Agent-based Hierarchical Planning and Scheduling Control in Dynamically Integrated Manufacturing System

*Submitted by **Naihui He** to the University of Exeter*
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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: ………………………………………

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ABSTRACT

It has been broadly recognised that today's manufacturing organisations face increasing pressures from continuous and unexpected changes in the business environment such as changes in product types, changes in demand pattern, changes in manufacturing technologies etc. To enable manufacturing organisations to rapidly and timely deal with these changes, operational decisions (e.g., process planning and production scheduling) have to be integrated with dynamic system restructure or reconfiguration so that manufacturing organisations do not only use the flexible resource utilisations to deal with these changes, but also can dynamically reconfigure their existing system structures in response these changes. A manufacturing system concept and implementation methodology is proposed by the Exeter Manufacturing Enterprise Centre (XMEC), which is called the Dynamically Integrated Manufacturing System (DIMS). The overall aim of DIMS is to provide a systematic modelling and control framework in which operational decisions can be integrated with the dynamic system restructuring decisions so as to help manufacturing systems to dynamically deal with changes in the business environment.

This PhD research is a part of DIMS research, which focuses on the investigation on operational control in DIMS. Based on the established agent-based modelling architecture in DIMS, this research develops two agent bidding mechanisms for the hierarchical control of production planning and scheduling. These two mechanisms work together to assist manufacturing systems in making optimal and flexible operational decisions in response to changes in the business environment. The first mechanism is the iterative agent bidding mechanism based on a Genetic Algorithm (GA) which facilitates the determination of the optimal or near optimal allocation of a production job containing a set of sub-jobs to a pool of heterarchical resources. The second mechanism is the hierarchical agent bidding mechanism which enables product orders to be cost-efficiently and flexibly planned and scheduled to meet the orders' due dates. The novelty of this mechanism is that it enables orders to be fulfilled within structural constraints of manufacturing systems as far as possible and however enables resources to be regrouped flexibly across system boundaries when orders cannot be fulfilled within structural constraints of manufacturing systems.

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Chapter 1

DIMS: Dynamically Integrated Manufacturing System

MAS: Multi-agent System

XMEC: Exeter Manufacturing Enterprise Centre

GA: Genetic Algorithm

Chapter 2

CLPP: Closed-loop Process Planning

CNC: Computer Numerically Controlled

DPLAN: Dynamic Process Planner

DTPP: Distributed Process Planning

DYNACAPP: Dynamic Computer Aided Process Planning

FMC: Flexible Manufacturing Cell

FMS: Flexible Manufacturing System

IPPM: Integrated Process Planning Model

IPPS: Integrated Process Planning System

MPA: Manufacturing System Performance Analyser

NC: Numerically Controlled

NLPP: Non-linear Process Planning

NP complete: Non-deterministic Polynomial Complete

PFA: Production Flow Analysis

PN: Petri Net

QAP: Quadratic Assignment Problem

RMS: Reconfigurable Manufacturing System

RMT: Reconfigurable Manufacturing Tool

SPLAN: Standard Process Planner

Chapter 3

ADACOR: Adaptive Holonic Control Architecture

AIR: Autonomous and Intelligent Resource

BMS: Bionic Manufacturing System

CNP: Contract Net Protocol

FrMS: Fractal Manufacturing System

HMS: Holonic Manufacturing System

PROSA: Product-Resource-Order-Staff Architecture

r-FrMS: Relation-driven Fractal Manufacturing System

Chapter 4

DIMS: Dynamically Integrated Manufacturing System

HAAN: Hierarchical Autonomous Agent Network

KB: Knowledge Base

KQML: Knowledge Query Manipulation Language

FIFO: First-in-First-out

PN: Petri Net

XMEC: Exeter Manufacturing Enterprise Centre

Chapter 5

GA: Genetic Algorithm

MS: Manufacturing System

NP hard: Non-deterministic Polynomial-time Hard

PO: Product Order

Chapter 6

GA: Genetic Algorithm

HAAN: Hierarchical Autonomous Agent Network

HMS: Holonic Manufacturing System

MS: Manufacturing System

PA: Part Agent

PO: Product Order

RA: Resource Agent

Chapter 7

AA31: Advanced Assembly A31 (machine)

AA32: Advance Assembly A31 (machine)

AB31: Basic Assembly B31 (machine)

BA_A1: Assembly A1 (Assembly Operation)

BA_B1: Assembly B1 (Assembly Operation)

BC_A1: Basic Component A1

BC_A2: Basic Component A2

BC_B1: Basic Component B1

BC_B2: Basic Component B2

DA21: Drill A21 (machine)

DA22: Drill A22 (machine)

DB11: Drill B11 (machine)

DB12: Drill B12 (machine)

FCFS: First-come-First-served

GA: Genetic Algorithm

GA11: Grind A11 (machine)

GB21: Grind B21 (machine)

JDK: Java Development Kit

LA11: Lathe A11 (machine)

LA12: Lathe A12 (machine)

LA21: Lathe A21 (machine)

LB11: Lathe B11 (machine)

LB21: Lathe B21 (machine)

MA11: Mill A11 (machine)

MA21: Mill A21 (machine)

MB11: Mill B11 (machine)

MB21: Mill B21 (machine)

PA: Product A

PB: Product B

TA31: Test A31 (machine)

TB31: Test B31 (machine)

Chapter 8

DIMS: Dynamically Integrated Manufacturing System

GA: Genetic Algorithm

HAAN: Hierarchical Autonomous Agent Network

IMC: Inventory Monitoring Component

MAS: Multi-agent System

MIPA: Material Inventory and Procurement Agent

ADACOR: Adaptive Holonic Control Architecture

AIR: Autonomous and Intelligent Resource

BMS: Bionic Manufacturing System

CLPP: Closed-loop Process Planning

CNC: Computer Numerically Controlled

CNP: Contract Net Protocol

DIMS: Dynamically Integrated Manufacturing System

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This PhD research is a part of a bigger research which is referred to as the Dynamically Integrated Manufacturing System (DIMS). DIMS aims at providing systematic modelling and control methodologies to assist manufacturing systems in optimally and flexibly utilising and organising manufacturing resources for dealing with changes in the business environment. This chapter is an introduction of this PhD thesis, which is organised into five sections. Following the introduction section, section 1.2 provides a description about the research background and concept of DIMS. Section 1.3 describes the research questions to be answered in DIMS. Section 1.4 presents the major objectives to be achieved in this PhD research. Section 1.5 provides an overview of this PhD thesis.

1.2 Research Background

Today's business environment for manufacturing organisations is characterised by continuous and unexpected changes (Koren et al. 1999) which mainly involve changes in the marketplace, changes in the business competition, changes in customer requirements, changes in manufacturing technology and changes in social environment (Zhang and Sharifi 2000). In this condition, apart from focusing on typical competitive issues such as cost and quality, current manufacturing systems have to effectively and rapidly deal with dynamic changes in the business environment so as to enhance their competitiveness against business rivals and survive in the turbulent business environment.

In order to assist manufacturing systems in dealing with changes in the business environment, a new manufacturing system concept was proposed by Koren et al. (1999) at the end of last century, which is termed as the reconfigurable manufacturing system. In this concept, a new class of machines is introduced, which is designed with modular hardware and software architectures and allows for easy tool change and updating in response to changes in the business environment. Meanwhile, coupled with the new class of machines, a new kind of layout design is proposed in reconfigurable manufacturing system, which enables system layout to be adjusted for accommodating a variety of products since the newly introduced machines allow for quick tool change and updating. The advocators of reconfigurable manufacturing system argue that such a layout is able to balance productivities and flexibilities of manufacturing systems, reduce structural complexities of manufacturing systems and in turn allow for quick launching of new systems and rapid reconfiguration of existing system structures. The concept of the reconfigurable manufacturing system is very promising for manufacturing systems to cope with dynamic changes in the business environment. However, to have a reconfigurable manufacturing system requires a large amount of initial capital investment on building of the new class of machines and further investment on building material handling systems and designing of new system architectures, communication networks etc so that every hardware and software in manufacturing systems could be compatible with the new class of machines. Therefore, for many manufacturing systems with existing manufacturing resources, the way of reconfigurable manufacturing system is not realistic and economical to use for dealing with changes in the business environment.

Currently, there are two kinds of manufacturing system approaches which enable manufacturing systems to flexibly utilise or organise existing manufacturing resources for dealing with changes in the business environment. The first kind of approaches is concerned with the operational level of manufacturing systems, in which the operations of process planning and production scheduling are integrated together so as to enhance the optimality and flexibility of resource utilisations of manufacturing systems to changes in the business environment. This kind of approaches mainly involves the non-linear process planning, the close-loop process planning and the distributed process planning. The second kind of approaches is associated with the layout design level of manufacturing systems, in which the machine layout on the shop floor is designed with priori flexibility or robustness to anticipated changes in the future market or, is reconfigued dynamically corresponding to changes in the business environment. This kind of approaches includes the dynamic layout, the robust layout and the reconfigurable layout. However, these two kinds of approaches cannot provide sufficient, accurate or/and cost-efficient flexibility and responsiveness for manufacturing systems to changes in the business environment. The problems with these approaches mainly include:

- As for approaches at operational level (i.e., the first kind of approaches), although they facilitate flexible resource utilisation of manufacturing systems, the level of the flexibility is restricted by the existing structures of manufacturing systems. In other words, they do not enable manufacturing systems to cope with some changes in the business environment which cannot be accommodated by the existing systems structures.
- In the approaches at layout design level, the major concept is to let layouts of manufacturing systems to be adjusted in response to market changes so as to maintain the performances of manufacturing systems. However, these approaches either do not provide accurate and dynamic flexibility for manufacturing systems since the layout adjustment is designed as a static plan based on the anticipation of future market, or are not implementable due to the lack of practical methodologies. Meanwhile, approaches at layout design level only consider the system structure at the bottom level but do not enable the entire structures of manufacturing systems to be adjusted or restructured in response to changes in the business environment. Furthermore, the layout adapatation based on these approaches enables a manufacturing system to accommodate the average changes (some times anticipated changes) in marketplace over a certain period, however does not enable a manufacturing system to continously deal with unexpected changes incurred within this period.

To overcome the problems of existing manufacturing system approaches to dealing with changes in the business environment, a novel approach is needed for enabling manufacturing systems to not only make flexible operational decisions (e.g., process planning and production scheduling) for dealing with changes in the business environment, but also dynamically reconfigure existing system structures for dealing with these changes. In doing so, the novel apporach must be an integrated approach considering operational decisions and system restructuring decisions concurrently so as to enable manufacturing systems to make the most appropriate decisions in response to the continous and unexpected changes in the business environment.

To provide the integrated approach, a manufacturing system concept and implementation methodology is proposed by the Exeter Manufacturing Enterprise Centre (XMEC), which is named as the Dynamically Integrated Manufacturing System (DIMS). The aim of DIMS is to develop a systematic modelling and control architecture for estalishing an integrated decision platform on which changes in the business environemnt can be captured continously and operational decisions of manufacturing systems can be integrated with the dynamic system restructure. Four requirements have to be satisfied simultaneously by the modelling and control architecture in DIMS. Firstly, the architecture must be able to model the complex hierarchies of manufacturing systems. This is because that manufacturing systems in real situations always have complex organisational structures, whereas having the modelling architecture to capture the hierarchical natures of manufacturing systems may enhance the architecture's applicability and also facilitate the decision-making of system restructure based on the architecture. Secondly, this architecture must avoid centralized control so that the control models of manufacturing systems can be easily and rapidly modified in response to possible changes in the physical structures of manufacturing systems resulting from the dynamic system restructure. Thirdly, production planning and scheduling (i.e., operational decision-making) based on this architecture must first enable manufacturing resources to be optimally utilised within structural constraints of manufacturing systems so that product orders can be cost-efficiently fulfilled within the structural constraints as far as possible. However, when orders cannot be fulfilled within the structural constraints, production planning and scheduling based on this architecture must enable the structural constraints to be relaxed gradually so that resources can be flexibly regrouped across system boundaries to fulfil product orders however with low disturbances to existing system structures. Fourthly, this architecture must enable structures of manufacturing systems to be dynamically evaluated based on the continuous analysis of operational decisions and in turn reconfigured at the most appropriate time with the most appropriate restructuring decisions.

