverse effects of variable customer order arrivals in that fluctuations in material and manufacturing resource requirements are reduced, and
- e) tardiness increased as the backlog of planned orders increased.

## 9 Further work

The current work examined the effects of batching and release control on cycle time and tardiness establishing the connections between order release, planning and capacity decisions. However, the production costs were not considered particularly inventory carrying costs and those associated with set-up and procurement. Hence further work needs to be carried out to identify the effects on costs of batching, variable customer demand, manufacturing facilities (ie machines), and alternative planning algorithms.

The ability to dynamically adjust batch sizes depending on incoming customer demand (ie planned order backlogs) could assist in reducing planning errors and improving delivery reliability. Hence further work needs to be directed towards identifying procedures for determining batch sizes under conditions of variable customer demand.

An additional area for further research should be aimed at improving the supply chain planning processes examining the affects of backlog recalculation frequency, planning accuracy and delivery reliability.



## 10 References

- Abacus Digital, Int. (1995). The WinRobust User's Manual. Abacus Digital, Int. New Jersey, USA
- Bagnell, Bill (2000). The promise and pitfalls of Enterprise Application Intergration. Midrange ERP, March
- Battezzati, Luigi; Magnani, Roberto. (2000). Supply chains for FMCG and industrial products in Italy: Practices and advantages of postponement. International Journal of Physical Distribution and Logistics Management. Vol. 30, No. 5, pp. 413-424
- Bermudez, John. (1998). Advanced Planning and Scheduling: Is it as good as it sounds? The Report on Supply Chain Management, AMR Research, Inc. March 1998.
- Bermudez, John. (1998). Can I Get APS From My ERP Provider? The Report on Supply Chain Management, AMR Research, Inc. December
- Billington, C. (1994). Strategic supply chain manegement. OR/MS Today, April, pp. 76-82
- Blumenfeld, Dennis E; Daganzo, Carlos F.; Frick Michael C.; Gonsalvez, David J.A. (1999). Impact of manufacturing response time on retailer inventory. International Journal of Operations and Production Management. Vol. 19, No. 8, pp. 797-811
- Chambers, Nick. (1996). Beyond MRPII: A new approach to manufacturing planning and simulation. Industrial Management and Data Systems. Vol. 96, No. 4, pp.3-5
- Chizzo, Scott A. (1998). Supply chain strategies: solutions for customer-driven enterprise. Supply Chain Management Directions, January
- Christopher, Martin. (2000). The agile supply chain: competing in volatile markets. Industrial Marketing Management, 29, pp. 37-44

- Cohen, Morris A.; Zheng, Yu-Sheng; Wang, Yunzeng (1999). Identifying opportunities for improving Teradyne's service-parts logistics system. *Interfaces*, Vol. 29, No. 4, pp. 1-18
- Czupryna, Ed (2000). Supply chain collaboration starts with plant scheduling. *Midrange ERP*, April
- D'Amours, Sophie; Montreuil, Benoit; Lefrancois, Pierre; Soumis, Francois. (1999). Networked manufacturing: The impact of information sharing. *International Journal of Production Economics*. Vol. 58, pp. 63-79
- Daugherty, Patricia J.; Ellinger, Alexander E. (1995). Information accessibility: Customer responsiveness. *International Journal of Physical Distribution and Logistics Management*. Vol. 25, No. 1, pp. 4-17
- Dilger, Karen (2000). Supply chain execution: The value of versatility. *Manufacturing Systems*, Vol. 18, No. 3
- Disney, S.M.; Naim, M.M.; Towill, D.R. (1997). Dynamic simulation modelling for lean logistics. *International Journal of Physical Distribution and Logistics Management*. Vol. 27, No. 3/4, pp. 174-196
- Dullin, Eric. (1998). Enterprise and plant-centric scheduling. *IIE Solutions*, February
- Ellinger, Alexander E. (2000). Improving marketing/logistics cross-functional collaboration in the supply chain. *Industrial Marketing Management*, 29, pp. 85-96
- Enslow, Beth. (1999). The zero-latency enterprise. *APS Magazine*, February
- Erengüç, Selçuk Ş.; Simpson, N. C.; Vakharia, Asoo J. (1999). Integrated production-distribution planning in supply chains: An invited review. *European Journal of Operational Research*, 115, pp. 219-236
- Ernst, Ricardo; Kamrad, Bardia. (2000). Evaluation of supply chain structures through modularization and postponement. *European Journal of Operational Research*, 124, pp. 495-510



- Fulcher, Jim (2000). Make the connection. *Manufacturing Systems*, Vol. 18, No. 3
- Girard, Greg. (1998). Inventory Management: Do You Have the Goods? The Report on Supply Chain Management, AMR Research, Inc. August
- Graham, Gary; Hardaker, Glenn. (2000). Supply chain management across the Internet. *International Journal of Physical Distribution and Logistics Management*. Vol. 30, No. 3/4, pp. 286-295
- Gumaer, Robert. (1998). New rules, new tools: attaining optimal financial performance with APS technology, November
- Hatcher, James (2000). The internet-based supply web. *Midrange ERP*, March
- Hicks, C.; McGovern, T.; Earl, C. F. (2000). Supply chain management: A strategic issue in engineer to order manufacturing. *International Journal of Production Economics*. Vol. 65, pp. 179-190
- Hill, Sidney (2000). Stand together or fail alone. *Manufacturing Systems Europe*, Summer 2000
- Hill, Sidney Jr. (1999). APS and ERP work together, but is full integration inevitable? *Manufacturing Systems Europe*, May/June
- Hinerhuber, H. H.; Levin, B. M. (1994). Strategic networks: the organisation of the future. *Long Range Planning*, Vol. 27, No. 3, pp. 43-53
- Hollinger, Bruce (2000). Building a customer focused value chain. *Manufacturing Systems*, Vol 18, No 4
- Horiguchi, Kazuo; Raghavan, Narasimhan; Uzsoy, Reha; Venkatesvaran, Suresh. (2000). Finite capacity production planning algorithms for semiconductor wafer fabrication facility. Research Memorandum No. 2000-6, School of Industrial Engineering, Purdue University, USA. February, 2000

- Inman, Robert R.; Gonsalvez, David J. (1997). Measuring and analysing supply chain schedule stability: a case study in the automotive industry. *Production Planning and Control*, Vol. 8, No. 2, pp. 194-204
- Karmarkar, Uday S. (1987). Lot sizes, lead times and in-process inventories. *Management Science*. Vol. 33, No. 3, March
- Karmarkar, Uday S. (1989). Capacity loading, release planning and master scheduling with WIP and lead times. *Journal of Manufacturing Operations Management*. Vol. 2, No. 2, pp. 105-123
- Karmarkar, Uday S. (1993). Manufacturing lead times, order release and capacity loading. *Handbooks in OR & MS*, Vol. 4
- Karmarkar, Uday S.; Kekre, Sham; Kekre, Sunder. (1992). Multi-item batching heuristics for minimization of queueing delays. *European Journal of Operational Research*. No. 58, pp. 99-111
- Karmarkar, Uday; Kekre, Sunden. (1987). Manufacturing configuration, capacity and mix decisions considering operational costs. *Journal of Manufacturing Systems*. Vol. 6, No. 4
- Korpela, Jukka; Lehmusvaara, Antti. (1999). A customer oriented approach to warehouse network evaluation and design. *Industrial Journal of Production Economics*, 59, pp. 135-146
- Kotzab, Herbert. (1999). Improving supply chain performance by efficient consumer response. *Journal of Business and Industrial Marketing*. Vol. 14, No. 5/6, pp. 364-377
- Laarhoven, Peter van; Berglund, Magnus; Peters, Melvin. (2000). Third-party logistics in Europe - five years later. *International Journal of Physical Distribution and Logistics Management*. Vol. 30, No. 5, pp. 425-442
- Lamming, Richard; Johnsen, Thomas; Zheng, Jurong; Harland, Christine. (2000). An initial classification of supply chain networks. *International Journal of Operations and Production Management*. Vol. 20, No. 6, pp. 675-691



- Lancioni, Richard A.; Smith, Michael F.; Oliva, Terence A. (2000). The Role of the Internet in Supply Chain Management. *Industrial Marketing Management*, 29, pp. 45-56
- Lapide, Larry. (1998). Are we moving from buyers are sellers to collaborators? The Report on Supply Chain Management. AMR Research, Inc. July
- Lapide, Larry. (1998). Demand Planning and Forecasting: There Is a Difference. The Report on Supply Chain Management, AMR Research, Inc. February
- Lapide, Larry. (1998). Supply chain optimisation: just the facts. AMR Research, Inc.
- Laurence, P. D. (2000). Developing in harmony: Case study. *International Journal of Physical Distribution and Logistics Management*, Vol. 30, No. 5, pp. 409-412
- Layden, John. (1998). Thoughts on supply-chain management. *Manufacturing Systems*, March
- Layden, John. (1999). APS is here to stay. *Manufacturing Systems*, February
- Layden, John. (2000). The digital supply chain network architecture. Symix, Inc., 2000
- Lee, H. L.; Billington, C. (1993). Material management in decentralized supply chains. *Operations Research*, Vol. 41, No. 5
- Lewis, Jayne C.; Naim, Mohamed M.; Towill, Denis R. (1997). An integrated approach to reengineering material and logistics control. *International Journal of Physical Distribution and Logistics Management*. Vol. 27, No. ¾, pp. 197-209
- Lin, F. (1996). Reengineering the order fulfillment process in supply chain networks: a multiagent information systems approach. Ph.D. Thesis, University of Illinois at Urbana-Campaign
- Logility. (1998). Logility value-chain solutions, Logility Inc.
- Manugistics<sup>6</sup> (1998) For customer-centric supply chain optimization, Manugistics, Inc
- Mason-Jones, R; Towill, D.R. (1997). Information enrichment: designing the supply chain for competitive advantage. *Supply Chain Management*. Vol. 2, No. 4, pp. 137-148

- Michel, Roberto (2000). The road to extended ERP. *Manufacturing Systems*, Vol 18, No 3
- Min, Hole; Galle, William P. (1999). Electronic commerce usage in business-to-business purchasing. *International Journal of Operations and Production Management*. Vol. 19, No. 9, pp. 909-921
- Mitchell, Pierre (2000). Trading Exchange Infrastructure. AMR Research, Inc, July
- Owen, Terry (2000). Real value in real time. *Manufacturing Systems*, Vol .18, No. 3
- Pancucci, Don. (1998). Forecasting for the Supply Chain – Future Imperfect. *Manufacturing Computer Solutions*, March
- Parker, Kevin (2000). Planning begins in the plant. *Manufacturing Systems*, Vol. 18, No. 2
- Parker, Kevin (2000). Supply chain planning. *Manufacturing Systems*, Vol. 18, No. 2
- Pawar, Kulvant S.; Driva, Helen. (2000). Electronic trading in the supply chain: a holistic implementation framework. *Logistics Information Management*. Vol. 13, No. 1, pp. 21-32
- Skjoett-Larsen, Tage. (2000). European logistics beyond 2000. *International Journal of Physical Distribution and Logistics Management*. Vol. 30, No. 5, pp. 377-387
- Smith, Chris (2000). Spotlight: Vendor managed inventory. *Midrange ERP*, March
- Snitkin, Sid (2000). Supply chain collaboration is more than just software. *Midrange ERP*, April
- Souza, R.; Zice, S.; Chaoyang, L. (2000). Supply chain dynamics and optimization. *Integrated Manufacturing Systems*. Vol. 11, No. 5, pp. 348-364
- Stalk, George. (1988). Time-the next source of competitive advantage. *Harvard Business Review*, July-August



Stalk, George; Evans, Philip; Shulman, Lawrence (1992). Competing on capabilities: The new rules of corporate strategy. Harvard Business Review, March-April

Stock, Gregory N.; Greis, Noel P.; Kasarda, John D. (2000). Enterprise logistics and supply chain structure: the role of fit. Journal of Operations Management, 18, pp. 531-547

Swaminathan, J M; Smith, S. F.; Sadeh, N. M. (1994). Modeling the Dynamics of Supply Chains. The Robotics Institute, Carnegie Mellon University

Symix. (2000). APS - Functionality Overview. Symix Systems, Inc.

Tan, Gek Woo; Shaw Michael J. (1998). The supply chain network in a component environment. Department of Business Administration. University of Illinois at Urbana Campaign

Thomas, Douglas J.; Griffin, Paul M. (1996). Coordinated supply chain management. European Journal of Operational Research. Vol. 94, pp. 1-15

Towill, Denis R. (1996). Industrial dynamics modelling of supply chains. International Journal of Physical Distribution and Logistics Management. Vol. 26, No. 2, pp.23-42

Turbide, Dave (2000). Market overview: A stormy year for ERP. Midrange ERP, June

Turbide, Dave. (1998). Advanced Planning and Scheduling (APS) Systems. Midrange ERP, January/February

Turbide, Dave. (1998). Why APS? Production Solutions, Inc.