1.3 Research Questions

Over the past decades, the technology of Multi-agent System (MAS) has received significant attentions of academic scholars for modelling and control of manufacturing systems. As for DIMS, the MAS technology has three supporting advantages including: firstly, the distributed and modular natures of MAS enable it to be used for distributed problem solving (Bond and Gasser 1988). Secondly, MAS can be used to model systems with complex hierarchices since it can encompass a variety of individual agents which take specific roles or responsibilities, and coordinate their knowledge, capabilities and goals with one another for achieving their responsibilities (Fox et al. 2000). Thridly, MAS has been broadly used for solving problems of different fields such as production planning, production scheduling and simulation (Caridi and Cavalieri 2004), which provides the feasibility for DIMS to use MAS for developing a modelling and control architecture wherein operational and restructuring decisions can be considered concurrently. Motivated by the three advantages aforementioned, DIMS invesitgates the applicability of MAS technology in developing the modelling and control architecture as required above. Three research questions in this context have to be answered in DIMS, including:

Question 1: How to model manufacturing systems based on MAS technology so that the established system models are able to represent complex hierarchies of manufacturing systems and avoid centralized control of manufacturing systems and most importantly, can be used to provide concurrent operational and restructuring controls of manufacturing systems?

Question 2: How to control production planning and scheduling of manufacturing systems based on the established agent-based model for making the optimally and flexibly coordinated operational decisions which enable product orders to be cost-efficiently fulfilled within structural constraints of manufacturing systems and also to be fulfilled with flexible resource regroupings across system boundaries when orders cannot be fulfilled within the structural constraints.

Question 3: How to control system restructure based on the established agent-based model so that manufacturing systems structures can be continuously evaluated and dynamically reconfigured at the right time with the right decisions.

1.4 Research Objectives

The system modelling (i.e., question 1) and dynamic system restructure (i.e., question 3) in DIMS have been successfully investigated by the author's colleagues. This PhD research, in this context, focuses on the investigation on the control of production planning and scheduling (i.e., question 2) based on the established agent-based modelling architecture in DIMS. The overall objectives of this PhD research are listed as following:

- To investigate the existing approaches to modelling and control of manufacturing systems.
- To identify technical requirements for production planning and scheduling method based on the established agent-based modelling architecture in DIMS.
- To develop an agent-based bidding mechanism for production planning and scheduling which enables resource of manufacturing systems to be optimally grouped within structural constraints or flexibly regrouped across system boundaries so that product orders can be fulfilled to meet the given due dates at low production costs.
- To validate the feasibility of the mechanism using numerical tests.

1.5 Thesis Organisation

Apart from the introduction chapter, namely Chapter 1, the rest of the thesis is organised in seven Chapters.

Chapter 2 provides a literature review about the existing manufacturing system approaches to dealing with changes in the business environment. Major problems associated with these approaches are identified and discussed in this chapter and also the necessity of an integrated approach to dealing with changes in the business environment is also discussed.

Chapter 3 reviews the major modelling and control architectures for manufacturing systems and discusses the feasibility of these architectures for providing the integrated approach.

Chapter 4 describes the agent-based modelling architecture in DIMS which was developed by one of the author's colleagues. In this chapter, the MAS-based organisational structures of manufacturing systems and product orders are described and the generic architecture for individual agents is also presented.

Chapter 5 and 6 describe two agent bidding mechanisms that work together to achieve the control of production planning and scheduling based on the agent-based modelling architecture in DIMS. Chapter 5 describes an iterative agent bidding mechanism based on Genetic Algorithm (GA) which aims at solving one of the common problems in production planning and scheduling, namely determining the optimum allocation of a production job containing a set of sub-jobs to a pool of resources within a given system so that the entire job can be completed within a given time at the lowest or near lowest cost. Chapter 6 describes a hierarchical agent bidding mechanism based on which an entire product order can be cost-efficiently planned and scheduled within a manufacturing system to meet the order's due date. Meanwhile, this mechanism enables product orders to be fulfilled within the structural constraints of manufacturing systems as far as possible and however is able to consider resource regroupings across system boundaries when current resource configurations of manufacturing systems cannot fulfil orders.

Chapter 7 provides numerical tests to validate the applicability of the two agent bidding mechanisms and Chapter 8 summarises the conclusions of this PhD research and discusses the future work.

CHAPTER 2

A LITERATUREW REVIEW ON MANUFACTURING SYSTEM APPROACHES TO DEALTING WITH CHANGES IN THE BUSINESS ENVIRONMENT

2.1 Introduction

This chapter provides a literature review of existing manufacturing system approaches to dealing with changes in the business environment, aiming at identifying the overall aims of this work through the literature review. The rest of this chapter is organised into four sections. Section 2.2 identifies the major changes in today's business environment and introduces the required capabilities for manufacturing systems to deal with these changes. The core part of this chapter is the literature view section—section 2.3 which is divided into three sub-sections according to the specific levels of manufacturing systems on which the related work focuses. Section 2.4 discusses shortcomings of the existing approaches to dealing with changes in the business environment. A summary is given in the last section, namely section 2.5.

2.2 Changes in the Business Environment

Today's manufacturing organisations face increasing pressures resulting from the aggressive global competition, as well as the continuous and unexpected changes in the business environment which are forced by several drivers including the globalisation of markets, the rapid pace of changes in manufacturing technology, the rapid expanding of technology access in manufacturing systems, the increasing environmental responsibility, resource limitation, and more educated and demanding customers (St John et al. 2001). Based on a survey involving 1000 companies, Zhang and Sharifi (2000) identify the detailed changes in today's business environment and classify them into five major groups including changes in marketplace, changes in business competition, changes in customer requirements, changes in manufacturing technology and changes in social environment. The changes in marketplace include the growth of niche market, the increasing changes in product models and shrinkage of products lifecycles. The changes in business competition mainly involve the increasing pressures on cost, the shortening products' time-to-market, quick innovation and changes in competitors. The changes in customer requirements consist of the fluctuation of product demand and mix, the changes in product quality expectations and the changes in customer demand patterns. The changes in manufacturing technology incorporate frequent introductions of new production facilities, new process technologies and new materials. The changes in social environment contain the changes in environmental, political and cultural regulations. Among the five groups of changes, the changes in marketplace and customer requirements are directly associated with the production system of a manufacturing organisation (i.e., directly impacting the production performance and efficiency), whereas the other three groups of changes exert influence on manufacturing organisations at strategic level. In other words, the changes in market place and customer requirements are the most crucial changes directly faced by manufacturing systems. As a result, in order to survive under today's turbulent business environment, manufacturing systems must be flexible and responsive to changes in marketplace and simultaneously, must be always able to optimally satisfy customer demands and requirements so as to compete against rivals in the niche market.

2.3 The Approaches of Manufacturing Systems to Dealing With Changes in the Business Environment

In manufacturing systems, existing approaches to dealing with changes in the business environment can be classified into three groups each of which focuses on a specific level of manufacturing system. These levels consist of the operational level, the layout design level and the system design level. Basically, the approaches associated with the operational level aim at flexible resource utilisations of manufacturing systems in response to changes in the business environment. The approaches related to layout design level aim at using flexible, robust or dynamically reconfigured layout to meet changes in the business environment. The approaches concerned with the system design level aim at designing advanced manufacturing facilities so as to deal with changes in the business environment through built-in flexibility or/and reconfigurability of these facilities. The approaches in regard to different levels are reviewed respectively in the following.

2.3.1 The Integrated Process Planning and Production Scheduling—The Operational Level

There are two crucial issues at the operational level of manufacturing systems including process planning and production scheduling. The process planning is an operational function determining the sequence of production operations and processing information (i.e., the methods of production, tooling, fixtures and machinery for operations) according to product design specifications. The production scheduling is another operational function determining the execution plans for product orders or jobs based on given process plans, i.e., when an order or a job is processed by which machine[1]. Conventionally, these two operational functions are sequentially performed in manufacturing systems, which is broadly acknowledged to be only suitable for mass production factories facing a stable market with certain demand patterns and product mixes. However, when the business environment is frequently changed, such sequential operations have become obstacles for manufacturing systems to efficiently deal with market changes due to three major shortcomings (Khoshnevis and Chen 1991; Tan and Khoshnevis 2000). Firstly, the production scheduling is always performed on the basis of a fixed process plan, which cannot take advantages of alternative process plans to deal with changes in the business environment. Secondly, the process planning is performed based on a static shop floor situation wherein all of manufacturing resources are assumed to be available, which may lead to infeasible process plans due to the unexpected disturbances on the shop floor such as unavailability of resources, machines' breakdown etc. Thirdly, since a process plan is optimised under the ideal situation, the most desirable process routes and manufacturing resources are repeatedly selected without the consideration of dynamic status on the shop floor and in turn production scheduling based on the generated plan may result in low utilisation of manufacturing resources and poor delivery performance. As a result, to enhance manufacturing flexibility and responsiveness to changes in the business environment at operational level, one of the promising ways is to integrate the operations of

[1] The detailed introduction of process planning and production scheduling can be referred to Hitomi (1996)

process planning and production scheduling such that the decision-makings of these two operations can be considered simultaneously. In this regard, process planning is able to access the dynamic status of the shop floor obtained from production scheduling, which would lead to more feasible and flexible process plans than that determined by the process planning under sequential scenario. Also, production scheduling has the ability to dynamically evaluate alternative process plans and select the optimal one for execution of scheduling function. In the literature, there are three major approaches to integrating process planning and production scheduling, namely the Non-linear Process Planning (NLPP), the Closed-loop Process Planning (CLPP) and the Distributed Process Planning (DTPP) (Larsen and Alting 1990).

2.3.1.1 The Non-linear Process Planning (NLPP)

Similar to the process planning in the sequential scenario, NLPP generates process plans based on static shop floor situations. However, NLPP does not generate a fixed process plan. Instead, it generates a set of possible plans prior to production scheduling. Before these plans enter the shop floor, they are ranked in the light of process planning criteria and stored in a process planning database. The most possible plan which can be executed on the shop floor and results in the best performance for the manufacturing system, is given the first priority and always ready for submission when a job is required. However, production scheduling makes the final decision by considering current status on the shop floor. If the first priority plan cannot be executed on the shop floor, the second priority plan will be provided to the scheduling function. This process will be repeated until a suitable production schedule is found.

In the literature, there are quite a number of studies related to the approach of NLPP. One of the typical examples is the FLEXPLAN system (Tonshoff et al. 1989) in which the operations of process planning and production scheduling are integrated following the above procedures of NLPP. Meanwhile, FLEXPLAN also involves a reactive re-planning strategy in order to quickly respond to dynamic disturbances incurred on the shop floor during the fabrication period. Another example of NLPP is proposed by Hou and Wang (1991) who investigate the integrated planning problem under the Flexible Manufacturing

Cell (FMC) environment. Following the planning procedures of NLPP to generate alternative process plans for parts scheduled on the shop floor of FMC, this work uses a simulation model to evaluate these plans and select the best one that will be employed by the production scheduling function.

The typical planning procedures of NLPP intend to enhance scheduling flexibility of manufacturing systems through the utilisation of alternative process plans. However, these plans are still based on static situations on the shop floor, and do not take into consideration of dynamic status on the shop floor. Therefore, some of scholars propose two-stage planning systems based on the approach NLPP in order to add dynamic environmental conditions in process plans. For example, Ssemakula and Cloyd (1994) propose a Dynamic Computer Aided Process Planning (DYNACAPP) system in the context of Flexible Manufacturing System (FMS). The DYNACAPP involves two planning parts including a Standard Process Planner (SPLAN) and a Dynamic Process Planner (DPLAN). The SPLAN is used to determine the general process plans considering the overall feasibility and efficiency based on the static capability of shop floor and also to select cells for executing these plans. The DPLAN is a cell-oriented process planner, which takes the output plans selected by the SPLAN and validates these plans according to a variety of viewpoints including the availability and loading of machines, operators, material handling devices etc. A similar scheme of such a two–stage planning system is also presented in Usher and Fernandes (1996).

As described above, the way of NLPP to integrate process planning and production scheduling is based on the generation of alternative process plans so that the production scheduling is able to take part in the decision-making process of the process planning. Theoretically, the approach of NLPP is able to cover all of possible process plans so as to optimise the process plans and resource utilisation and meanwhile provide high flexibility to changes in business environment. However, in real situations especially in manufacturing systems with complex hierarchical structures, covering all of possible process plans is difficult to achieve. Therefore, alternative process plans of NLPP are always arbitrarily determined and ranked in the light of users' knowledge and experience. In this context, the approach of NLPP may not be able to well address the optimisation of resource utilisation. More importantly, since the flexibility of NLPP to changes in the business environment is solely based on generated alternative process plans, the limited alternative process plans in real situations may correspondingly result in low flexibility of NLPP to changes in the business environment.

2.3.1.2 The Closed-loop Process Planning (CLPP)

As aforementioned above, some of studies related to NLPP use an additional planning stage—dynamic process planning stage to validate the alternative process plans generated in the static planning stage so as to eliminate possible infeasibilities of the alternatives. However, the additional planning stage causes further efforts in process planning which lower the efficiency of the planning function. In order to overcome this shortcoming of NLPP, different from the two-stage planning system, CLPP employs an information feedback loop to enable the process planning function to directly consider the dynamic shop floor situations and resource requirements in the process planning process. In other words, alternative process plans generated by CLPP are based on the real time feedback from the shop floor with respect to resources' status at that time. The feedback is created by the production scheduling function, which is based on the current availabilities of manufacturing resources required by the coming job. As a result, due to the involvement of real time availability, every process plan in CLPP is believed to be feasible in terms of the required resources.

The idea of real time feedback of CLPP is employed by many of studies to facilitate the integration of process planning and production scheduling. For example, Iwata and Fukuda (1989) propose a dynamic process planning system. In their work, dynamic process plans are generated on the basis of order information including product design data, due date requirements and production volume, as well as the scheduling feedback from the shop floor including the machine loading and utilisation status. Kempenaers et al. (1996) develop an integrated automatic process planning and scheduling system to overcome the aforementioned drawback of NLPP. The proposed system is termed as COMPLAN consisting of a collaborative approach based on the formalism of production constraints as a means to realise feedback from scheduling to process planning. The production constraints involve two major types including general constraints and specific constraints.

The general constraints are generated by a schedule evaluator of production scheduling department based on the consideration of current and predicted loading of workshops. The specific constraints are associated with specific requirements of orders. Kiritsis and Porchet (1996) propose a Petri Net (PN) based model for dynamic process planning which contains three modules. In the first module, a machining table is constructed to indicate the allocation of machining operations to design entities (e.g., manufacturing features). In the second module, a PN model is constructed according to the established machining table. The PN model represents the graphic process planning procedures for a given manufacturing part. Finally, in the third module, a reachability analysis of the PN is conducted to generate all possible process plans described in the form of a so-called reachability graph. Since the reachability graph may lead to a large number of possible process plans, this work also proposes a simple optimisation method based on heuristic algorithms to reduce solution space of process plans.

Compared to NLPP, the implementation of real time feedback information from the shop floor to process planning enables the CLPP-based process planning function to work more efficiently for generating feasible process plans. However, from the reviewed work of CLPP, it is indicated that CLPP still follows the underlying principles of NLPP to integrate process planning and production scheduling. As a result, similar to NLPP, the approach of CLPP still cannot well address the optimisation of resource utilisation and achieve high flexibility to changes in the business environment.

2.3.1.3 The Distributed Process Planning (DTPP)

As discussed previously, despite the efforts to integrate process planning and production scheduling, process plans based on the approaches of NLPP and CLPP are generated prior to production scheduling, which limits the operational flexibility of manufacturing systems to changes in the business environment. Zhang (1993) denotes that such a way is only able to address the interfacing of process planning and production scheduling, but cannot realise the full integration of these two operations. In order to overcome the shortcoming of the former two approaches, the approach of DTPP is proposed to integrate operations of process planning and production scheduling starting from an early stage. In DTPP, the tasks of process planning and production scheduling are divided into three phases including pre-planning, paring planning and final planning. The pre-planning phase represents an off-line technical manufacturing analysis in which process planning identifies the initial processing requirements such as manufacturing features and job operations corresponding to these features and the production scheduling analyses and estimates the potential capabilities of equipments in regard to these identified job operations. The paring planning phase matches the required job operations with the operational capabilities of available production resources by considering the real time status on the shop floor. The paring solutions are found when the resources are available and the job operations are required. The final planning phase prepares the manufacturing of products on selected equipments, such as job sequencing and NC-program (Numerically Controlled Program) generating etc.

A typical example of DTPP is the integrated process planning model (IPPM) proposed by Zhang (1993) which consists of three modules: a process planning module, a production scheduling module and a decision-making module. At the pre-planning level, according to the product design specification, the process planning module performs three activities involving feature reasoning, machining process recognition and setup determination, whereas the production scheduling module intends to identify production resources available in the next time window. At the paring planning level, the available resources are matched with the requirements of setup and machining processes by production scheduling module. The process planning module performs machine selection, tool and fixture selection and exact time calculation based on the real time feedback from scheduling. The process planning module at the final planning level works in three steps including the operational tolerance analysis, operation sequencing and overall time and cost calculation. The detailed process planning and detailed production scheduling are performed simultaneously at this level so as to generate the detailed process plan, requirements of machines, tools, fixtures and personnel, as well as material handling information for shop floor. In IPPM, the decision-making module is the central element and performs by means of real time information. This module mainly works in the paring planning phase and intends to eliminate the conflicts between process planning and production scheduling. Huang et al. (1995) present an integrated process planning system (IPPS) based on the concept of DTPP. The IPPS consists of two modules, namely a process planning module and a production scheduling module that are similar to the corresponding modules in IPPM.

In addition, a progressive approach is also proposed in this work, which reduces the computational complexity of the integration problem of process planning and scheduling along the three planning phases of DTPP. The authors denote that such a way of reducing computational complexity enables the approach of DTPP to be realised in a real time manufacturing environment where time is crucial.

As described above, the approach of DTPP performs operations of process planning and production scheduling simultaneously at all of task stages i.e., starting from a global level and ending at a detailed level. In this condition, unlike the approaches of NLPP and CLPP, the DTPP generates dynamic operational decisions based on the dynamic information in the business environment, rather than based on alternative process plans. This provides DTPP higher flexibility and efficiency to deal with changes in the business environment than the former two approaches. Despite such advantages of DTPP, from the reviewed work discussed above, it is indicated that due to the implementation of simple paring method to determine the process plan, the approach of DTPP may not be able to optimise the resource utilisation of manufacturing systems.

2.3.2 The Dynamic, Robust and Reconfigurable Layouts—The Layout Design Level

The layout design of manufacturing systems determines a spatial structure for arranging manufacturing resources in order to ensure the efficiency of production (i.e., satisfying customer demands), the stability of resource utilisation, low inventory level, flexibility and adaptability of production, and economy of production (i.e., minimisation of production cost) (Hitomi 1996). Conventionally, the layout design is based on a forecast of average market condition in a long-term planning period which corresponds to the lifecycles of existing product types, which aims at minimising the average material handling cost of manufacturing system over the entire period. Once a layout design is implemented on the shop floor of a manufacturing system, it will be static and unchanged to external manufacturing environment over the entire planning period. In this context, due to the unforeseen environmental changes incurred within the planning period, the deterministic design feature of such a layout may cause infeasibility in the future. In other words, the conventional layout design cannot provide manufacturing systems with flexibility and responsiveness to changes in the business environment. In order to overcome the drawbacks of conventional layout design, three approaches to layout design have been proposed so as to build potential flexibility, robustness or reconfigurability to market changes in system layout. The three approaches include dynamic layout, robust layout and reconfigurable layout (Meng et al. 2004).

2.3.2.1 The Dynamic Layout

As aforementioned above, the layout of a manufacturing system based on the conventional layout design is fixed and static over a long-term planning period, which is not able to accommodate future market changes incurred within this period. One of the simple methods for overcoming this drawback is to shorten the lifecycle of a static layout, i.e., to shorten the planning period in conventional layout design mentioned above. In this context, the long-term planning period in conventional layout design is divided into several short-term planning periods for each of which a new layout is designed. However, if so, another problem would be encountered, which is associated with the reconfiguration cost resulting from the frequent relocation of manufacturing resources due to the introduction of new layouts (Balakrishnan and Cheng 1998). The shorter the planning period is, the more significant the influence of reconfiguration cost on manufacturing systems is. However, this problem cannot be solved when every layout for a short-term planning period is separately designed in that these layout designs are only based on the minimisation of material handling cost. This induces the advent of the approach of dynamic layout in the literature.

In dynamic layout, a long-term planning period is split into several short-term planning horizons and the market information of these horizons is assumed to be deterministic at the beginning of the long-term planning period. The dynamic layout then performs an aggregate planning to determine the static layouts for all of these planning horizons by simultaneously considering the minimisation of overall material handling cost and overall reconfiguration cost. The overall reconfiguration cost represents the sum of relocation cost of machines between consecutive planning horizons. Moreover, due to the sequence of the planning horizons, the aggregate decision of dynamic layout consists of a set of sequenced layout solutions each of which is associated with a short-term planning horizon.

The decision-making process of dynamic layout is referred to as the dynamic layout problem which is NP complete (non-deterministic polynomial complete) since there may be plenty of feasible candidate layouts for every planning horizon and the layouts for different planning horizons are interrelated with each other in terms of reconfiguration cost (Balakrishnan and Cheng 1998). In this regard, most of literature studies use near or towards-optimal algorithms to cope with dynamic layout problem. For example, Rosenblatt (1986) proposes a multiphase selection algorithm for dynamic layout problem. At the beginning, conventional techniques of layout design are used to determine a set of candidate layouts for every planning horizon. A dynamic programming model is then used to find the optimal decision from these candidates by considering the minimisation of global material handling cost and reconfiguration cost. A similar scheme is proposed by Balakrishnan et al. (1992), however in which the dynamic layout problem does not only consider the material handling cost and reconfiguration cost, but also considers the budget constraints for manufacturing systems. In addition, apart from mathematical programming techniques, heuristic and random-based searching algorithms are also used to solve the dynamic layout problem [2], such as the heuristic techniques (Urban 1993), Genetic Algorithms (Conway and Venkataramanan 1994; Kochhar and Heragu 1999) and Tabu Search techniques (Kaku and Mazzola 1997).