Weil, Marty (2000). Closer to the Customer. Manufacturing Systems, Vol. 18, No. 1

## 11 Bibliography

Allen, Paul R.; Frost, Stuart; Yourdon, Edward. (1998). Component-Based Development for Enterprise Systems: Applying the Select Perspective. Cambridge University Press

Christopher, Martin. (1992). Logistics and supply chain management: Strategies for reducing costs and improving services. Pitman Publishing

De Rosa, Catherine. (1999). Customer trade: the next industrial revolution. Symix Systems Inc. 1999

Forrester, Jay. (1961). Industrial dynamics. Productivity Press

Fowlkes, William, Y.; Creveling, Clyde M. (1995). Engineering methods for robust product design: Using Taguchi methods in technology and product development. Addison-Wesley Publishing Company, 1995

Hopp, Wallace J.; Spearman, Mark L. (1996). Factory physics. The McGraw-Hill Companies, Inc.

Ohno, Taiichi. (1988). Toyota Production System: Beyond Large-Scale Production. Productivity, Inc. 1988

Orlicky, Joseph; Plossl, George W. (1994). Orlicky's material requirements planning. McGraw-Hill, 2<sup>nd</sup> edition

Ross, David Frederick. (2000). Competing through supply chain management: creating market-winning strategies through supply chain partnerships. Kluwer Academic Publishers

Sandras, William A. (1995). Just-in-Time: Making it Happen: Unleashing the Power of Continuous Improvement. John Wiley & Sons



SIMUL8 Corp. (1999). SIMUL8 User's Manual. SIMUL8 Corporation, USA

Stalk, G.H.; Hout, T.M. (1990). Competing against time: How time based competition is reshaping global markets. Free Press, New York

Vollman, Thomas E.; Berry, William Lee; Whybark, David C. (1997). Manufacturing planning and control systems. McGraw-Hill, 4<sup>th</sup> edition

Wallace, Thomas. (1994). MRPII: Making it happen: The implementer's guide to success with manufacturing resource planning. Oliver Wight Ltd., 2<sup>nd</sup> edition

Wight, Oliver W. (2000). The Oliver Wight ABCD checklist for operational excellence. John Wiley & Sons, 5<sup>th</sup> edition

## 12 Appendix A

### 12.1 Route determination

VL SECTION: Planning 1 Work Complete Logic

Signal VBA "ALL"

SET temp3 = Quantity

IF Rest > 0

SET Quantity = 4

IF Item = 1

SET temp1 = [[WIP1+WIP3]+WIP6]+BL1

SET Routing = 1

IF temp1 > [[WIP1+WIP4]+WIP6]+BL2

SET temp1 = [[WIP1+WIP4]+WIP6]+BL2

SET Routing = 2

IF temp1 > [[WIP1+WIP3]+WIP7]+BL3

SET temp1 = [[WIP1+WIP3]+WIP7]+BL3

SET Routing = 3

IF temp1 > [[WIP1+WIP4]+WIP7]+BL4

SET temp1 = [[WIP1+WIP4]+WIP7]+BL4

SET Routing = 4

IF temp1 > [[WIP1+WIP4]+WIP8]+BL5

SET temp1 = [[WIP1+WIP4]+WIP8]+BL5

SET Routing = 5

IF temp1 > [[WIP1+WIP4]+WIP9]+BL7

SET temp1 = [[WIP1+WIP4]+WIP9]+BL7

SET Routing = 7

IF Routing = 1

SET LT = Supplier 1.Min Wait Time+[Quantity\*[Time5+Time6+Time1+Time2]]

SET BL1 = BL1+LT

SET Promised Delivery Time = [[Simulation Time+BL1]+WIP1]+WIP3

IF Routing = 2

SET LT = Supplier 1.Min Wait Time+[Quantity\*[Time7+Time8+Time1+Time2]]

SET BL2 = BL2+LT

SET Promised Delivery Time = [[Simulation Time+BL2]+WIP1]+WIP4

IF Routing = 3

SET LT = Supplier 2.Min Wait Time+[Quantity\*[Time5+Time6+Time1+Time2]]

SET BL3 = BL3+LT

SET Promised Delivery Time = [[Simulation Time+BL3]+WIP1]+WIP3

IF Routing = 4

SET LT = Supplier 2.Min Wait Time+[Quantity\*[Time7+Time8+Time1+Time2]]

SET BL4 = BL4+LT

SET Promised Delivery Time = [[Simulation Time+BL4]+WIP1]+WIP4

IF Routing = 5

SET LT = Supplier 3.Min Wait Time+[Quantity\*[Time7+Time8+Time1+Time2]]

SET BL5 = BL5+LT

SET Promised Delivery Time = [[Simulation Time+BL5]+WIP1]+WIP4

IF Routing = 7

SET LT = Supplier 4.Min Wait Time+[Quantity\*[Time7+Time8+Time1+Time2]]

SET BL7 = BL7+LT

SET Promised Delivery Time = [[Simulation Time+BL7]+WIP1]+WIP4

SET Projected Delivery Time = Promised Delivery Time

SET SF = 1

Signal VBA "SPL"



```

Select Current Work Item Planning 1 , 1
SET temp1 = [[WIP1+WIP4]+WIP6]+BL2
SET Routing = 2
IF temp1 > [[WIP1+WIP4]+WIP7]+BL4
    SET temp1 = [[WIP1+WIP4]+WIP7]+BL4
    SET Routing = 4
IF temp1 > [[WIP1+WIP4]+WIP8]+BL5
    SET temp1 = [[WIP1+WIP4]+WIP8]+BL5
    SET Routing = 5
IF temp1 > [[WIP1+WIP5]+WIP8]+BL6
    SET temp1 = [[WIP1+WIP5]+WIP8]+BL6
    SET Routing = 6
IF temp1 > [[WIP1+WIP4]+WIP9]+BL7
    SET temp1 = [[WIP1+WIP4]+WIP9]+BL7
    SET Routing = 7
IF temp1 > [[WIP1+WIP5]+WIP9]+BL8
    SET temp1 = [[WIP1+WIP5]+WIP9]+BL8
    SET Routing = 8
IF Routing = 2
    SET LT = Supplier 1.Min Wait Time+[Quantity*[Time7+Time8+Time1+Time2]]
    SET BL2 = BL2+LT
    SET Promised Delivery Time = [[Simulation Time+BL2]+WIP1]+WIP4
IF Routing = 4
    SET LT = Supplier 2.Min Wait Time+[Quantity*[Time7+Time8+Time1+Time2]]
    SET BL4 = BL4+LT
    SET Promised Delivery Time = [[Simulation Time+BL4]+WIP1]+WIP4
IF Routing = 5
    SET LT = Supplier 3.Min Wait Time+[Quantity*[Time7+Time8+Time1+Time2]]
    SET BL5 = BL5+LT
    SET Promised Delivery Time = [[Simulation Time+BL5]+WIP1]+WIP4
IF Routing = 6
    SET LT = Supplier 3.Min Wait Time+[Quantity*[Time9+Time 10+Time1+Time2]]
    SET BL6 = BL6+LT
    SET Promised Delivery Time = [[Simulation Time+BL6]+WIP1]+WIP5
IF Routing = 7
    SET LT = Supplier 4.Min Wait Time+[Quantity*[Time7+Time8+Time1+Time2]]
    SET BL7 = BL7+LT
    SET Promised Delivery Time = [[Simulation Time+BL7]+WIP1]+WIP4
IF Routing = 8
    SET LT = Supplier 4.Min Wait Time+[Quantity*[Time9+Time 10+Time1+Time2]]
    SET BL8 = BL8+LT
    SET Promised Delivery Time = [[Simulation Time+BL8]+WIP1]+WIP5
SET Projected Delivery Time = Promised Delivery Time
SET SF = 2
Signal VBA "SPL"
Select Current Work Item Planning 1 , 1
SET Quantity = temp3
IF Item = 2
    SET temp1 = [[WIP2+WIP3]+WIP6]+BL9
    SET Routing = 9
    IF temp1 > [[WIP2+WIP3]+WIP7]+BL11
        SET temp1 = [[WIP2+WIP3]+WIP7]+BL11
        SET Routing = 11
    IF temp1 > [[WIP2+WIP5]+WIP8]+BL14
        SET temp1 = [[WIP2+WIP5]+WIP8]+BL14
        SET Routing = 14
    IF temp1 > [[WIP2+WIP5]+WIP9]+BL16
        SET temp1 = [[WIP2+WIP5]+WIP9]+BL16

```

```

SET Routing = 16
IF Routing = 9
  SET LT = Supplier 1.Min Wait Time+[Quantity*[Time5+Time6+Time3+Time4]]
  SET BL9 = BL9+LT
  SET Promised Delivery Time = [[Simulation Time+BL9]+WIP2]+WIP3
IF Routing = 11
  SET LT = Supplier 2.Min Wait Time+[Quantity*[Time5+Time6+Time3+Time4]]
  SET BL11 = BL11+LT
  SET Promised Delivery Time = [[Simulation Time+BL11]+WIP2]+WIP3
IF Routing = 14
  SET LT = Supplier 3.Min Wait Time+[Quantity*[Time9+Time 10+Time3+Time4]]
  SET BL14 = BL14+LT
  SET Promised Delivery Time = [[Simulation Time+BL14]+WIP2]+WIP5
IF Routing = 16
  SET LT = Supplier 4.Min Wait Time+[Quantity*[Time9+Time 10+Time3+Time4]]
  SET BL16 = BL16+LT
  SET Promised Delivery Time = [[Simulation Time+BL16]+WIP2]+WIP5
SET Projected Delivery Time = Promised Delivery Time
SET SF = 3
Signal VBA "SPL"
Select Current Work Item Planning 1 , 1
SET temp1 = [[WIP2+WIP4]+WIP6]+BL10
SET Routing = 10
IF temp1 > [[WIP2+WIP4]+WIP7]+BL12
  SET temp1 = [[WIP2+WIP4]+WIP7]+BL12
  SET Routing = 12
IF temp1 > [[WIP2+WIP4]+WIP8]+BL13
  SET temp1 = [[WIP2+WIP4]+WIP8]+BL13
  SET Routing = 13
IF temp1 > [[WIP2+WIP5]+WIP8]+BL14
  SET temp1 = [[WIP2+WIP5]+WIP8]+BL14
  SET Routing = 14
IF temp1 > [[WIP2+WIP4]+WIP9]+BL15
  SET temp1 = [[WIP2+WIP4]+WIP9]+BL15
  SET Routing = 15
IF temp1 > [[WIP2+WIP5]+WIP9]+BL16
  SET temp1 = [[WIP2+WIP5]+WIP9]+BL16
  SET Routing = 16
IF Routing = 10
  SET LT = Supplier 1.Min Wait Time+[Quantity*[Time7+Time8+Time3+Time4]]
  SET BL10 = BL10+LT
  SET Promised Delivery Time = [[Simulation Time+BL10]+WIP2]+WIP4
IF Routing = 12
  SET LT = Supplier 2.Min Wait Time+[Quantity*[Time7+Time8+Time3+Time4]]
  SET BL12 = BL12+LT
  SET Promised Delivery Time = [[Simulation Time+BL12]+WIP2]+WIP4
IF Routing = 13
  SET LT = Supplier 3.Min Wait Time+[Quantity*[Time7+Time8+Time3+Time4]]
  SET BL13 = BL13+LT
  SET Promised Delivery Time = [[Simulation Time+BL13]+WIP2]+WIP4
IF Routing = 14
  SET LT = Supplier 3.Min Wait Time+[Quantity*[Time9+Time 10+Time3+Time4]]
  SET BL14 = BL14+LT
  SET Promised Delivery Time = [[Simulation Time+BL14]+WIP2]+WIP5
IF Routing = 15
  SET LT = Supplier 4.Min Wait Time+[Quantity*[Time7+Time8+Time3+Time4]]
  SET BL15 = BL15+LT
  SET Promised Delivery Time = [[Simulation Time+BL15]+WIP2]+WIP4

```



```

IF Routing = 16
    SET LT = Supplier 4.Min Wait Time+[Quantity*[Time9+Time 10+Time3+Time4]]
    SET BL16 = BL16+LT
    SET Promised Delivery Time = [[Simulation Time+BL16]+WIP2]+WIP5
    SET Projected Delivery Time = Promised Delivery Time
    SET SF = 2
    Signal VBA "SPL"
    Select Current Work Item Planning 1 , 1
    SET Quantity = temp3
IF Rest > 0
    Signal VBA "ALL"

```

```

Private dActualDeliveryTime As Double
Private dCODeliveryTime As Double
Private sCOOrderNumber As String
Private iDestination As Integer
Private iItem As Integer
Private dLT As Double
Private lOrderNumber As Long
Private lPriority As Long
Private dProjectedDeliveryTime As Double
Private dPromisedDeliveryTime As Double
Private dQuantity As Double
Private dRest As Double
Private iRouting As Integer
Private dWaitingTime As Double
Private siSF As Single
Private dActCODelTime As Double
Private dActStart As Double
Private dTotWIP As Double