From the above description of dynamic layout, it is indicated that this approach intends to deal with market changes through the built-in flexibility of system layout. However, the basic assumption of dynamic layout, namely the deterministic market condition of multiple short-term planning horizons, is unrealistic under real situations, in particular under current manufacturing environment where market changes are continuous and unexpected. Meanwhile, the flexibility provided by dynamic layout is fixed and static because the layouts with respect to different short-term planning horizons are all pre-determined at the early stage of a long-term planning period. One cannot ensure whether the new layout is introduced timely and also cannot ensure whether the newly introduced layout is feasible at that time. Moreover, another problem is that the way of dynamic layout to deal with changes in the business environment only focuses on the system structure at the bottom/machine level, but does not consider the flexibility and responsiveness of the overall structure of complex manufacturing systems.

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[2] The details of optimisation techniques used in dynamic layout problem can be viewed in Balakrishnan and Cheng (1998)

2.3.2.2 The Robust Layout

Compared to the way of dynamic layout to respond to changes in the business environment, the approach of robust layout intends to generate a fixed layout for manufacturing system across a long-term planning period, rather than a set of sequenced layouts (i.e., the dynamic layout). However, robust layout considers the stochastic market conditions in the layout design so that the fixed layout is robust and commonly feasible for different market scenarios (e.g., market conditions different from product demands). In the literature, the robust layout considering a single stochastic period is termed as the robust layout of single period. Meanwhile, the robust layout considers another situation in which the layout adjustment over multi-planning period (i.e., dynamic layout) is not feasible due to the high reconfiguration cost therefore manufacturing systems may prefer a fixed layout that is robust for different planning periods (Benjaafar et al. 2002). The robust layout under this situation is referred to as the robust layout of multiple periods.

Rosenblatt and Lee (1987) and Rosenblatt and Kropp (1992) present a method for evaluating the layout robustness by considering demand uncertainty. In their work, the layout robustness is represented as an indicator of flexibility for handling demand changes. When designing a robust layout, every possible layout has a fitness value represented as the number of times that the material handling costs of the layout under different demand scenarios are located within a pre-defined percentage of a best known optimal solution. The higher the fitness value is, the more robust the layout is. In the literature, the problem of how to find robust layout candidates for manufacturing systems is termed as the robust layout problem. Kouvelis et al. (1992) present a well known approach to robust layout problem of single or multiple periods based on the aforementioned evaluation method. In their work, candidates of robust layout for a manufacturing system is generated through a heuristic algorism based on the Branch and Bound procedures of Quadratic Assignment Problem (QAP). The robust layout problem of single period considers the stochastic product demand. The optimal solution or objective value for every demand scenario is obtained through the QAP formulation. Then, a candidate of robust layout represents a layout whose total material handing cost under different demand scenarios is within a pre-specified percentage (*p%*) of the optimal solution and also the lower bound of the layout calculated by the Branch and Bound procedures is *p%* greater than the upper bound of the optimal solution. In comparison to the robustness evaluation method of Rosenblatt and Lee (1987), the additional constraint, i.e., lower bound of a candidate layout is *p%* greater than the upper bound of the optimal solution, aims at reducing the candidate numbers and in turn lowering the efforts for layout evaluation and cost-benefit analysis. In Kouvelis et al. (1992), the robust layout problem of multiple periods considers changes in product mix and demand, which is solved in a separate manner. Based on the similar approach to the problem of single period, the candidate layouts for every planning period are obtained. The candidate layouts belonging to different planning periods are then grouped into different layout families according to the monuments of layouts. The monuments represent manufacturing facilities that are difficult to be relocated. Finally, for each layout family, a fixed layout is determined, which is feasible for all demand scenarios and planning periods.

Compared to the dynamic layout, the robust layout is designed based on the consideration of stochastic market condition, which enables the obtained layout to be more feasible for real manufacturing environment than that based on the approach of dynamic layout. However, since the robust layout is a fixed layout which serves for different market scenarios and planning periods, it is not the optimal one for every scenario and period in order to maintain the feasibility. In other words, the ability of robust layout to deal with changes in the business environment is based on the consumption of manufacturing efficiency. Meanwhile, although robust layout considers the stochastic market condition, it is still determined at the early stage of a long-term planning period. In this context, it still requires the overall production data to be available at the outset, which always suffers from the obstacles from the dynamic environment (Benjaafar et al. 2002). Furthermore, similar to dynamic layout, the approach of robust layout also considers the system structure at the bottom level only, being not be able to enhance the responsiveness of overall system structure to the changes in the business environment.

2.3.2.3 The Reconfigurable Layout

The reconfigurable layout is proposed by Meng et al. (2004), which aims at enabling a manufacturing system to be able to dynamically adjust its layout in response to changes in the business environment whenever it is needed. Different from the dynamic layout and the robust layout which determine a prior and static layout plan for manufacturing systems executed in a long-term planning period of the future, there is not such a timing assumption for the approach of reconfigurable layout in which the adjustment of system layout is assumed to be dynamically triggered by changes in operational performance of manufacturing systems which is affected by the changes in the business environment.

Currently, the core issues related to the reconfigurable layout is to determine the optimal layout to meet the current or near future changes in the business environment, which is termed as the reconfigurable layout problem. Meng et al. (2004) propose a three-phase framework for solving such a problem. In the first phase, a number of candidate layouts of manufacturing systems are generated through the use of conventional layout design techniques. However, unlike other approaches (e.g., dynamic layout or robust layout) using the forecast of production data in a long-term planning period, reconfigurable layout uses current or near future market condition to obtain these candidates. In the second phase, these candidates are evaluated by using a Manufacturing System Performance Analyser (MPA) (Meng and Heragu 2004) incorporating a set of evaluation criteria associated with operational performance of manufacturing systems such as setup time, transportation time, machine failure etc. Meng et al. (2004) denote that the implementation of MPA is to quickly eliminate some of candidates with very poor performances, and reduce the overall efforts to determine the final layout because the simulation process in the third phase is very slow.

Compared to the approaches of dynamic layout and robust layout, the approach of reconfigurable layout has proposed a more convincing idea for manufacturing systems to deal with changes in the business environment, namely the dynamic layout restructure which enables manufacturing layout to be adjusted more timely and accurately in response to changes in the business environment than the way of dynamic layout. However, similar to the previous two approaches, the approach of reconfigurable layout still focuses on the system structure at the bottom level only and hence can not address the overall system restructure of manufacturing systems. More importantly, although the base point of reconfigurable layout to deal with market changes is the dynamic restructure of layout, to date, the proposed work with respect to reconfigurable layout does not provide any methodologies and mechanisms for the so-called triggering process that can be regarded as the central element of reconfigurable layout to meet changes in the business environment. This leads to the inapplicability of the approach of reconfigurable layout.

2.3.3 The Flexible Manufacturing System and Reconfigurable Manufacturing System—The System Design Level

The system design is a comprehensive issue related to a number of design issues in manufacturing system such as the design of equipments, modules, structures, communication interfaces etc. Based on the literature review, it is indicated that the existing manufacturing system approaches to dealing with changes in the business environment at system design level mainly stem from the introduction of advanced manufacturing facilities with built-in flexibility to changes in the business environment. In the literature review, such approaches mainly consist of Flexible Manufacturing System (FMS) and Reconfigurable Manufacturing System (RMS).

2.3.3.1 Flexible Manufacturing System (FMS)

Since the 1980's, with the demand pattern shifting from the mass production of single product type to small or medium volume production of various product types, manufacturing organisations recognised that traditional dedicated machines and material handling systems become obstacles to improving the flexibility and responsiveness of manufacturing systems. The FMS is then proposed under this situation, which combines the technology of Numerically Controlled manufacturing, automated material handling and computer controlled hardware and software to create an integrated system that can be used to produce a variety of product types across various workstations (Stecke 1983; Buzacott and Yao 1986). The design of FMS consists of three issues including the design of machines/workstations, the design of material handling system and the design of network of supervisory computers and microprocessors (Buzacott and Yao 1986). Compared to traditional dedicated machines, machines in FMS are able to incorporate a number of functionalities on a single machine. Meanwhile, by combining the Computer Numerically Controlled (CNC) technology, these machines do not require significant set-up time and changeover time between successive jobs needing different functionalities. In this context, machines in FMS are also referred to as flexible CNC machines. The flexible CNC machines have fixed hardware architecture therefore the multiple functionalities of these machines have to be determined and installed prior to the utilisation on the shop floor in order to address the functional flexibility. Basically, built-in functionalities of flexible CNC machines are determined based on the current production requirements and also the forecast of possible requirements in the future market. Compared to traditional material handling systems in which part movement between different machines is dedicatedly designed, the material handling system in FMS is automated and flexible, which permits the jobs to move between any pair of machines so that any job routing can be allowed. The network of supervisory computers and microprocessors in FMS performs four activities including directing job routings, tracking the status of jobs in process, passing instructions of job operations to machines and monitoring the operations' performance and problems.

From the above introduction of FMS, it is indicated that the flexible CNC machines are the core and basic components enabling FMS to have high flexibility to meeting demand fluctuations with respect to existing product types and unforeseen changes in the business environment. However, the use of such machines causes two crucial disadvantages for FMS (Koren et al. 1999). Firstly, the fixed hardware architecture of flexible CNC machines does not support the dynamic upgrading of machines' functionalities in response to unforeseen changes in the business environment. In other words, it can be regarded that the flexibility of FMS is fixed and rigidly restricted by the prior built-in functionalities of flexible CNC machines. In addition, since some of functionalities of flexible CNC machines are based on the forecast of future production requirements, these functionalities may be useless in the future due to the failure of the forecast, which may cause unnecessary capital wastes. Secondly, although a flexible CNC machines is able to carry out several operations which should be performed on different traditional dedicated machines, it is only able to process one operation at a time, which makes the throughput of FMS to be very low.

2.3.3.2 The Reconfigurable Manufacturing System (RMS)

Since the end of last century, a new class of manufacturing system—RMS has been proposed, which is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements (Koren et al. 1999). The aim of RMS is to balance the productivity and flexibility of manufacturing systems rather than focus only on fixed productivity (i.e., mass production system) or fixed flexibility (i.e., FMS). In doing so, there are two critical design issues in RMS including the Reconfigurable Manufacturing Tools (RMTs) and the layout design of RMS. The details of these two issues are provided in the following.

Reconfigurable Manufacturing Tools (RMTs)

RMTs are the main components of RMS, representing a new kind of CNC machines designed with modular architectures to facilitate the adjustment of machines' functionalities and structures and the integration of new functionalities to existing machines such as adding a new spindle unit (Koren et al. 1999). Similar to flexible CNC machines, a RMT also has some degree of flexibility in terms of functionality. Also, the CNC technology enables the automation of RMTs to be programmable so that RMTs are able to easily and quickly perform user-defined activities. In this regard, similar to the FMS, the RMS is also able to accommodate the production of different product types on the same system/sub-system and in turn is flexible and scalable to meet changes in demands fluctuations of existing product mix. However, unlike the flexible CNC machines built based on a general purpose to involve all possible functionalities for meeting both current and forecasted production requirements, at the beginning of RMTs' design, functionalities on RMTs are only determined on the basis of current product types and customer demands so as to find a balance point between productivity and flexibility under current scenario. In addition, the modular design architectures of RMTs enable them to easily and quickly integrate new functionalities in response to market changes incurred in the future. As a result, compared to flexible CNC machines, RMTs perform more cost-efficiently and dynamically in dealing with unexpected changes in the business environment.

Layout Design of RMS

RMS is a production system designed to produce a variety of products. As aforementioned above, a RMT is similar to a flexible CNC machine which is able to provide several functionalities. This may result in a low throughput of RMS because operations which can be processed concurrently in a traditional manufacturing system may need to be processed in sequence on a RMT. In order to avoid this drawback, a new class of layout design is proposed in RMS, which follows some of underlying principles of the group or cellular layout of manufacturing systems. Conventionally, the group layout consists of two design steps. At the first step, a variety of products is classified into different product families by using Group Technology (Suresh and Kay 1998) such as the classification and coding techniques (Ham et al. 1985) and the production flow analysis (PFA) (Burbidge 1991) which are based on the similarities of operational requirements and process routings respectively. At the second step, resources of manufacturing systems are grouped and arranged into distinguished manufacturing cells each of which is responsible for producing a fixed product family.