```

```

Private iLoop As Integer

```

```

Public Sub Split(sSignal As String)

```

```

    GetLabels
    dRest = dQuantity

```

```

    Select Case iRouting

```

```

        Case 1, 2, 9, 10

```

```

            AddWItoQueue "Order", "Dummy Bin 4"
            SetLabels

```

```

        Case 3, 4, 11, 12
            AddWItoQueue "Order", "Dummy Bin 5"
            SetLabels

```

```

        Case 5, 6, 13, 14
            AddWItoQueue "Order", "Dummy Bin 6"
            SetLabels

```

```

        Case 7, 8, 15, 16
            AddWItoQueue "Order", "Dummy Bin 7"
            SetLabels

```

```

    End Select

```

```

End Sub

```

```

Private Sub SetLabels()

```

```

SetAttribValue "Actual Delivery Time", dActualDeliveryTime
SetAttribValue "LT", dLT
SetAttribValue "Order Number", lOrderNumber
SetAttribValue "Item", iItem
SetAttribValue "Promised Delivery Time", dPromisedDeliveryTime
SetAttribValue "Quantity", dQuantity
SetAttribValue "Routing", iRouting
SetAttribValue "Projected Delivery Time", dProjectedDeliveryTime
SetAttribValue "Destination", iDestination
SetAttribValue "CO Delivery Time", dCODeliveryTime
SetAttribValue "Rest", dRest
SetAttribText "Customer Order", sCOOrderNumber
SetAttribValue "Prior", lPriority
SetAttribValue "SF", siSF
SetAttribValue "Waiting time", dWaitingTime
SetAttribValue "Actual CO Delivery Time", dActCODelTime
SetAttribValue "Actual Start", dActStart
SetAttribValue "TotWIP", dTotWIP
End Sub

```

```

Private Sub GetLabels()
    dActualDeliveryTime = AttribValue("Actual Delivery Time")
    dLT = AttribValue("LT")
    lOrderNumber = AttribValue("Order Number")
    iItem = AttribValue("Item")
    dPromisedDeliveryTime = AttribValue("Promised Delivery Time")
    dQuantity = AttribValue("Quantity")
    iRouting = AttribValue("Routing")
    iDestination = AttribValue("Destination")
    dProjectedDeliveryTime = AttribValue("Projected Delivery Time")
    dCODeliveryTime = AttribValue("CO Delivery Time")
    dRest = AttribValue("Rest")
    sCOOrderNumber = AttribText("Customer Order")
    lPriority = AttribValue("Prior")
    dWaitingTime = AttribValue("Waiting time")
    siSF = AttribValue("SF")
    dActCODelTime = AttribValue("Actual CO Delivery Time")
    dActStart = AttribValue("Actual Start")
    dTotWIP = AttribValue("TotWIP")
End Sub

```

## 12.2 Release control

VL SECTION: Dummy 5 On Exit Logic

```

IF Routing = 1
    SET Waiting time = WIP3
    IF WIP3 > WIP1
        SET Projected Delivery Time = [Simulation Time+LT]+WIP3
    ELSE
        SET Projected Delivery Time = [Simulation Time+LT]+WIP1
    SET BL1 = BL1-LT
IF Routing = 2
    SET Waiting time = WIP4
    SET BL2 = BL2-LT
    IF WIP4 > WIP1
        SET Projected Delivery Time = [Simulation Time+LT]+WIP4

```



```

ELSE
    SET Projected Delivery Time = [Simulation Time+LT]+WIP1
IF Routing = 9
    SET Waiting time = WIP3
    SET BL9 = BL9-LT
    IF WIP3 > WIP2
        SET Projected Delivery Time = [Simulation Time+LT]+WIP3
    ELSE
        SET Projected Delivery Time = [Simulation Time+LT]+WIP2
IF Routing = 10
    SET Waiting time = WIP4
    SET BL10 = BL10-LT
    IF WIP4 > WIP2
        SET Projected Delivery Time = [Simulation Time+LT]+WIP4
    ELSE
        SET Projected Delivery Time = [Simulation Time+LT]+WIP2
SET Waiting time = Waiting time/2
SET WIP6 = WIP6+Waiting time
SET Actual Start = Simulation Time

```

### *12.3 Selection and merging of semi-finished items*

```

Option Explicit
Private dActualDeliveryTime As Double
Private dCODeliveryTime As Double
Private sCOOrderNumber As String
Private iDestination As Integer
Private iItem As Integer
Private dLT As Double
Private lOrderNumber As Long
Private lPriority As Long
Private dProjectedDeliveryTime As Double
Private dPromisedDeliveryTime As Double
Private dQuantity As Double
Private dRest As Double
Private iRouting As Integer
Private dWaitingTime As Double
Private siSF As Single
Private dActCODelTime As Double
Private dActStart As Double
Private dTotWIP As Double

Private iLoop As Integer
Private iLoop1 As Integer

Public Sub Selection(sSignal As String)

Select Case Right$(sSignal, 3)

Case "WC1"
    If QueueSize("Dummy Bin 1") < 2 Then GoTo EMPTY_QUEUE

    For iLoop1 = 1 To QueueSize("Dummy Bin 1")
        SelectWI_in_Object "Dummy Bin 1", iLoop1
        GetLabels

        For iLoop = QueueSize("Dummy Bin 1") To 1 Step -1
            If iLoop <> iLoop1 Then

```

```

        SelectWI_in_Object "Dummy Bin 1", iLoop
        If lOrderNumber = AttribValue("Order Number") Then
            SetOrder20 "Dummy Bin 1", lOrderNumber
            AddWItoQueue "Order", "Queue for F1"
            SetLabels
            GoTo EMTPY_QUEUE
        End If
    End If
Next iLoop
Next iLoop1

```

Case "WC3"

```

    If QueueSize("Dummy Bin 2") < 2 Then GoTo EMTPY_QUEUE

```

```

    For iLoop1 = 1 To QueueSize("Dummy Bin 2")
        SelectWI_in_Object "Dummy Bin 2", iLoop1
        GetLabels
    
```

```

        For iLoop = QueueSize("Dummy Bin 2") To 1 Step -1
            If iLoop <> iLoop1 Then
                SelectWI_in_Object "Dummy Bin 2", iLoop
                If lOrderNumber = AttribValue("Order Number") Then
                    SetOrder20 "Dummy Bin 2", lOrderNumber
                    AddWItoQueue "Order", "Queue for F2"
                    SetLabels
                    GoTo EMTPY_QUEUE
                End If
            End If
        Next iLoop
    Next iLoop1

```

Case "DY1"

```

    If QueueSize("CO Backlog 1") < 1 Then GoTo EMTPY_QUEUE
    For iLoop1 = 1 To QueueSize("CO Backlog 1")
        SelectWI_in_Object "CO Backlog 1", iLoop1
        GetLabels
    
```

```

        'If Count_Attribute("Finished Goods 1", "Quantity", 0) >= dQuantity Then
            SetCollect "CO Backlog 1", dQuantity, "Dummy 1"
            SetCollect "Finished Goods 1", dQuantity, "Dummy 1"
            CollectComplete "Dummy 1"
        
```

```

        'End If
    Next iLoop1

```

Case "DY2"

```

    If QueueSize("CO Backlog 2") < 1 Then GoTo EMTPY_QUEUE
    For iLoop1 = 1 To QueueSize("CO Backlog 2")
        SelectWI_in_Object "CO Backlog 2", iLoop1
        GetLabels
    
```

```

        'If Count_Attribute("Finished Goods 2", "Quantity", 0) >= dQuantity Then
            SetCollect "CO Backlog 2", dQuantity, "Dummy 2"
            SetCollect "Finished Goods 2", dQuantity, "Dummy 2"
            CollectComplete "Dummy 2"
        
```

```

        'End If
    Next iLoop1

```



End Select

EMPTY\_QUEUE:

End Sub

Private Sub SetLabels()

    SetAttribValue "Actual Delivery Time", dActualDeliveryTime  
    SetAttribValue "LT", dLT  
    SetAttribValue "Order Number", lOrderNumber  
    SetAttribValue "Item", iItem  
    SetAttribValue "Promised Delivery Time", dPromisedDeliveryTime  
    SetAttribValue "Quantity", dQuantity  
    SetAttribValue "Routing", iRouting  
    SetAttribValue "Projected Delivery Time", dProjectedDeliveryTime  
    SetAttribValue "Destination", iDestination  
    SetAttribValue "CO Delivery Time", dCODeliveryTime  
    SetAttribValue "Rest", dRest  
    SetAttribText "Customer Order", sCOOrderNumber  
    SetAttribValue "Prior", lPriority  
    SetAttribValue "SF", siSF  
    SetAttribValue "Waiting time", dWaitingTime  
    SetAttribValue "Actual CO Delivery Time", dActCODelTime  
    SetAttribValue "Actual Start", dActStart  
    SetAttribValue "TotWIP", dTotWIP

End Sub

Private Sub GetLabels()

    dActualDeliveryTime = AttribValue("Actual Delivery Time")  
    dLT = AttribValue("LT")  
    lOrderNumber = AttribValue("Order Number")  
    iItem = AttribValue("Item")  
    dPromisedDeliveryTime = AttribValue("Promised Delivery Time")  
    dQuantity = AttribValue("Quantity")  
    iRouting = AttribValue("Routing")  
    iDestination = AttribValue("Destination")  
    dProjectedDeliveryTime = AttribValue("Projected Delivery Time")  
    dCODeliveryTime = AttribValue("CO Delivery Time")  
    dRest = AttribValue("Rest")  
    sCOOrderNumber = AttribText("Customer Order")  
    lPriority = AttribValue("Prior")  
    dWaitingTime = AttribValue("Waiting time")  
    siSF = AttribValue("SF")  
    dActCODelTime = AttribValue("Actual CO Delivery Time")  
    dActStart = AttribValue("Actual Start")  
    dTotWIP = AttribValue("TotWIP")

End Sub

Private Sub SetOrder20(sWC As String, lOrder As Long)

    For iLoop = 1 To QueueSize(sWC)  
        SelectWI\_in\_Object sWC, iLoop  
        If lOrder = AttribValue("Order Number") Then  
            SetAttribValue "Order Number", 0  
        End If  
    Next iLoop

End Sub

## 12.4 Customer order allocation to batches

Option Explicit

Private dActualDeliveryTime As Double

Private dCODeliveryTime As Double

Private sCOOrderNumber As String

Private iDestination As Integer

Private iItem As Integer

Private dLT As Double

Private lOrderNumber As Long

Private lPriority As Long

Private dProjectedDeliveryTime As Double

Private dPromisedDeliveryTime As Double

Private dQuantity As Double

Private dRest As Double

Private iRouting As Integer

Private dWaitingTime As Double

Private siSF As Single

Private dActCODelTime As Double

Private dActStart As Double

Private dTotWIP As Double

Private bLoop As Boolean

Private dAllocCODelTime As Double

Private siSemifItem As Single

Private sSF As String

Private sSemifOrder As String

Private sObjects As String

Private sSelectedObj As String

Private lAllocOrder As Long

Private lSelectedOrder As Long

Private dAllocQty As Double

Private dAllocQty1 As Double

Private iAllocRouting As Integer

Private iLoop As Integer

Private iLoop1 As Integer

Public Sub Allocate(sSignal As String)

' -----

' Initialize Variables

' -----

GetLabels

dAllocQty = dQuantity

If dRest <> 0# Then dAllocQty = dRest

dAllocQty1 = 0#

lAllocOrder = lOrderNumber

sSemifOrder = ""

sSF = ""

dAllocCODelTime = dCODeliveryTime

iAllocRouting = 0

' -----

' Allocate Item 1 Customer Order Quantity



```

' -----
If iRouting <= 8 Then
    iAllocRouting = 8

    sObjects = Left$("Finished Goods 1" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 2" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 1" + String(50, " "), 50)
    sObjects = sObjects + Left$("Queue for F1" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 1" + String(50, " "), 50)

    ObjectString

Do
    sSelectedObj = Trim(Left$(sObjects, 50))
    sObjects = Right$(sObjects, Len(sObjects) - 50)

    Select Case sSelectedObj

    Case "Finished Goods 1", _
        "Work Center 2", _
        "Work Center 1"

        siSemifItem = 0
        AllocOrder sSelectedObj

    Case "Queue for F1"

        siSemifItem = 0
        AllocOrder sSelectedObj
        dAllocQty1 = dAllocQty

    Case "Dummy Bin 1", _
        "Work Center 6", _
        "Work Center 8", _
        "Work Center 10", _
        "Work Center 5", _
        "Work Center 7", _
        "Work Center 9", _
        "Dummy 3", "Dummy 4", "Dummy 9", "Dummy 10", _
        "Supplier 1", "Supplier 2", "Supplier 3", "Supplier 4", _
        "Dummy 5", "Dummy 6", "Dummy 7", "Dummy 8", _
        "Dummy Bin 4", "Dummy Bin 5", "Dummy Bin 6", "Dummy Bin 7"

        siSemifItem = 1
        AllocOrder sSelectedObj

    Case ""
        Exit Do

    End Select

    Loop While dAllocQty > 0 And sObjects <> ""
End If

If iAllocRouting = 8 And sSemifOrder = "" And dAllocQty > 0# Then GoTo STOP_ALLOC

' -----
' Allocate Item 2 Customer Order Quantity