The layout design of RMS shares the first design step of the classical group layout, i.e., the variety of products of RMS is also grouped into different product families by using classical grouping techniques. However, unlike the manufacturing systems based on classical group layout in which different manufacturing cells are built with different manufacturing resources to produce different product families, RMS integrates the production of different product families on the same system (e.g., a manufacturing cell). As for a specific product family, a configuration is assigned to this family, which represents the specific arrangement of RMTs, allocations of workers and tooling of RMTs. When producing a particular product family, the system is structured according to the specific configuration assigned to the family. In other words, RMS is operated by changing the configurations for product families, i.e., using specific configuration to produce corresponding part family. In RMS, such an integrated and reconfigurable layout is supported by the modular architectures of RMTs which facilitate the adjustment of machines' functionalities and structures.

Two important stages are involved in the layout design of RMS including the determination of optimal configurations for product families and the optimal selection policy in the utilisation (Xiaobo et al. 2000a). The optimal configuration determines the optimal arrangement of RMTs, allocations of workers and tooling of RMTs for a specific product family, whereas the optimal selection policy determines the optimal sequence to produce different product families such that the overall reconfiguration cost[3] of RMS can be minimised. The reason for the later issue is that: since different product families of RMS are produced on shared resources on the same system, the production of different product families should be performed sequentially, whilst not concurrently. When switching to another product family, the RMS has to change the details on the shop floor (e.g., rearrangement and retooling of machines and reallocation of workers) based on the optimal configuration of this product family, which leads to a reconfiguration cost for RMS including the cost of rearranging equipments, cost of retooling machines etc. Usually, the optimal sequence is a cyclical production sequence around the existing product families. The cyclical production sequence means when a RMS accomplishes the production of one product family, it then reconfigures the workshop and manufactures the next product family according to the determined sequence; however, if the accomplished product family is the last one in the sequence, then the subsequent production will be concerned with the first product family in the sequence (Galan et al. 2007). In theory, the designs of optimal configurations and optimal selection policy are interdependent with each other, which should be determined simultaneously. However, since both of designs are complicated, current literature studies of RMS consider them separately. For example, Xiaobo et al. (2000a; 2000b; 2001) propose a stochastic model for design of RMS where the existing products of RMS have already been classified into different product families and customer orders belonging to different product families follow a random stream of a Poisson distribution. At the beginning of the design, the optimal configurations for product families are determined by considering an estimated selection policy based on a long-term forecast of the average market condition. The optimal selection policy is then determined on the basis of the previously obtained optimal configurations for product families.

At the system design level, RMS has two major advantages for manufacturing systems to deal with unexpected changes in the business environment. Firstly, RMTs allow for the convenient adjustment of machines' functionalities and structures in response to different

[3] Shifting to another product family leads to a system reconfiguration in order to satisfy the distinguished process routings and operational requirements, which in turn results in a reconfiguration cost.

production requirements. Also, the modular architectures of RMTs facilitate the easy integration of new functionalities on existing machines to meet unexpected environmental changes as needed and when needed. Secondly, the integrated and reconfigurable layout of RMS does not only balance the productivity and flexibility of manufacturing systems, but also reduces the amount of manufacturing resources and the complexity of system structure, which reduces the lead time for launching new systems and reconfiguring existing systems and in turn enables manufacturing systems to acquire benefits through capturing emerging market opportunities resulting from the changes in the business environment. However, there is a serious problem associated with the approach of RMS to dealing with changes in the business environment which is also shared by the approach of FMS. Although the approach of RMS improves the flexibility of manufacturing systems through the introduction of advanced machines with built-in flexibility, it does provide effective methodologies to assist manufacturing systems in flexibly and responsively organising and utilising existing manufacturing resources to meet unexpected changes in the business environment. Moreover, the use of RMTs will correspondingly lead to the necessities of building of new material handling systems, design of new system architectures, building of new communication networks etc., which requires a large amount of capital investment and enormous timing efforts. As a result, the way of RMS is not realistic and economical for manufacturing organisations with existing manufacturing resources to use.

2.4 Discussions

The current manufacturing approaches intend to improve the manufacturing flexibility and responsiveness at operational level, layout design level and system design level so as to facilitate manufacturing systems in dealing with continuous and unexpected changes in the business environment.

The approaches at system design level consist of FMS and RMS both of which aim at designing flexible or/and reconfigurable machines to enable manufacturing systems to deal with continuous and unexpected changes in the business environment. In addition, the proposed layout design of RMS is able to integrate the production of different product families on the same system, which reduces the complexity of manufacturing system structure and in turn allows for quick launching of new systems and reconfiguring existing systems. However, as discussed previously, both of the approaches require a large amount of capital investment on building of newly defined machines and further investment on building material handling system, design of system architecture and communication network etc., which is not realistic and economical for manufacturing organisations with existing manufacturing resources. Furthermore, since these two approaches only focus on the flexibility at machine level, they do not provide methods for manufacturing systems to flexibly and responsively organise and utilise existing manufacturing resources to meet changes in the business environment.

The approaches at operational level aim at achieving flexible resource utilisation based on the integration of process planning and production scheduling so as to deal with changes in the business environment. As for the approaches of NLPP and CLPP, the operational flexibility is achieved through the generation of alternative process plans and the dynamic evaluation of production scheduling. However, from the literature review of NLPP and CLPP, it can be found that although these two approaches are theoretically able to optimise the resource utilisation and provide operational flexibility to changes in the business environment, it is unrealistic to consider all of possible process plans in the real situations. This limits these two approaches' optimality to resource utilisation and more importantly, flexibility to changes in the business environment. Unlike the former two approaches, DTPP performs the operations of process planning and production scheduling simultaneously in order to dynamically generate flexible operational decisions based on the dynamic information in the business environment. This approach is able to provide very high operational flexibility for manufacturing systems to deal with changes in the business environment. However, from the literature review of DTPP, it is indicated that this approach is unable to optimise the resource utilisation of manufacturing systems. In this regard, it is imperative to develop an effective approach to integrating process planning and production scheduling so that manufacturing systems are able to dynamically generate operational decisions which can optimise the resource utilisation and simultaneously deal with changes in the business environment.

At the layout design level, the approaches of dynamic layout and robust layout add the information of possible market changes in the layout design so that the layout of manufacturing system is either adjusted in response to market changes or always feasible for changed market environment. However, it is argued that since both of the approaches must be based on the availability of production data over a long-term period in the future, they are unrealistic in real manufacturing environment, in particular in today's manufacturing environment. The layout adjustment provided by dynamic layout is based on a static plan determined at the early stage of a long-term planning period, which may not enable system layout to be adjusted with the right decision at the right time due to the unexpected changes in the business environment; whereas the way of robust layout to deal with changes in the business environment cannot enable manufacturing systems to achieve the optimal performance and efficiency. Meanwhile, in terms of using structural flexibility or robustness to deal with changes in the business environment, these two approaches only consider the system structure at the bottom level, whilst cannot address the overall system structure of manufacturing systems. Compared to the approaches of dynamic layout and robust layout, the reconfigurable layout uses a dynamic approach in which the system layout of manufacturing systems is proposed to be adjusted dynamically in order to deal with unexpected changes in the business environment. However, similar to the approaches of dynamic layout and robust layout, the approach of reconfigurable layout also considers the system structure at the bottom level only. Moreover, the literature review on reconfigurable layout indicates that current related work only focuses on how to design system layout based on current or near future market conditions, while does not provide effective methodologies to answer how the system structure can be dynamically reconfigured at the appropriate time with the appropriate decision in response to changes in the business environment. Inspired from the approach of reconfigurable layout, it is essential to develop a dynamic restructure approach which enables a manufacturing system to dynamically restructure the overall system structure in response to dynamic changes in the business environment. It should be noted that the meaning of the word "*dynamic*" consists of two levels: firstly, this approach must be able to find the most appropriate time for system restructure; secondly, this approach has to be able to determine the optimal option for system restructure.

Based on the above discussion, it is indicated that the most appropriate way for current manufacturing systems to deal with changes in the business environment is to flexibly organise and utilise existing manufacturing resources. From this point of view, manufacturing systems have to enhance their flexibility at operational level and structural level so as to cope with changes in the business environment. However, solely focusing on a single level may not provide sufficient flexibility and responsiveness for manufacturing systems to deal with dynamic changes in the business environment. For example, the operational flexibility of manufacturing systems may be restricted by the existing system structures. As for a manufacturing system, when the existing structure cannot accommodate market changes, it is essential for this manufacturing system to adapt the system structure to the market changes. On the other hand, the system restructure enables a manufacturing system to accommodate the average changes in marketplace over a certain period and however dynamic market changes incurred within this period have to be dealt with by flexible decisions at operational level. As a result, it is imperative for current manufacturing systems to consider the flexibilities at operational level and structural level concurrently. In doing so, there must be an integrated approach which is able to provide manufacturing systems with the capability to optimally achieve flexible utilisations of manufacturing resources within the existing system structures to fulfil the dynamically changed customer requirements and simultaneously restructure manufacturing systems dynamically at the right time with the right decisions when the market changes cannot be accommodated within the existing system structures.

2.5 Summary

This chapter started from the discussion of changes in the business environment faced by today's manufacturing systems. It was indicated that in order to survive in the turbulent business environment, manufacturing systems must perform production cost-efficiently so as to compete against their rivals in the niche market and also must be flexible and responsive to changes in the business environment. This chapter then reviewed the existing manufacturing system approaches to dealing with changes in the business environment. Based on the specific capability they focus on, these approaches were categorized into three levels including operational level, layout design level and system design level. It was argued that although the approaches at system design level are able to deal with changes in the business environment through built-in flexibility of advanced machines, such approaches require highly expensive manufacturing systems to be designed and built from the beginning, which is not realistic and cost-efficient. The approaches at operational level are unable to address the optimisation issues with respect to production cost, delivery performance and utilisation of manufacturing resources. The approaches at layout design level only focus on the layout design issue at the bottom level of system structure, and cannot address the overall structure of manufacturing systems and ignore the restructure issue of manufacturing system. As a result, in order to help manufacturing systems to flexibly organise and utilise manufacturing resources to deal with changes in the business environment, an integrated approach is needed, which simultaneously enhances the flexibility and responsiveness of manufacturing systems at the operational level and system restructure level.

CHAPTER 3

MODELING AND CONTROL OF MANUFACTURING SYSTEMS

3.1 Introduction

This chapter provides a literature review about the existing modeling and control architectures for manufacturing systems, aiming at finding whether these architectures are able to support the integrated approach discussed in the last chapter. The rest of this chapter is organised into four sections. Section 3.2 discusses the requirements of an integrated decision platform and identifies four requirements to provide such an integrated decision platform. Section 3.3 reviews the existing modeling and control architectures for manufacturing systems. Section 3.4 discusses these architectures in the light of the identified requirements for providing the integrated decision platform. Section 3.5 is a summary section.

3.2 The Requirements of an Integrated Decision Platform

As discussed in the last chapter, today's manufacturing systems need an integrated approach to considering operational decisions with system restructure together so that manufacturing systems are able to cost-efficiently and flexibly plan and control system productions to fulfill the dynamic requirements of customer orders and meanwhile, simultaneously consider the system restructure to meet dynamic changes in the business environment. In this context, to provide such an integrated approach, an integrated decision platform is required, whereby the operational decisions can be considered concurrently with system restructure. Meanwhile, in order to provide such an integrated decision platform there are four requirements which have to be met simultaneously. Firstly, this platform requires a modeling architecture which is able to represent the hierarchies of manufacturing systems. This is because in real situations manufacturing systems are always complex systems consisting of several hierarchical layers in their organisation networks. Secondly, as the integrated approach considers system restructure which may cause frequent changes in the physical environment of manufacturing systems, the required modelling architecture of this platform must enable decision-making models of manufacturing systems to be easily and rapidly modified in response to these changes. Thirdly, this platform requires a planning and scheduling mechanism enabling customer orders to be planned and scheduled cost-efficiently to meet the time and quantity requirements within the constraints of current structures of manufacturing systems so as to reap the benefits derived from the current system structures such as low material handling costs. Nevertheless, when needed, this mechanism is able to support resource regroupings across system boundaries by relaxing the constraints of system structures. Finally, this platform requires a dynamic restructure mechanism enabling system structures of manufacturing systems to be continuously evaluated and dynamically reconfigured at appropriate time with appropriate decisions so as to deal with dynamic changes in the businesses environment.

3.3 Modeling and Control of Manufacturing Systems

In the literature, there are four major modelling and control architectures for manufacturing systems including centralized, hierarchical, heterarchical and hybrid control architectures. These four architectures and their related work are reviewed respectively in the following.

3.3.1 Centralized Control Architecture

In centralised control architecture, there is a central controller responsible for all of operational functions (e.g., production planning, process planning and production scheduling) and information processing of manufacturing systems. This controller makes control decisions based on a global decision-making model which is designed on the basis of the global information and purposes of manufacturing systems. Due to the access to global information and purposes in decision-making, centralized control architecture offers several advantages such as global optimisation, predictability and robustness (Dilts 1991). However, there are also several disadvantages of centralized control architecture including: Firstly, since all of control decisions are concentrated on a single controller, it may cause enormous efforts on the controller design since a large number of interrelationships between resources with respect to possible failures need to be programmed in order to generate a fault-tolerant control system. Secondly, centralized control leads to structure rigidity of decision-making models. Every slight change in manufacturing system causes the re-building of the entire model, which results in the difficulty of model modification when the physical environment of manufacturing system is changed. Thirdly, since the decision-making models of centralized control architecture are rigidly designed based on static information of manufacturing systems, control decisions in centralized control architecture cannot consider the dynamic information on the shop floor. As a result, centralized control architecture is not flexible and responsive to changes in the business environment.

3.3.2 Hierarchical Control Architecture

In hierarchical control architecture, a control system is composed of a set of controllers connected together in a hierarchical manner. These controllers are responsible for different operational functions of manufacturing systems. According to their functionalities, they are positioned at different hierarchical layers of the control system and the relationships amongst controllers are formed as the master-slave/subordinate relationships. For example, Jones and McLean (1986) and Jackson and Jones (1987) present a five-layer hierarchical control architecture for planning and control of a factory. The control modules from the top hierarchical layer to the bottom hierarchical layer are respectively facility module, shop module, cell module, workstation module and equipment module. The facility module controls production planning in a long planning period. The shop module is responsible for a relatively short-term production planning and process planning. Production scheduling is undertaken by the cell control module. The workstation and equipment modules mainly take charge of production control on the shop floor.

In hierarchical control architecture, although different operational functions are controlled by different controllers, control decisions with respect to one function is still centrally generated by a single controller. These control decisions are then rigidly followed by the subordinates of the controller to make control decisions for anther operational function or to be executed as commands on the shop floor. In other words, control decisions in hierarchical control architecture are centrally generated by higher-level controllers for their lower-level subordinates and flow top-down from the top hierarchy to the bottom hierarchy.

Since hierarchical control architecture still uses the centralized scheme in decision-making, it shares the major advantages of centralized control architecture such as global optimisation, predictability and robustness. However, compared to centralized control architecture, as all control decisions are no longer concentrated on a single controller, the design complexity of a single controller in hierarchical control architecture is reduced. Nevertheless, due to the implementation of centralized decision-making, hierarchical control architecture still extends the major drawbacks of centralized control architecture such as difficulty with controller design, structure rigidity of decision-making models and lack of flexibility in decision-making.

3.3.3 Heterarchical Control Architecture

In heterarchical control architecture, a manufacturing system is represented as a collection of manufacturing resources each of which is controlled by an individual controller. There is no hierarchy and centralized decision-makings in heterarchical control architecture. Every manufacturing resource is given a full autonomy to make local decisions based on its local information and objectives. The global control decisions are achieved based on the communication and cooperation amongst different manufacturing resources considering their local decisions.

Since there is no hierarchy, heterarchical control architecture is only able to model single-layer systems (e.g., shop floor). In the literature, the application of heterarchical control architecture is always based on the use of agent-based technology whereby manufacturing resources are represented as resource agents. The communication between different resource agents is achieved by using bidding mechanisms such as Contract Net Protocol (CNP) (Smith 1980). For example, Lin and Solberg (1992) present an agent-based heterarchical control architecture for distributed resource allocation in a shop floor. In their work, apart from resource agents, production tasks are also represented as agents which are termed as part agents. The shop floor is represented as a marketplace where a part agent acts exactly like a customer carrying specific “currency” and bargains with resource agents to find the lowest price. When a production task occurs in the shop floor, a part agent is created and given a specific “currency”, which then passes the task requirements and “currency” limitation to every resource agent. As for one resource agent, it proposes a production cost for the task based on the local status of the manufacturing resource represented. When the production cost is within the “currency” limitation, the resource agent bids for the production task. The part agent selects the resource agent with lowest production cost to undertake the production task. Gu et al. (1997) also propose an agent-based heterarchical control architecture for the resource allocation in a shop floor. In their work, there is a shop floor manager responsible for broadcasting technical and time requirements of specific product orders. Coordination amongst resource agents is also achieved by using CNP. Macchiaroli and Riemma (2002) present a similar control architecture to the one of Lin and Solberg (1992). However, a re-negotiation process is added in their work so as to achieve a negotiation convergence if agreements cannot be met between part agent and resource agents at the first time.

In heterarchical control architecture, the global control decisions are based on the self-organisation of manufacturing resources considering their local information, which are flexible and responsive to changes in the business environment. Meanwhile, due to the distributed decision-making, heterarchical decision-making models are fault-tolerant to changes in manufacturing systems and in turn can be easily modified according these changes. For example, when a manufacturing resource is unavailable to undertake a production task, the representative agent will not take part in bidding and however the decision-making is still able to carry on amongst agents of the rest of manufacturing resources. Nevertheless, heterarchical control architecture is unable to represent complex hierarchical structures of manufacturing systems. Furthermore, as control decisions of heterarchical control architecture only attempt to satisfy local objectives of manufacturing resources without considering global objectives of the entire system, heterarchical control architecture may not be able to optimise and maintain global performances of manufacturing systems.

3.3.4 Hybrid Control Architecture

From the above description of hierarchical and heterarchical control architectures, it is indicated that these two architectures have mutually supplementary features to each other. For example, the hierarchical control architecture is able to represent the hierarchical structures of manufacturing systems and result in optimal control decisions, but leads to structure rigidity of decision-making models. On the other hand, the heterarchical control architecture provides fault-tolerant and easily modified decision-making models, however cannot represent the hierarchies of manufacturing systems and provide optimal decision-making. In this regard, the hybrid control architecture represents a new class of architecture that aims at capturing the positive features of both hierarchical and heterarchical control architectures.

In the literature, one of the simple approaches to hybrid control architecture is to involve a supervisory controller in heterarchical control architecture so as to provide a level of control over the operations of a set of heterarchical resources. Such a supervisory controller is responsible for managing the negotiation amongst the heterarchical resources, supervising the global performance of control decisions resulting from the negotiation, and/or providing some of initial decisions (e.g., process planning) by using centralized decision-making that will be inputted to individual controllers of the heterarchical resources for generating coordinated decisions (e.g., production scheduling). For example, Butler and Ohtsubo (1992) propose a hybrid control architecture for dynamic scheduling by using agent-based technology. Two kinds of agents are involved, including site agent and resource agent. Each resource agent represents a work cell of a manufacturing system. A site agent involves several connected sub-site agents or resource agents, and is responsible for allocating production tasks to its sub-agents. Ou-Yang and Lin (1998) develop a hybrid control architecture wherein two levels of controllers are involved, namely shop floor controller and cell controller. The shop floor controller takes charge of releasing production jobs to cell controllers, managing the negotiation amongst cell controllers, selecting appropriate cells for specific production jobs according to coordination results and global objectives. The cell controllers manage manufacturing cells of a manufacturing system, which bid for jobs released from the shop floor controller. Wong et al. (2006) present an agent-based hybrid control architecture for integrated process planning and scheduling in flexible manufacturing cells. This control architecture consists of two basic agents on the shop floor including part agents and resources agents, and a supervisory agent on the cell level. When a customer order is received, a part agent is created and given the specific order information such as quantity and time, as well as a set of process plans. The part agent then releases individual jobs specified by a chosen process plan and negotiates the jobs' scheduling with resource agents. The supervisory agent is responsible for managing the negotiation between part agents and resource agents and also selecting the best process plan based on global objectives such as minimising jobs' make spans, minimising jobs' tardiness, and/or balancing machines' loading etc.

The aforementioned approach to hybrid control architecture is easy to understand and implement. Although the presence of the supervisory controller enhances the global performances of heterarchical control systems, the major drawback of such hybrid control architecture is that it is still only able to model manufacturing systems with very simple structures. Recently, three alternative approaches to hybrid control architecture have attracted many scholars' attentions, which attempt to model a manufacturing system hierarchically and allow for the combination of hierarchical and heterarchical operations. These approaches consist of Holonic Manufacturing System (HMS), Fractal Manufacturing System (FrMS) and Bionic Manufacturing System (BMS). In the following, the three approaches are introduced respectively.

3.3.4.1 Holonic Manufacturing System (HMS)

In HMS, a manufacturing system is represented as a hierarchy of holons which represent autonomous and co-operative building blocks of manufacturing systems for transforming, transporting, storing and/or validating information and physical objects (Van Brussel et al. 1998). A holon may contain a hierarchy of children holons and meanwhile could be one of parts of another holon. In this regard, a HMS somehow can be viewed as a big holon which represents the entire manufacturing system. The hierarchy of HMS is formed through two stages including the aggregation and the specialization (Van Brussel et al. 1998; Giret and Botti 2004). In the aggregation stage, related holons are clustered together to construct upper-level holons. For example, several holons representing equipments on the shop floor are grouped to form a workstation holon which is in turn used to form a shop holon with other workstation holons. In the specialization stage, holons are differentiated from each other according to their characteristics and functionalities. For example, Shop holons can be classified as milling shop holons, grinding shop holons, assembly shop holons etc.

There are three kinds of basic holons in HMS including resource holon, product holon and order holon. A resource holon represents a manufacturing resource in a manufacturing system, which contains a physical part representing the physical object of the manufacturing resource and an information processing part responsible for controlling the manufacturing resource. A product holon holds and manages up-to-date processing and product information for a specific product, which acts as an information server to other kinds of holons. An order holon represents a customer order and is responsible for finding and grouping appropriate resources to produce this order. Apart from the basic holons, HMS also contains a kind of functional holons which are used to provide a level of centralized controls for HMS so as to assist basic holons in performing their work and maintain the global performance of the entire system. In the literature, the functional holon is mainly referred to as the staff holon in Product-Resource-Order-Staff reference architecture (PROSA) (Van Brussel et al. 1998) or the supervisory holon in Adaptive Holonic Control Architecture (ADACOR) (Leitao et al. 2005; Leitao and Restivo 2006).