```

```

' -----
If iRouting > 8 Then
    iAllocRouting = 9
    sObjects = Left$("Finished Goods 2" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 4" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 3" + String(50, " "), 50)
    sObjects = sObjects + Left$("Queue for F2" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 2" + String(50, " "), 50)

    ObjectString

Do
    sSelectedObj = Trim(Left$(sObjects, 50))
    sObjects = Right$(sObjects, Len(sObjects) - 50)

    Select Case sSelectedObj

    Case "Finished Goods 2", _
        "Work Center 4", _
        "Work Center 3"

        siSemifItem = 0
        AllocOrder sSelectedObj

    Case "Queue for F2"

        siSemifItem = 0
        AllocOrder sSelectedObj
        dAllocQty1 = dAllocQty

    Case "Dummy Bin 2", _
        "Work Center 6", _
        "Work Center 8", _
        "Work Center 10", _
        "Work Center 5", _
        "Work Center 7", _
        "Work Center 9", _
        "Dummy 3", "Dummy 4", "Dummy 9", "Dummy 10", _
        "Supplier 1", "Supplier 2", "Supplier 3", "Supplier 4", _
        "Dummy 5", "Dummy 6", "Dummy 7", "Dummy 8", _
        "Dummy Bin 4", "Dummy Bin 5", "Dummy Bin 6", "Dummy Bin 7"

        siSemifItem = 1
        AllocOrder sSelectedObj

    Case Else
        Exit Do

    End Select

Loop While dAllocQty > 0 And sObjects <> ""

End If

If sSemifOrder = "" And dAllocQty > 0# Then GoTo STOP_ALLOC

' -----
' Allocate Customer Order Quantity to the second semifinished item

```



```

' -----
sObjects = ""
If dAllocQty1 > 0# Then
    ObjectString

    If iAllocRouting = 8 Then
        sSelectedObj = "Dummy Bin 1"
    Else
        sSelectedObj = "Dummy Bin 2"
    End If

    siSemifItem = 2
    AllocOrder sSelectedObj
    If dAllocQty1 > 0# And sSemifOrder <> "" Then
        Do
            sSelectedObj = Trim(Left$(sObjects, 50))
            sObjects = Right$(sObjects, Len(sObjects) - 50)

            Select Case sSelectedObj

                Case "Work Center 6", _
                    "Work Center 8", _
                    "Work Center 10", _
                    "Work Center 5", _
                    "Work Center 7", _
                    "Work Center 9", _
                    "Dummy 3", "Dummy 4", "Dummy 9", "Dummy 10", _
                    "Supplier 1", "Supplier 2", "Supplier 3", "Supplier 4", _
                    "Dummy 5", "Dummy 6", "Dummy 7", "Dummy 8", _
                    "Dummy Bin 4", "Dummy Bin 5", "Dummy Bin 6", "Dummy Bin 7"

                    siSemifItem = 2
                    AllocOrder sSelectedObj

                Case Else
                    Exit Do

            End Select

        Loop While dAllocQty1 > 0# And sSemifOrder <> "" And sObjects <> ""
    End If
End If

STOP_ALLOC:

' -----
' Set Customer Order Delivery Time
' -----
SelectWI_in_Object "Planning 1", 1
GetLabels
dCODeliveryTime = dAllocCODelTime
dRest = dAllocQty1
SetLabels

End Sub

Private Sub AllocOrder(sWC As String)

```

```

bLoop = True
iLoop = 1
Do While iLoop <= QueueSize(sWC) And bLoop
    SelectWI_in_Object sWC, iLoop
    GetLabels
    If lOrderNumber <> 0 Then

        If (iAllocRouting = 8 And _
            iAllocRouting >= iRouting) Or _
            (iAllocRouting = 9 And _
            iAllocRouting <= iRouting) Then

            If dRest > 0# Then

                If siSemifItem = 2 And Val(Left$(sSemifOrder, 10)) = _
                    lOrderNumber And siSF = Val(Left$(sSF, 1)) Then

                    dRest = dRest - dAllocQty1
                    sSemifOrder = Right$(sSemifOrder, Len(sSemifOrder) - 10)
                    sSF = Right$(sSF, Len(sSF) - 1)

                    If Trim(sCOOrderNumber) = "" Then
                        sCOOrderNumber = Str$(lAllocOrder)
                    Else
                        sCOOrderNumber = sCOOrderNumber + ", " + Str$(lAllocOrder)
                    End If

                    If dRest < 0# Then
                        dAllocQty1 = Abs(dRest)
                    Else
                        dAllocQty1 = 0#
                        bLoop = False
                    End If

                    If dAllocCODelTime < dProjectedDeliveryTime Then
                        dAllocCODelTime = dProjectedDeliveryTime
                    End If
                    If sWC = "Finished Goods 1" Or sWC = "Finished Goods 2" Then
                        dAllocCODelTime = SimTime
                    End If
                    SetLabels

                End If

                If (siSemifItem = 1 And Val(Left$(sSemifOrder, 10)) <> _
                    lOrderNumber) Or siSemifItem = 0 Then
                    dRest = dRest - dAllocQty

                    If Trim(sCOOrderNumber) = "" Then
                        sCOOrderNumber = Trim(Str$(lAllocOrder))
                    Else
                        sCOOrderNumber = sCOOrderNumber + "," + Trim(Str$(lAllocOrder))
                    End If

                    If dRest < 0# Then
                        dAllocQty = Abs(dRest)
                    Else

```



```

        dAllocQty = 0#
        bLoop = False
    End If

    If dAllocCODelTime < dProjectedDeliveryTime Then
        dAllocCODelTime = dProjectedDeliveryTime
    End If
    If sWC = "Finished Goods 1" Or sWC = "Finished Goods 2" Then
        dAllocCODelTime = SimTime
    End If
    SetLabels

End If

If siSemifItem = 1 And Val(Left$(sSemifOrder, 10)) <> lOrderNumber Then
    sSemifOrder = sSemifOrder + _
        Left$(Str$(lOrderNumber) + String(10, " "), 10)
    If siSF = 1 Then
        sSF = sSF + "2"
    ElseIf siSF = 2 And iItem = 1 Then
        sSF = sSF + "1"
    ElseIf siSF = 2 And iItem = 2 Then
        sSF = sSF + "3"
    ElseIf siSF = 3 Then
        sSF = sSF + "2"
    End If
End If

End If

End If

    End If
    iLoop = iLoop + 1
Loop

End Sub

Private Sub SetLabels()
    SetAttribValue "Actual Delivery Time", dActualDeliveryTime
    SetAttribValue "LT", dLT
    SetAttribValue "Order Number", lOrderNumber
    SetAttribValue "Item", iItem
    SetAttribValue "Promised Delivery Time", dPromisedDeliveryTime
    SetAttribValue "Quantity", dQuantity
    SetAttribValue "Routing", iRouting
    SetAttribValue "Projected Delivery Time", dProjectedDeliveryTime
    SetAttribValue "Destination", iDestination
    SetAttribValue "CO Delivery Time", dCODeliveryTime
    SetAttribValue "Rest", dRest
    SetAttribText "Customer Order", sCOOrderNumber
    SetAttribValue "Prior", lPriority
    SetAttribValue "SF", siSF
    SetAttribValue "Waiting time", dWaitingTime
    SetAttribValue "Actual CO Delivery Time", dActCODelTime
    SetAttribValue "Actual Start", dActStart
    SetAttribValue "TotWIP", dTotWIP
End Sub

```

```

Private Sub GetLabels()
    dActualDeliveryTime = AttribValue("Actual Delivery Time")
    dLT = AttribValue("LT")
    lOrderNumber = AttribValue("Order Number")
    iItem = AttribValue("Item")
    dPromisedDeliveryTime = AttribValue("Promised Delivery Time")
    dQuantity = AttribValue("Quantity")
    iRouting = AttribValue("Routing")
    iDestination = AttribValue("Destination")
    dProjectedDeliveryTime = AttribValue("Projected Delivery Time")
    dCODeliveryTime = AttribValue("CO Delivery Time")
    dRest = AttribValue("Rest")
    sCOOrderNumber = AttribText("Customer Order")
    lPriority = AttribValue("Prior")
    dWaitingTime = AttribValue("Waiting time")
    siSF = AttribValue("SF")
    dActCODelTime = AttribValue("Actual CO Delivery Time")
    dActStart = AttribValue("Actual Start")
    dTotWIP = AttribValue("TotWIP")
End Sub

```

```

Private Sub ObjectString()

    sObjects = sObjects + Left$("Work Center 6" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 8" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 10" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 5" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 7" + String(50, " "), 50)
    sObjects = sObjects + Left$("Work Center 9" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 3" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 4" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 9" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 10" + String(50, " "), 50)
    sObjects = sObjects + Left$("Supplier 1" + String(50, " "), 50)
    sObjects = sObjects + Left$("Supplier 2" + String(50, " "), 50)
    sObjects = sObjects + Left$("Supplier 3" + String(50, " "), 50)
    sObjects = sObjects + Left$("Supplier 4" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 5" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 6" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 7" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy 8" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 4" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 5" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 6" + String(50, " "), 50)
    sObjects = sObjects + Left$("Dummy Bin 7" + String(50, " "), 50)
9
End Sub

```



12.5 Data collection

CUSTOMER ORDERS						MANUFACTURING ORDERS								
Order Number	Promised CO Delivery Time	Actual CO Delivery Time	Quantity	CO Lateness	Cycle Time	Order Number	Promised Delivery Time	Projected Delivery Time	Actual Delivery Time	Quantity	MO Lateness	Cycle Time		
1	2526.6160278	1039.200439	189	512.5844116	1032.584399	1	2526.6160278	572.9612427	572.9612427	60	46.34521484	566.3452024		
						2	2526.6160278	855.4412231	855.4412231	60	328.8251953	848.8251829		
						3	2526.6160278	706.4003296	706.4003296	60	179.7843018	699.7842894		
						4	2526.6160278	1039.200439	1039.200439	60	512.5844116	1032.584399		
5	21108.545898	1655.604126	235	547.0582275	1457.058258	5	21108.545898	1169.200439	1169.200439	60	60.65454102	970.6545715		
						6	21108.545898	1498.148682	1498.148682	60	389.6027832	1299.602814		
						7	21108.545898	1329.534424	1329.534424	60	220.9885254	1130.988556		
						8	21108.545898	1655.604126	1655.604126	60	547.0582275	1457.058258		
9	11251.257813	2222.854492	155	971.5966797	1439.308594	9	11251.257813	1718.115234	1718.115234	60	466.8574219	1129.569336		
						10	11251.257813	2060.773193	2060.773193	60	809.5153809	1472.227295		
						11	11251.257813	2222.854492	2222.854492	60	971.5966797	1439.308594		
12	21645.619995	2160.293457	164	514.6734619	1311.747559	12	21645.619995	2160.293457	2160.293457	60	514.6734619	1311.747559		
						13	21645.619995	2030.293457	2030.293457	60	384.6734619	1246.747559		
14	22806.083008	2737.372559	216	68.71044922	1238.82666	14	22806.083008	2304.861084	2304.861084	60	-501.2219238	1196.315186		
						15	22676.083008	2434.861084	2434.861084	60	-241.2219238	1456.315186		

								16	22286.083008	2588.104248	2588.104248	60	302.0212402	1414.55835
								17	22676.083008	2737.372559	2737.372559	60	61.28955078	1238.82666
18	22806.083008	2737.372559			2068.71044922	-								
19	13644.586914	3188.641357			296455.9455566	-		19	12994.586914	2549.451416	2549.451416	60	-445.135498	594.864502
								20	13124.586914	2698.13208	2698.13208	60	-426.454834	743.545166
								21	13254.586914	3054.5	3054.5	60	-200.086914	969.9130859
								22	13254.586914	3188.641357	3188.641357	60	-65.94555664	1169.054443
								23	13644.586914	2903.771484	2903.771484	60	-740.8154297	624.1845703
24	13644.586914	3188.641357			20455.9455566	-								
25	23875.486572	3429.093994			19446.3925781			25	23875.486572	3429.093994	3429.093994	60	-446.3925781	1113.607422
26	13516.560791	3335.513184			21181.0476074			26	13516.560791	3335.513184	3335.513184	60	-181.0476074	988.9523926
								27	13516.560791	3571.609375	3571.609375	60	55.04858398	866.1228027
28	23875.486572	3429.093994			19446.3925781									
29	23420.486572	3429.093994			218.6074218									
30	13744.007813	3744.007813			19	0								
31	24497.470703	4562.297852			2264.8271484			31	24497.470703	4562.297852	4562.297852	60	64.8271484	584.8271484
32	15329.998535	5404.818848			254	74.8203125		32	15043.869629	5672.225098	5672.225098	60	628.3554688	1148.355469



13 Appendix B

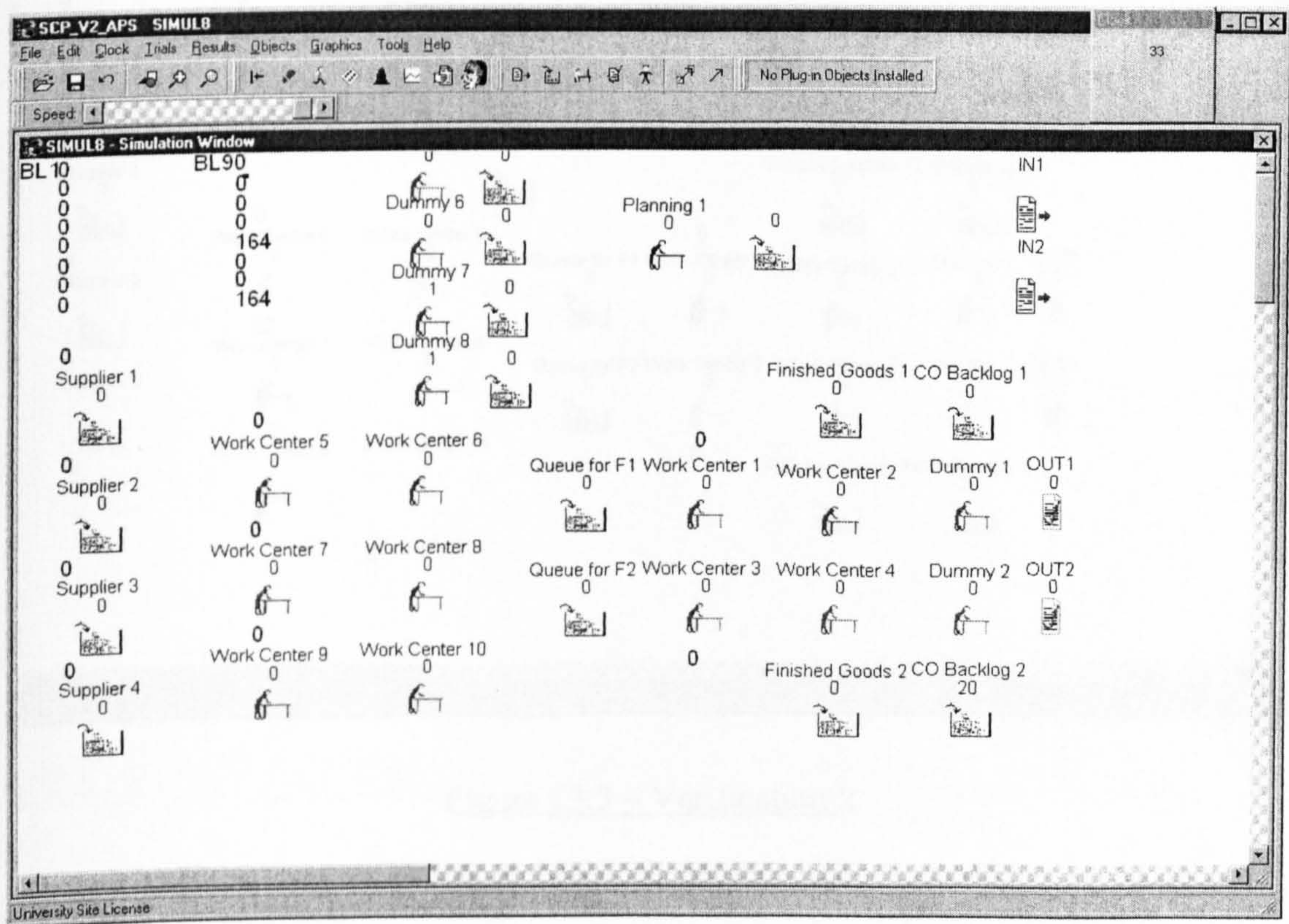


Figure 13.1 – Verification 1

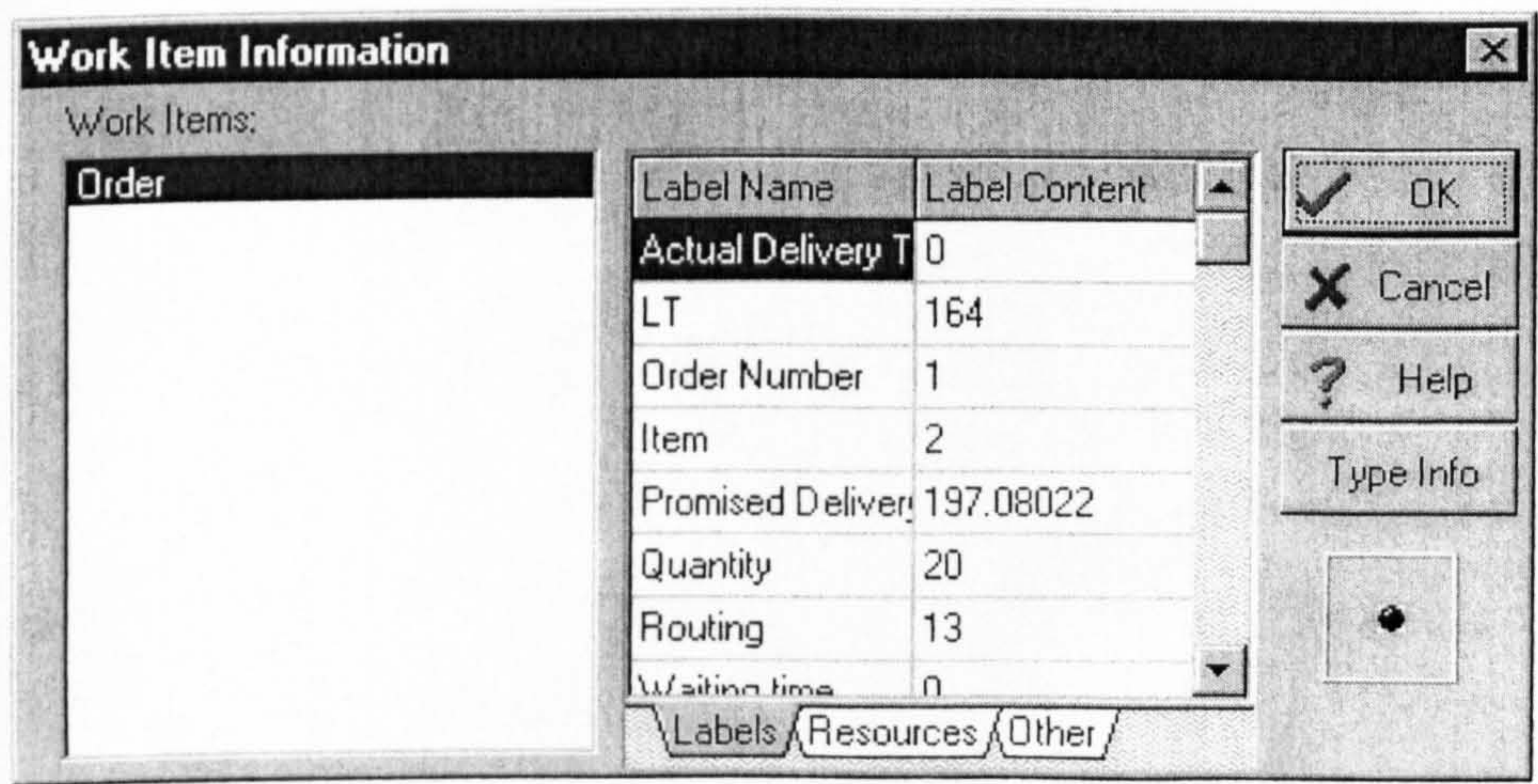


Figure 13.2 – Work item information window



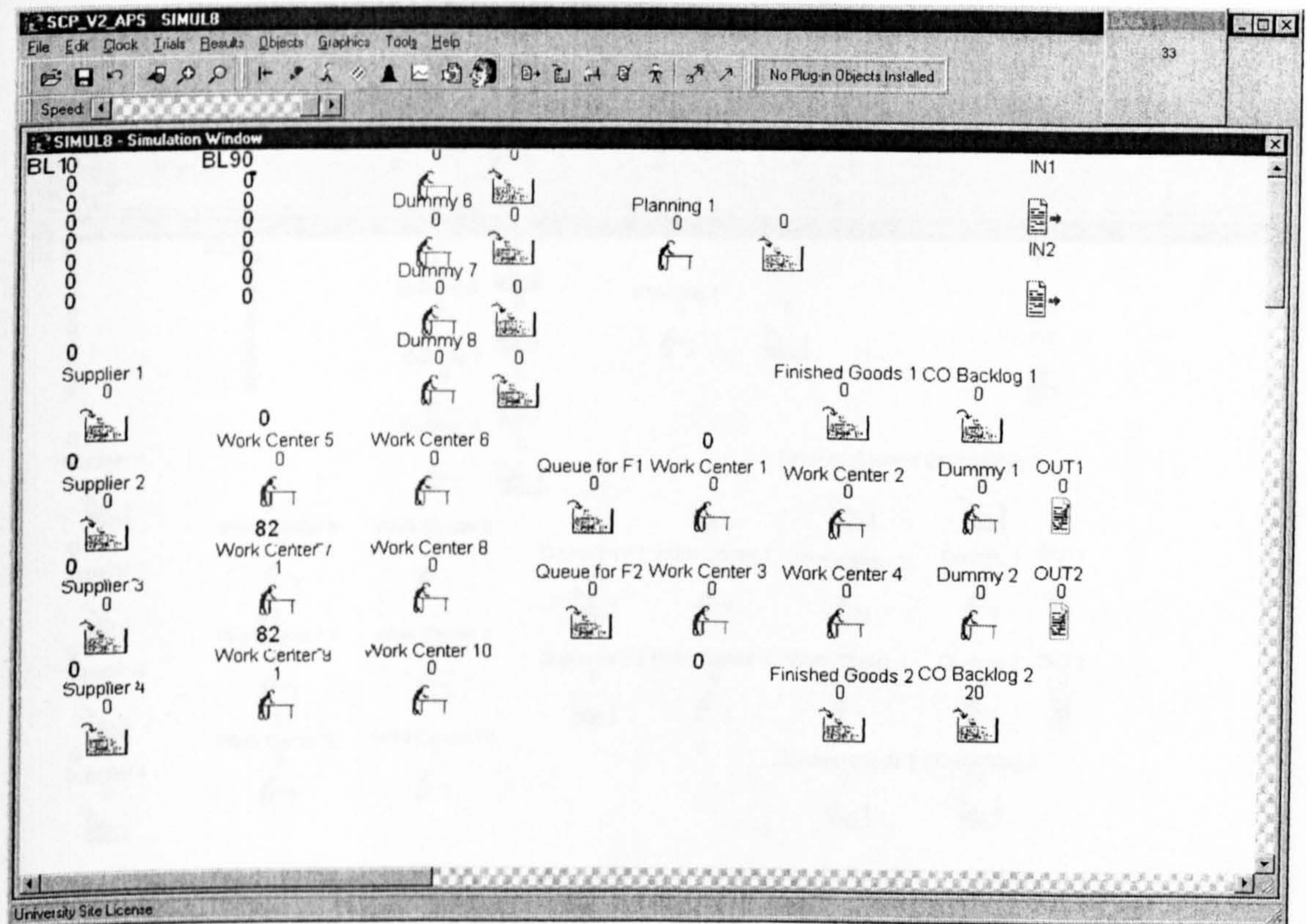


Figure 13.3 – Verification 2



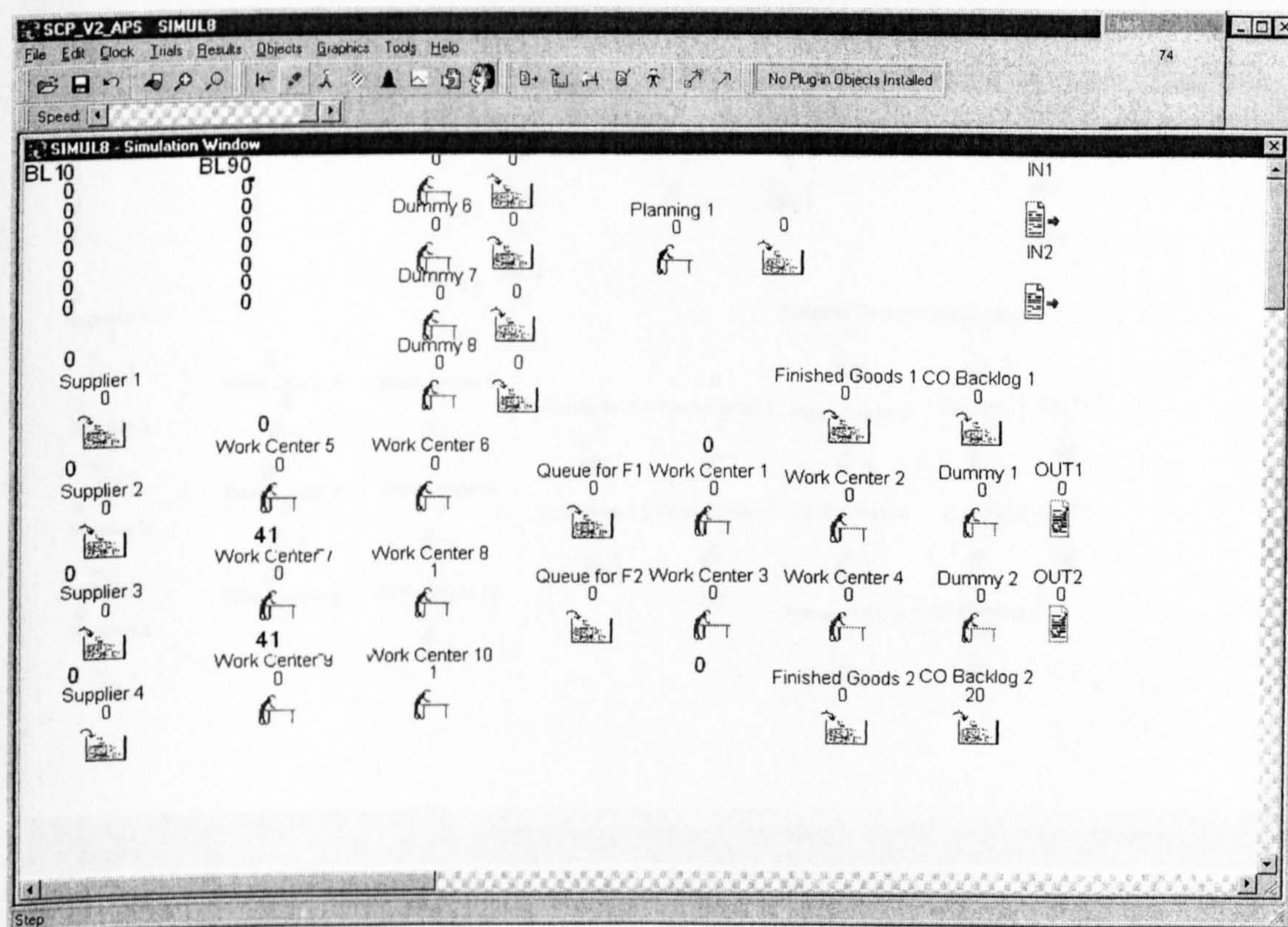


Figure 13.4 – Verification 3