In the literature of HMS, production scheduling on the shop floor is derived from the negotiation between order holons and resource holons which is always achieved by using CNP mechanisms. Functional holons are always responsible for generating higher-level control decisions such as process plans, providing advisory scheduling solutions for basic holons, or supervising and optimising coordinated results of basic holons. For example, Sousa and Ramos (1999) propose a holonic control architecture based on PROSA. When a production task is launched, an order holon with respect to the production task is created, which will contact a process planning holon (i.e., a functional holon) to obtain a process plan for this task. The order holon then releases individual operations of this task according to the process plan and negotiates with technically available resource holons by using CNP. The scheduling decision of each resource holon is determined by using a forward and backward influence method. When scheduling decisions for all of operations are received, the order holon then uses a heuristic rule to select the appropriate resource for each operation. Babiceanu et al. (2004) develop a holonic control architecture for a material-handling system. When a customer order is received, an order holon for this customer order is created, which recognises the product type required by the customer order and retrieves the process plan from a product holon related to the product type. According to the process plan, the order holon then announces individual jobs for resource holons and negotiates with them based on a CNP mechanism to find a coordinated scheduling decision. This decision may not be optimum, whereas it can be quickly obtained due to the low complexity of distributed problem solving. At the same time, the order holon also forwards the process plan to a global scheduler (i.e., a functional holon) which is able to find a globally optimised scheduling decision for the customer order. However, since the global scheduler is a centralized decision-maker, it may need a longer time to determine the optimum scheduling decision than using the coordination between basic holons. However, if the global scheduler is able to generate a scheduling decision within the lifetime of the order holon, this decision is then confirmed as the final one to be executed on the shop floor. Gou et al. (1998) present a holonic control architecture for production scheduling in a factory consisting of several cells. In their work, every product of the factory contains several sequenced production tasks each of which represents a part produced by a specific manufacturing cell. When receiving a customer order with respect to a specific product, the production schedule for the order is derived through two stages of coordination. In the first stage, every cell holon negotiates with its internal resource holons to find a coordinated scheduling solution for the part assigned to the cell. For every cell, there is a cell coordinator (i.e., a functional holon) which is able to adjust a price-based parameter to launch an iterative coordination so as to find the optimum schedule for a part. In the second stage, the factory holon negotiates with cell holons to determine the overall production schedule for the entire product. Similar to the supervised coordination at cell level, a factory coordinator is designed in the second stage to manage an iterative coordination between cells so that the production schedule for the entire product can be optimised. The similar scheme to Gou et al. (1998) is also presented in Babiceanu and Chen (2007) and Leitao and Restivo (2008).

HMS is able to represent the hierarchies of manufacturing systems. Moreover, due to the distributed nature of holons, holonic models of manufacturing systems can be easily and rapidly modified so as to meet changes in the physical environment of manufacturing systems. Meanwhile, the concurrent presence of basic holons and functional holons in HMS allows for the combination of heterarchical and hierarchical controls, which in turn enables HMS to be able to generate robust and agile control decisions. However, from the related work of HMS, current studies are only able to provide coordinated mechanisms for supporting the distributed scheduling at bottom level of manufacturing systems (e.g., a manufacturing cell), but cannot provide a mechanism for supporting the optimised and coordinated resource regroupings across system boundaries. Furthermore, the application of HMS only focuses on production planning and scheduling of manufacturing systems and however, does not consider system restructure of manufacturing systems. In other words, there are also not mechanisms in HMS to support the system restructure of manufacturing systems.

3.3.4.2 Fractal Manufacturing System (FrMS)

The Fractal Manufacturing System (FrMS) originates from the concept of fractal factory introduced by Warnecke (1993), in which a manufacturing system is represented as a hierarchy of autonomous units—fractals. In FrMS, a fractal models a manufacturing resource of a manufacturing system, which has individual goals and is able to communicate with another fractal to achieve its goals. Similar to holons, a fractal is able to involve a hierarchy of children fractals and meanwhile can be a part of another fractal. In this context, a FrMS can be also regarded as a big fractal with global goals and purposes. There are four basic characteristics for fractals including self-similarity, self-organisation, goal-orientation and dynamics (Ryu and Jung 2003). The self-similarity means fractals have similar functional structures, similar manners in performing jobs, and similar attributes to formulate and achieve goals. The self-organisation of fractals is related to a theoretical method and an operational method of FrMS. The theoretical method means the application of suitable methods to optimising the performance of fractals. The operational method is referred to as the dynamic restructuring process, which supports the reconfiguration of network connections between fractals so that FrMS can be optimised and adapted to dynamic changes in the business environment. The goal-orientation means a fractal makes control decisions and performs actions based on its individual goals. The dynamics denotes that a fractal has an ability to dynamically adapt to changes in its local environment. The adaptation may be achieved by dynamically changing the composition of fractals or adjustment of goals.

Since FrMS is a relatively new concept, early studies regarding FrMS mainly focus on the investigation on how to provide the basic characteristics of fractals. For example, Ryu and Jung (2003) and Ryu et al. (2003) propose a function-based fractal architecture by using agent-based technology so as to provide self-similarity of fractals. In their work, a fractal contains five functional modules including an observer, a resolver, an analyzer, an organiser and a reporter. The observer is responsible for monitoring the state, status and local environment of the owner fractal and also responsible for communication between the owner fractal and other fractals. The resolver manages the key functions of fractals including task generations, goal-formations and decision-makings. The analyzer has the ability to evaluate alternative decisions by simultaneously considering the actual status of the owner fractal and global goals of the entire system. The evaluation is achieved by using real-time simulation, which generates a rated solution that will be given to the resolver as a feedback. The organiser manages the fractal status and performs self-organisation and self-optimisation through coordination with other fractals in order to balance the productivity of the system. The reporter is responsible for collecting performance results of the owner fractal and reporting these results to other fractals. Ryu and Jung (2004), Shin et al. (2006) and Cha et al. (2007) respectively investigate the goal-generating process, the goal-harmonizing process and the goal-balancing process in FrMS which work together to provide a fractal control system with the ability to dynamically adjust global goals of the entire system and individual goals of fractals in response to changes in the business environment. As for a fractal control system, when a change in the business environment is detected, the fractal representing the entire manufacturing system firstly adapts global goals to this change. Then, according to the newly formed global goals, individual goals of every fractal will be re-formed based on a goal-generating process. The goal-harmonizing process is to detect and eliminate possible conflicts between goals of different fractals, which is based on the cooperation between different fractals. The goal-balancing process refines goals of fractals in order to enhance the global performance of the entire system. Ryu et al. (2006) investigate the dynamic restructuring process (i.e., self-organization) of fractals. In their work, every fractal has a functional agent which is responsible for periodically evaluating the performance of the fractal. When this agent considers that the fractal has to be restructured so as to improve the fractal's performance, a restructuring process is started including creating new structures for the fractal, evaluating the newly generated structures by simulation, selecting the best structure based on the evaluation, reconfiguring the fractal based on the selected structure, and re-forming goals of the fractal. However, Ryu et al. (2006) only propose a conceptual framework for the dynamic restructuring process of fractals, but do not provide detailed mechanisms such as how the functional agent evaluates the performances of fractals and how new structures of fractals are generated and evaluated etc.

Recently, Shin et al. (2009[a]; 2009[b]) use the fractal concept in production planning and scheduling of manufacturing systems and present a Relation-driven Fractal Manufacturing System—r-FrMS. In r-FrMS, manufacturing resources (e.g., machines, cells and factory) are represented as Autonomous and Intelligent Resource (AIR) units which can be viewed as fractals. When a customer order is received, the AIR unit at the top-level is given the processing and product information about the customer order. According to the information, the AIR unit at the top-level acts as an employer announcing production jobs for different parts to its employees (i.e., the AIR units at the next level). The negotiation between an employer and its employees is based on a CNP mechanism. As for an employee AIR unit, in order to bid for a production job released from its employer, it in turn becomes an employer as well and releases the sub-jobs of this production job to its own employees. This process is hierarchically carried out from the AIR unit at the top level to the AIR units at the bottom level. However, decisions are generated from the bottom level firstly and passed and integrated gradually to the top level.

FrMS is able to represent the hierarchies of manufacturing systems. The distributed nature and self-similarity of fractals enable fractal models of manufacturing systems to be easily modified in response to changes in the physical environment of manufacturing systems such as addition or removal of manufacturing resources. Moreover, the dynamics of fractals enables fractals to be able to dynamically adapt their goals and structures to the changing business environment, which provides potentials to support the dynamic restructure of manufacturing systems. However, current literature of FrMS only provides a conceptual framework for the dynamic restructure of fractals, but does not provide systematic and implementable mechanisms for this issue. In other words, there is not a mechanism in

FrMS to support the dynamic restructure of manufacturing systems. Furthermore, although the only one study concerned with planning and scheduling in FrMS provides a promising approach enabling manufacturing resources to be self-organised hierarchically to fulfill customer orders, this approach cannot optimise the resource allocation due to lack of optimisation method. Meanwhile, it does not support resource regroupings across system boundaries.

3.3.4.3 Bionic Manufacturing System (BMS)

The paradigm of Bionic Manufacturing System (BMS) is inspired from the biological systems (e.g., cells, organs, organisms and etc.) which contain a hierarchy of independent biological components with three basic characteristics including harmony, spontaneity and versatility (Okino 1989; 1992). The harmony means that although biological components are independent and autonomous, they are able to cooperate with one another so as to find commonly acceptable decisions. The spontaneity implies that a biological component is intelligent, self-organising, flexible and transformable to environmental changes. The versatility means that a biological component can be used for a wide range of activities.

The BMS represents a modeling and control architecture similar to the architecture of a biological system, whereby a manufacturing system is represented as a hierarchy of modelons (Okino 1989; 1992). Similar to holons and fractals, a modelon may contain a hierarchy of children modelons and could be a part of another modelon. Meanwhile, there are two functional components in a modelon which include an operator and a common memory. The operator takes charge of the communication and cooperation amongst modelons in order to eliminate conflicts between modelons so as to achieve global goals. The common memory exerts a role of communication medium for the operators and children modelons, which uses a similar technique to the blackboard system.

In the literature, there are few of studies concerned with BMS. In this condition, there is not a methodology to illustrate how to use BMS for assisting manufacturing systems in production planning and scheduling, as well as system restructure.

3.4 Discussions

Due to the implementation of centralized decision-making, the centralized and hierarchical control architectures are both able to provide robust and globally optimised control decisions. However, these two architectures lead to structure rigidity of decision-making models which in turn results in a very low responsiveness to changes in physical environment of manufacturing systems. Meanwhile, as decision-making models of centralized and hierarchical control architectures are rigidly designed with the static information of manufacturing systems, these two architectures cannot facilitate the generation of flexible control decisions to cope with changes in the business environment, and in turn cannot support resource regroupings across system boundaries.

On the contrary, in heterarchical control architecture, since control decisions are generated in a distributed manner rather than in a centralized manner, the heterarchical decision-making models are fault-tolerant and can be easily modified according to the changes in manufacturing systems. Moreover, since these decisions are made with consideration of local status of manufacturing resources, they are flexible and responsive to changes in the business environment. However, heterarchical control architecture is only able to model a single-layer system but cannot represent complex hierarchical structures of manufacturing systems. In addition, as heterarchical control decisions only consider the achievement of local objectives however ignore the global objectives, heterarchical control architecture does not support the global optimisation in decision-making.