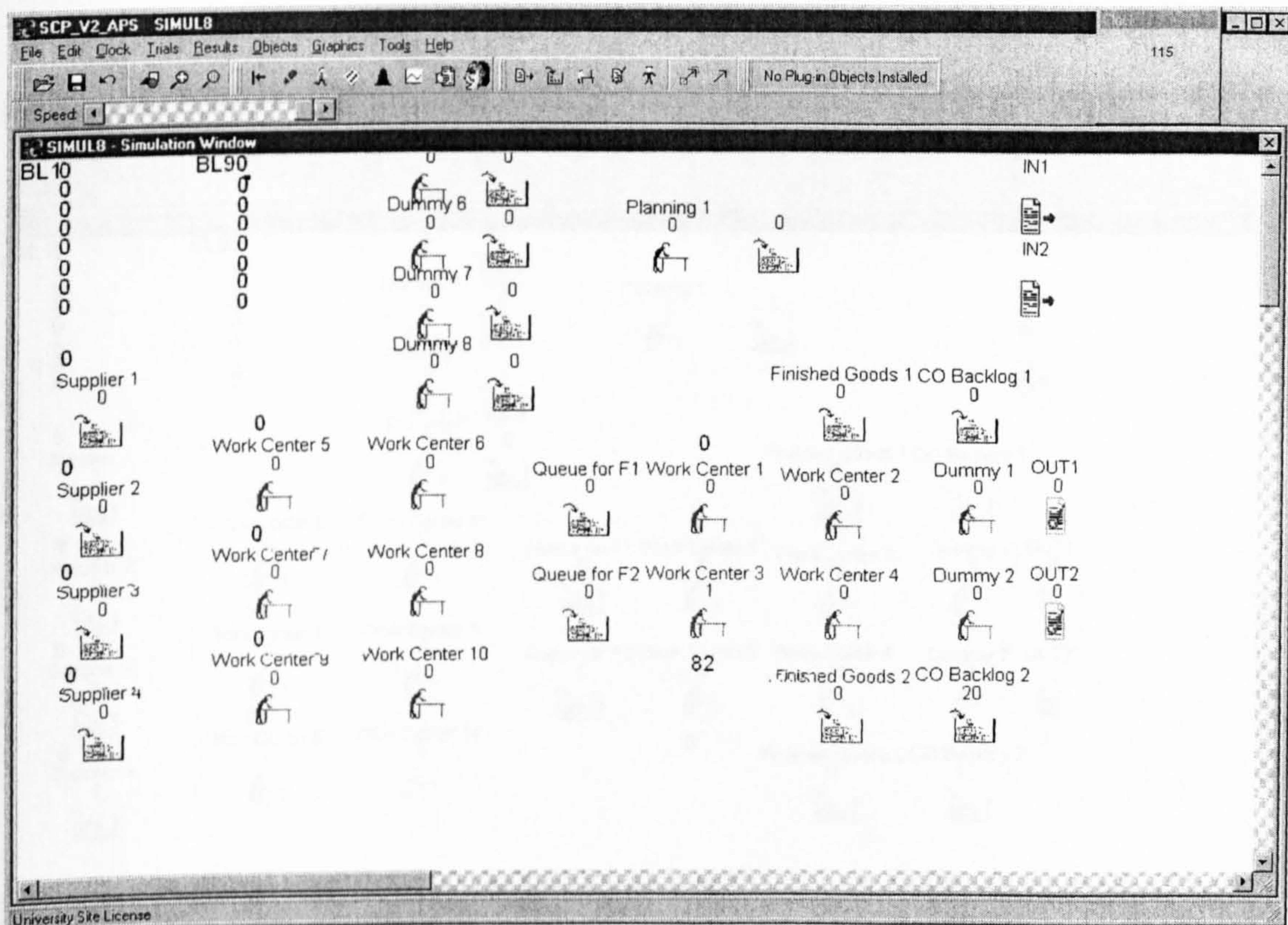


Figure 13.5 – Verification 4



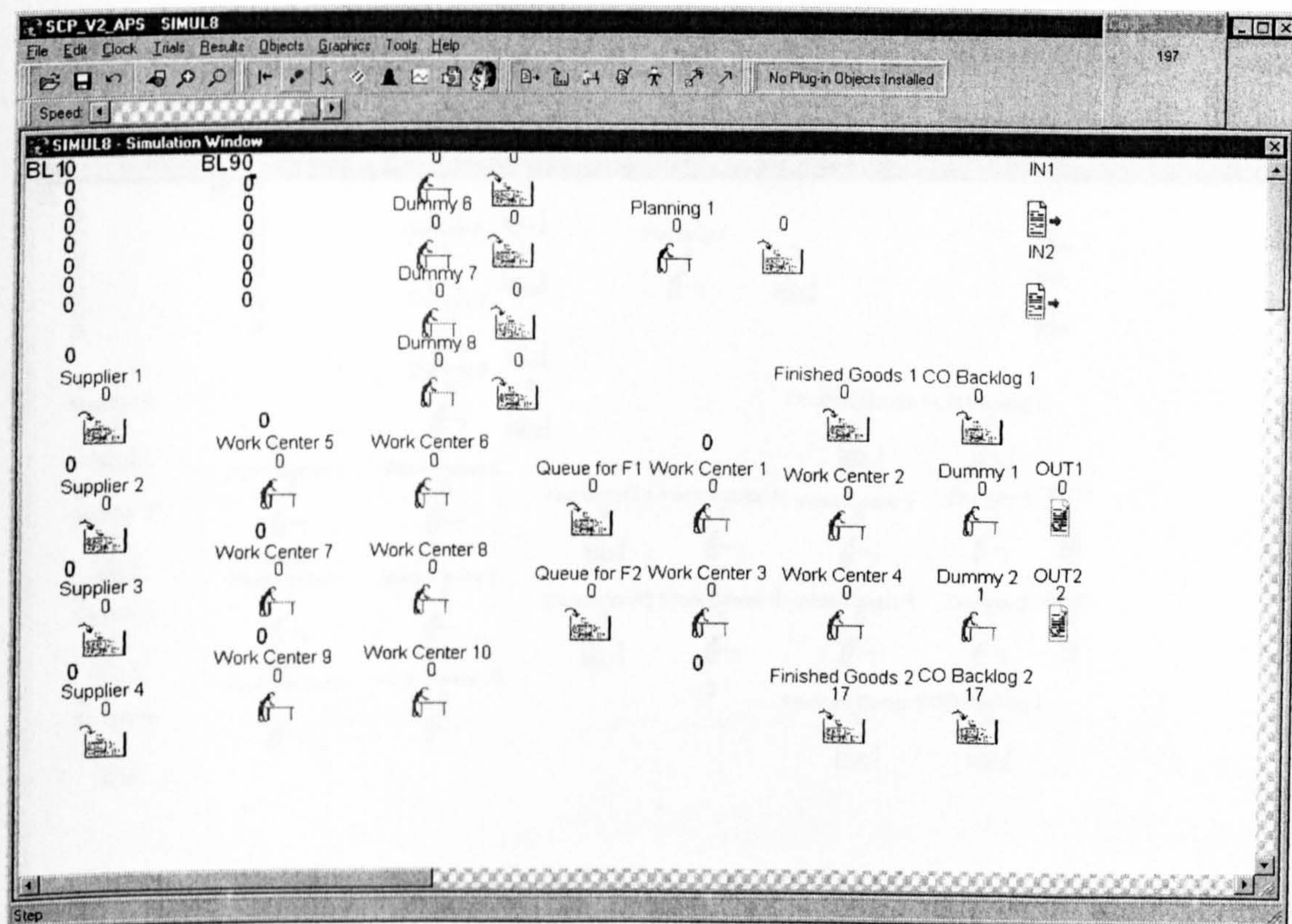


Figure 13.6 – Verification 5



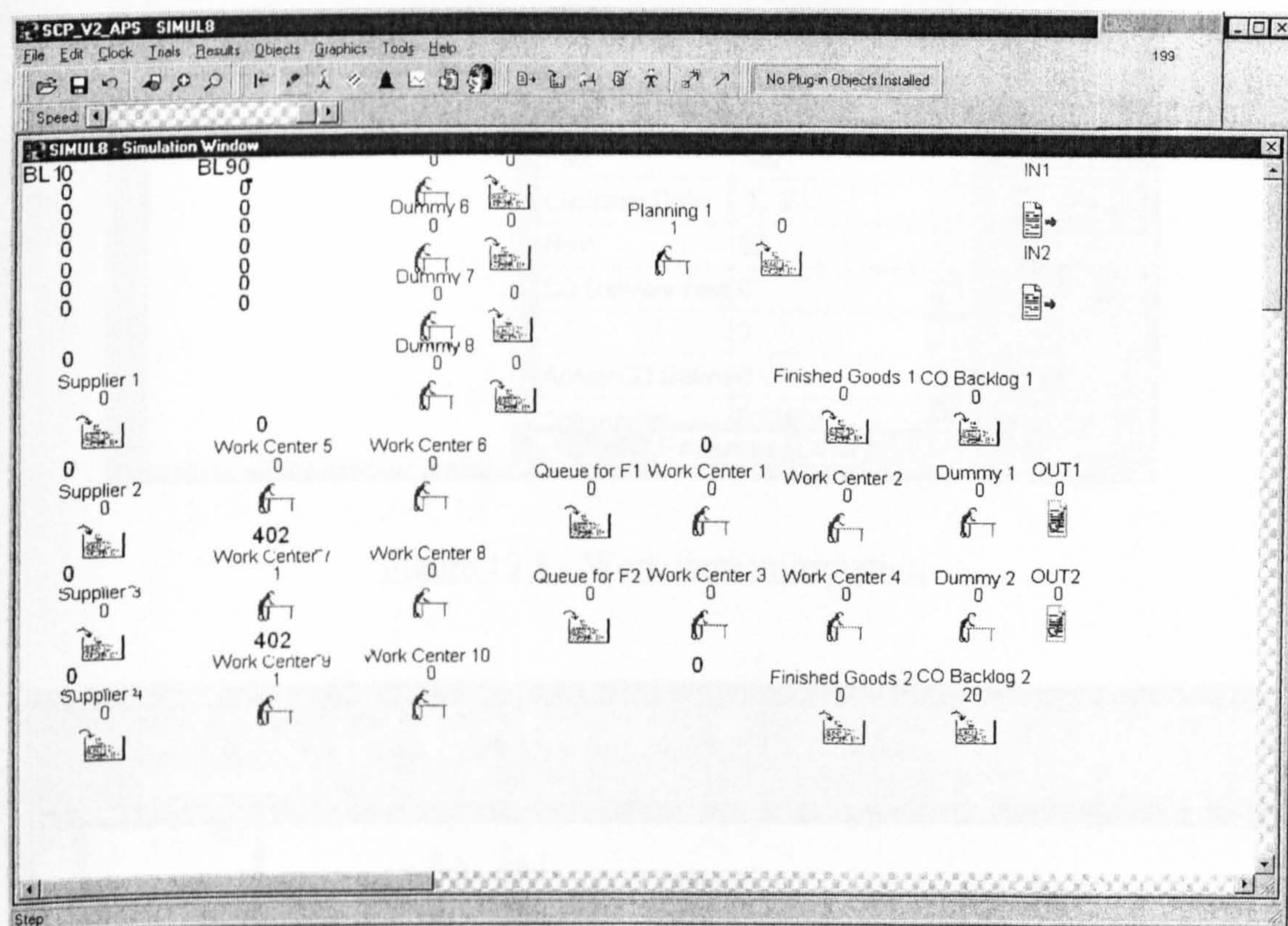


Figure 13.7 – Batching verification

The screenshot shows the "Work Item Information" dialog box. It contains a table with the following data:

Label Name	Label Content
Customer Order	1
Rest	80
CO Delivery Time	0
SF	2
Actual CO Delive	0
Actual Start	6.61604
CO Number	0
TOB/WIP	0

The dialog box also includes a "Work Items:" section on the left, a "Labels" tab (selected), and buttons for "OK", "Cancel", "Help", and "Type Info".

Figure 13.8 – Work item information



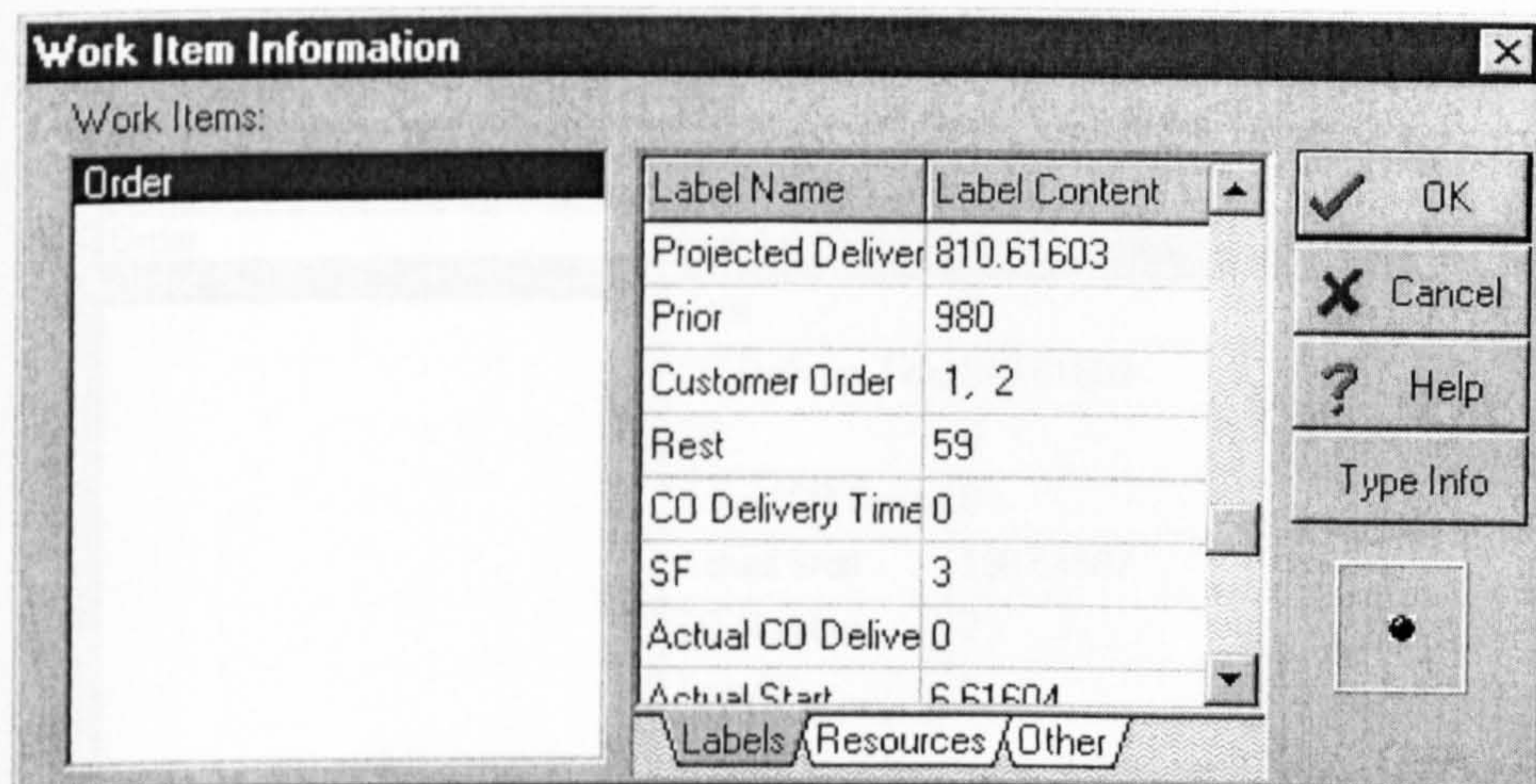


Figure 13.9 - Work item information

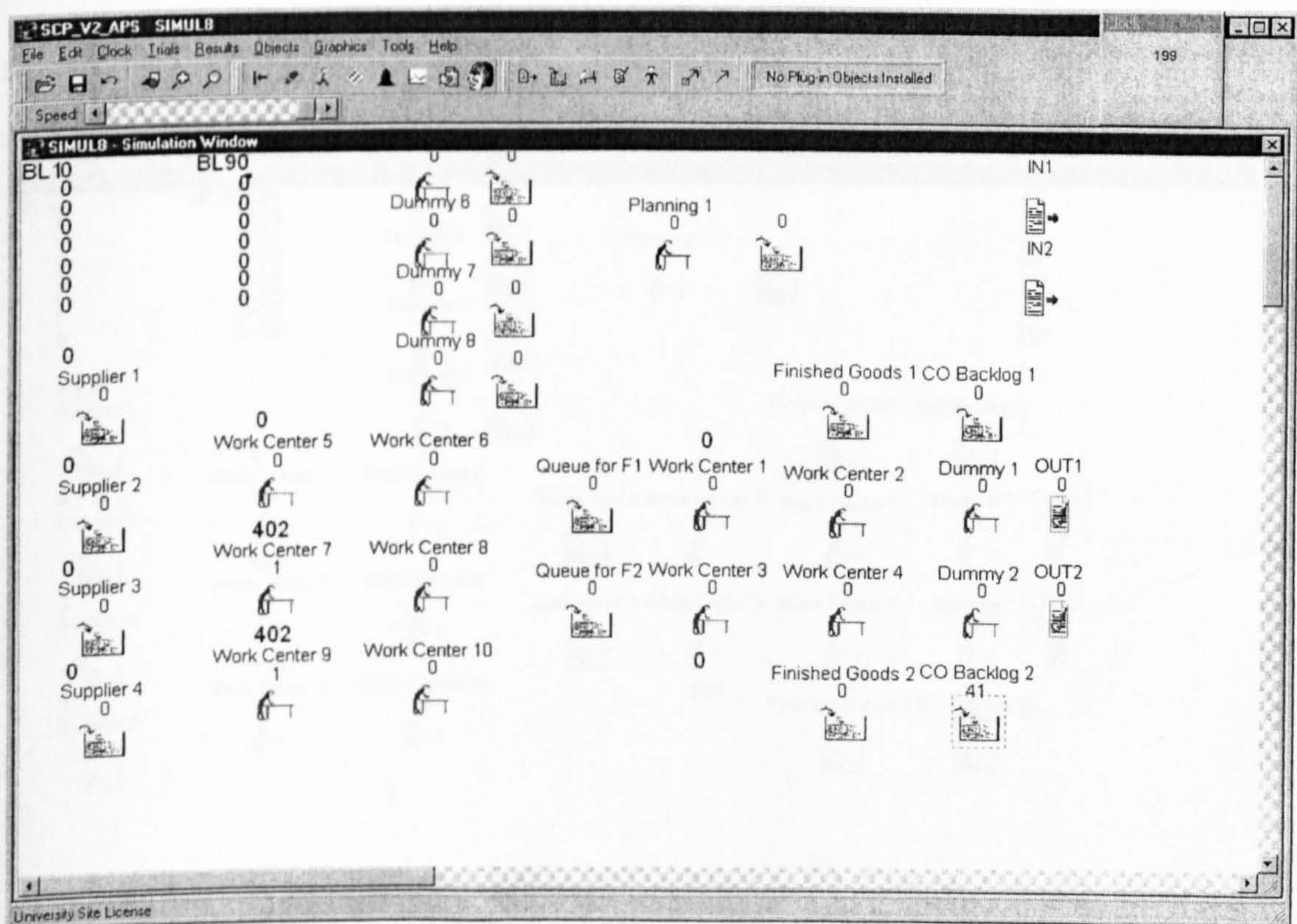


Figure 13.10 - Batching verification



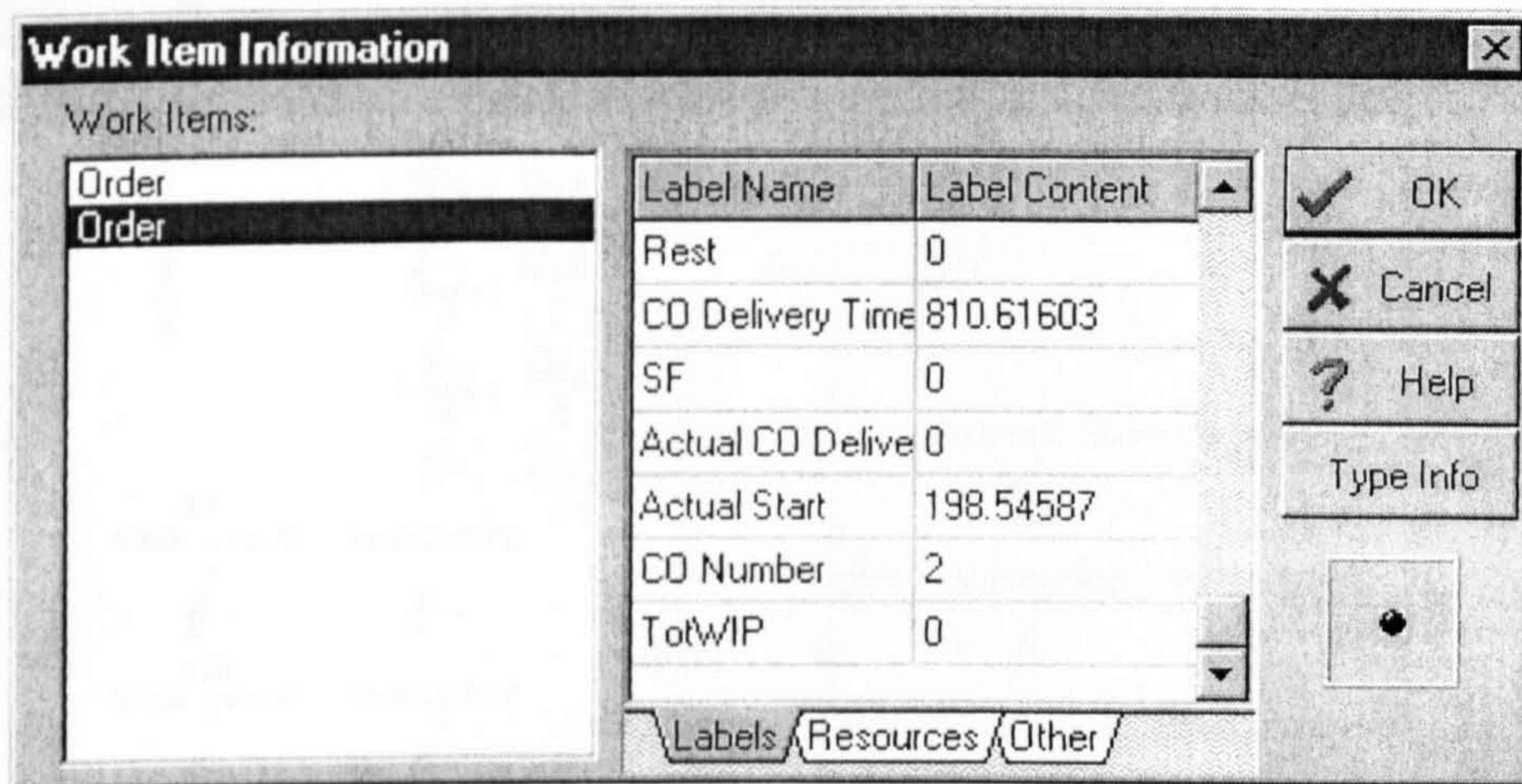


Figure 13.11 - Work item information

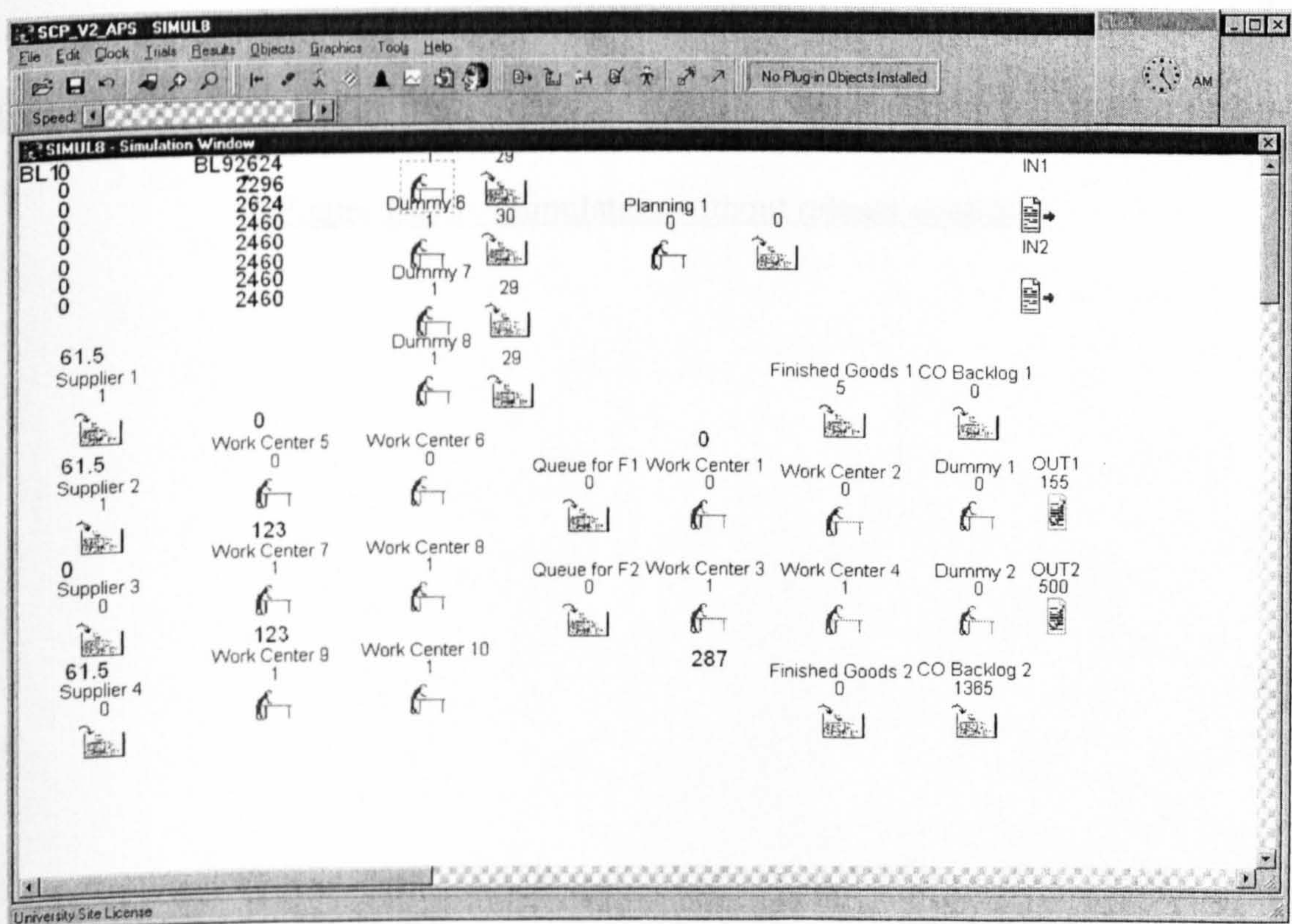


Figure 13.12 – Release control verification



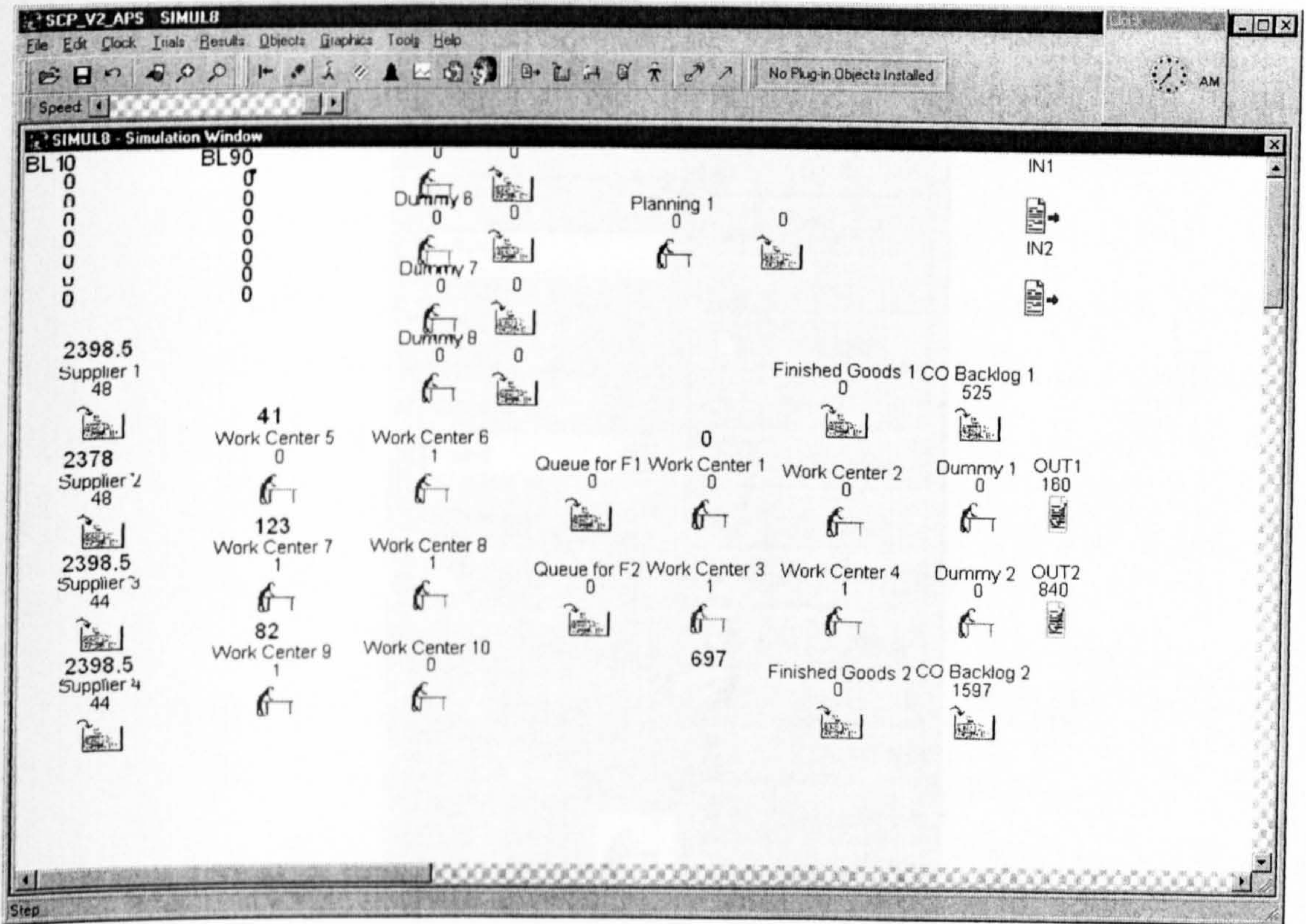


Figure 13.13 – Simulation without release control



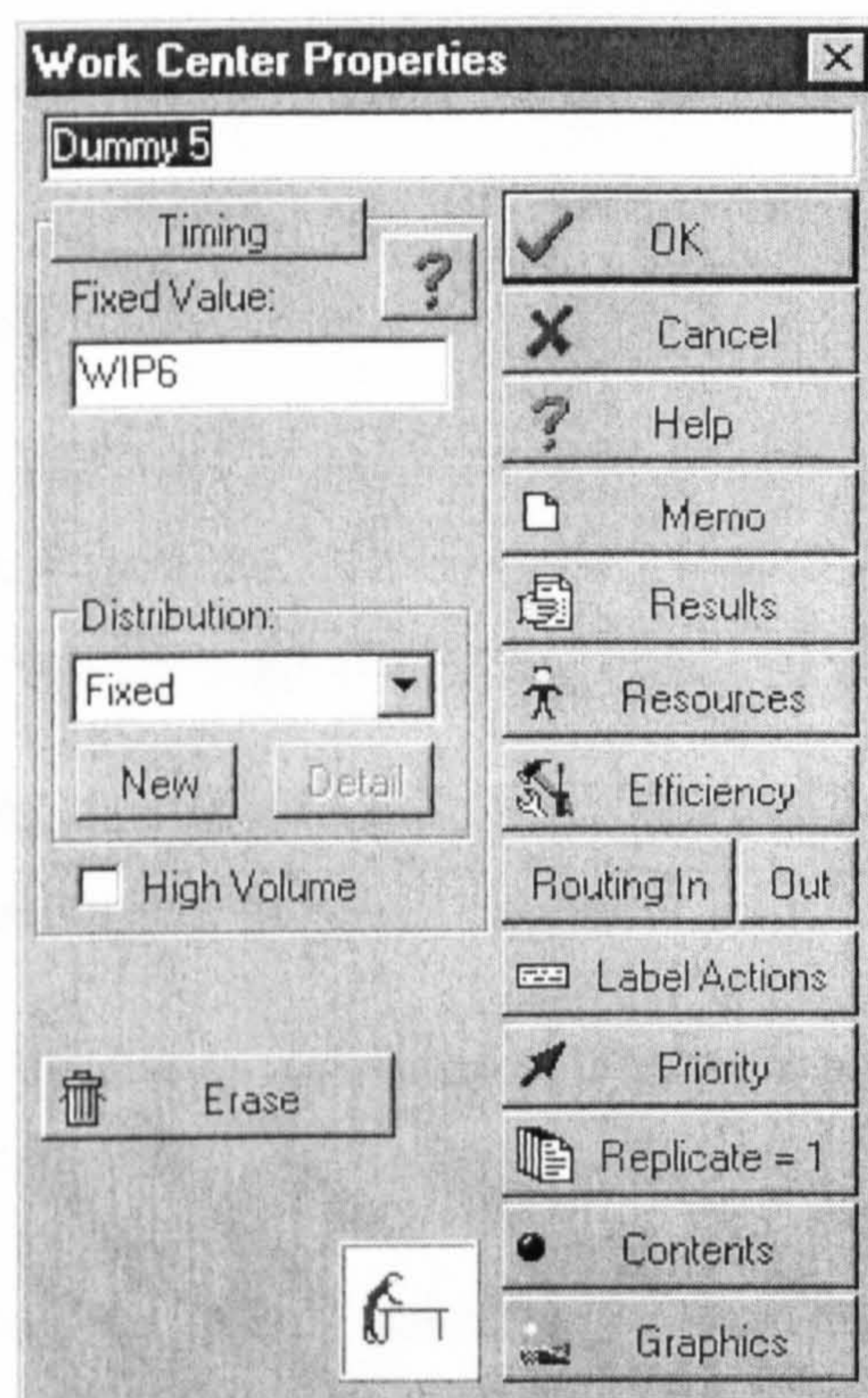


Figure 13.14 – Setting WIP levels for release control



## 14 Appendix C

### 14.1 List of Publications

R. Kyttner, I. Kiolein, M. Nafthal *Development of network-based environment for integrated product design, process and resource planning*. International Colloquium CAE Techniques. Bielefeld, 1995, pp.111-117

Küttner Rein, Nafthal Meelis *Integration of Product Design, Process and Resource Planning Systems*. Proceedings of Nord Design '96

M. Nafthal *Different Lot-Sizing Techniques*. Proceedings of the 1<sup>st</sup> International Conference DAAAM, Tallinn, September 1997, pp. 80-84

M. Nafthal, D. Stockton, J. Layden *Reducing time-delays in supply chains using advanced planning and scheduling*. Proceedings of the 2<sup>nd</sup> International Conference DAAAM, Tallinn, April 2000, pp. 90-94