HMS, FrMS and BMS represent hybrid control architectures which are all able to represent complex hierarchies of manufacturing systems. Since decision-makings in these architectures are mainly achieved in a distributed manner rather than in a centralized manner, decision-making models based on these architectures can be modified easily in response to changes in the physical environment of manufacturing systems. As for HMS, the concurrent presence of basic holons and functional holons allows for the generation of optimal and agile control decisions. However, since process plans in HMS are always centrally generated by functional holons, the agility of control decisions in HMS can only be achieved within the constraints of manufacturing system structure. That is to say, there is not a mechanism in HMS supporting the optimised resource regroupings across system boundaries. In FrMS, although some of literature has provided promising mechanisms enabling manufacturing resources to be self-organised hierarchically, these mechanisms do not support the optimisation of operational decisions and also do not support resource regroupings across system boundaries. Furthermore, in these three hybrid control architectures, there are also not mechanisms enabling manufacturing systems to dynamically reconfigure system structures.

In conclusion, it is indicated that current modeling and control architectures for manufacturing systems cannot simultaneously meet the identified four requirements for providing the integrated decision platform. As a result, a novel modeling and control architecture is needed. However, considering the low responsiveness of centralized and hierarchical control architectures, the novel modeling and control architecture must avoid the centralized control so that the decision-making model based on the architecture is flexible and responsive to changes in the physical environment of manufacturing systems. In other words, the integrated decision platform requires a distributed modeling and control architecture. In addition, in order to provide the integrated decision platform, this architecture needs a planning and scheduling mechanism supporting the optimised and coordinated resource groupings within structural constraints of manufacturing systems and resource regroupings across system boundaries to fulfill dynamic customer orders, and also needs a dynamic restructure mechanism assisting manufacturing systems in finding appropriate restructuring time and in creating new system structures.

3.5 Summary

At the beginning of this chapter, it was argued that to provide the integrated approach discussed in the last chapter, an integrated decision platform is needed and in turn to provide such a platform there are four critical requirements with respect to modelling and control of manufacturing systems. In the light of the four identified requirements, this chapter then went on reviewing the existing modelling and control architectures for manufacturing systems and discussing the advantages and disadvantages of these architectures. However, it was found that there is not a modelling and control architecture that is able to satisfy the four requirements simultaneously. Consequently, this work argued that it is essential to seek a novel modelling and control architecture so as to provide the integrated decision-making platform. In details, this architecture must be able to represent the hierarchies of manufacturing systems but avoid centralized control, must have a mechanism to support the optimal resource allocation within and across system boundaries of manufacturing systems, and also must have a mechanism to support the dynamic restructure of manufacturing systems.

CHAPTER 4

MODELING ARCHITECTURE IN DIMS

4.1 Introduction

This chapter provides an agent-based modelling architecture which supports the modelling requirements for providing the integrated decision platform, namely modelling the hierarchical structures of manufacturing systems and however avoiding centralized control. Three sections are contained in the rest of this chapter. Section 4.2 introduces the concept of the Dynamically Integrated Manufacturing System (DIMS) which is proposed by the Exeter Manufacturing Enterprise Centre (XMEC) for providing the integrated decision platform. Section 4.3 illustrates the modelling architecture in DIMS which is based on the agent-based technology. A summary is provided in section 4.4.

4.2 The Concept of Dynamically Integrated Manufacturing System (DIMS)

In the last chapter, it was discussed that an integrated decision platform is required to simultaneously consider the decisions of production planning and scheduling and system restructure so as to enable manufacturing systems to continuously and dynamically deal with changes in the business environment. However, the last chapter reveals that the existing modelling and control architectures for manufacturing systems are not suitable for providing such an integrated decision platform. A novel modelling and control architecture is needed, which should be able to represent the hierarchies of manufacturing systems and meanwhile avoid centralized control so that system models for decision-making can be easily and rapidly modified as needed and when needed. In addition, this architecture should have a mechanism for supporting the optimised and coordinated planning and scheduling within and across system boundaries according to the dynamic requirements from the marketplace and also provide a dynamic restructure mechanism which can be used to identify the appropriate restructuring time and appropriately create new structures for manufacturing systems.

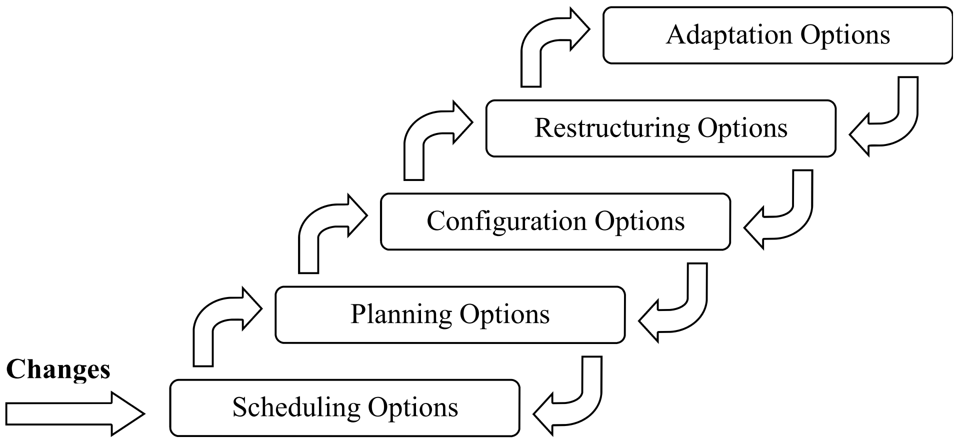

Figure 4.1 the Concept of DIMS

In the light of the above requirements with respect to modelling and control of manufacturing systems, a concept of Dynamically Integrated Manufacturing System (DIMS) is proposed by the Exeter Manufacturing Enterprise Centre (XMEC), which aims at providing a systematic methodology for modelling and control of manufacturing systems so as to facilitate the creation of the integrated decision platform for manufacturing systems and in turn enhance the responsiveness of manufacturing systems to changes in the business environment. In the concept of DIMS, five decision options (figure 4.1) are considered gradually for effectively dealing with changes in the business environment and meanwhile maintaining the minimum disturbance to existing structures of manufacturing systems. The five decision options include scheduling option, planning option, configuration option, restructuring option and adaption option. When changes in the business environment are perceived, alternative production schedules based on current planning and scheduling strategy should be considered firstly to deal with these changes. However, if the current strategy cannot accommodate these changes, alternative process plans should be considered simultaneously with production scheduling. Again, if it is still not possible to deal with these changes, alternative system configurations resulting from relaxing the structural constraints of manufacturing systems should be considered together with the operations of process planning and production scheduling. By this way, manufacturing resources can be regrouped across system boundaries of manufacturing systems to meet changes in the business environment. However, when alternative system configurations are consistently used, it is reflected that current structures of manufacturing systems are no longer suitable for meeting the major trends in the business environment. In this context, it might be imperative to seek alternative system structures (i.e., restructuring options) so that customer orders can be fulfilled as far as possible within the constraints of system structures to avoid extra material handling costs resulting from resource regroupings across system boundaries and improve the overall efficiency of manufacturing systems. The validation of restructuring options and determination of final restructuring decision is referred to as the adaptation option.

4.3 The Modelling Architecture in DIMS

As aforementioned above, the integrated decision platform requires a modelling architecture to be able to represent the hierarchies of manufacturing systems and avoid centralized control. In doing so, an agent-based modelling architecture is proposed in DIMS, which is referred to as Hierarchical Autonomous Agent Network (HAAN). Similar to holons in HMS, agents in this architecture represent building blocks of manufacturing systems for transforming, transporting, storing and/or validating information and physical objects. They are autonomous in decision-making, whereas they coordinate with each other to make global control decisions.

In DIMS, a manufacturing system is modelled as a HAAN through two processes including the physical decomposition of manufacturing system and the agent registration. In the first process, the manufacturing system is decomposed into a hierarchy of manufacturing resources according to the organisational structure of the manufacturing system. In turn, every manufacturing resource and also the entire manufacturing system are modelled as individual agents which are given the crucial information about their physical objects such as hierarchical positions and functionalities. For example, considering a shop floor (S) containing two cells (C1 and C2) each of which involves two machines (C1: M11 and M12, C2: M21 and M22), seven agents are created based on the physical decomposition process including a shop floor agent (SA), two cell agents (CA1 and CA2) and four machine agents (MA11, MA12, MA21 and MA22). In the second process, agents representing manufacturing resources at lower hierarchical layers will automatically register as children in specific agents representing manufacturing resources at higher hierarchical layers according to hierarchical positions of their physical objects. As in the above example, the two cell agents (CA1 and CA2) register in the shop floor agent (SA) as children agents. In a recursive way, the four machine agents will also register as children agents in specific cell agents, such as MA11 and MA12 register in CA1, and MA21 and MA22 register in CA2. In this context, it is indicated that a HAAN formed through the two processes models the hierarchical structure of a manufacturing system with heterarchically operating agents. Moreover, the simple connection between agents based on the registration process enables structures of HAANs to be dynamically changed as agents register with or deregister from their parents.

In manufacturing systems, products are also hierarchically structured entities containing assemblies, components and operations which are manufactured hierarchically. Product orders therefore are also modelled as HAANs in DIMS by using the similar approach to modelling manufacturing systems. Agents in this sense represent the whole product orders and production jobs of components/operations, which are connected together through the registration process in accordance with their hierarchical relationships. In DIMS, when a product order is received, a HAAN of the product order is created, agents among which will negotiate with agents in the HAAN representing a manufacturing system to fulfil the product order (as figure 4.2).

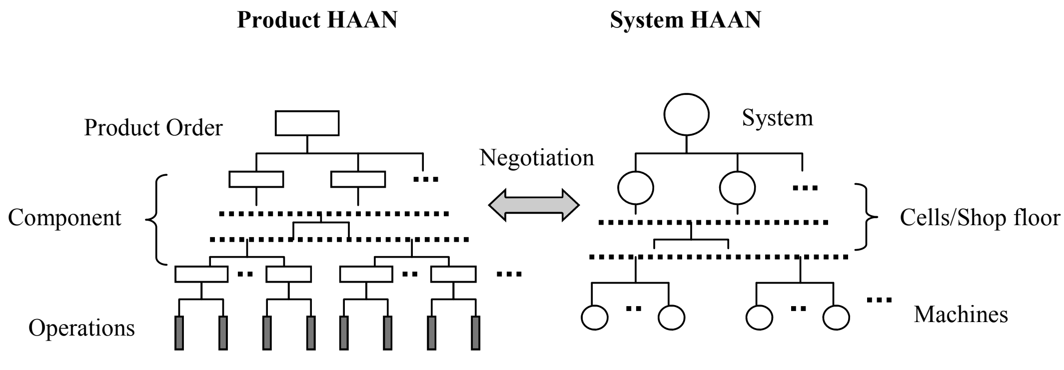

Figure 4.2 the Modeling Architecture of DIMS

4.3.1 Agents in DIMS

As described above, manufacturing systems and product orders in DIMS are modelled as HAANs. Agents contained in the HAAN of a manufacturing system are referred to as resource agents which are responsible for the control and information processing with respect to corresponding manufacturing resources. On the other hand, agents involved in the HAAN of a product order are termed as part agents which consist of the order information and processing information of specific components/operations and also are responsible for fulfilling the production of the components/operations. In DIMS, the resource agent and the part agent are both operational agents which work together to make operational control decisions such as process planning and production scheduling. However, another type of agents—functional agents also exist in DIMS, which are responsible for specific work that cannot be performed by operational agents or responsible for providing strategic control decisions (e.g., system restructure) for manufacturing systems. There are three major functional agents in DIMS including order-handling agent, DIMS interface agent and restructuring agent. The order-handling agent is responsible for receiving orders from customers and dealing with dynamic events with respect to some of orders, such as order cancellation. The DIMS interface agent is an agent particularly developed for DIMS, which provides an interaction interface for the order-handling system and the production system. The restructuring agent[4] is responsible for continuously tracing operational decisions resulting from the interaction between HAANs of manufacturing systems and product orders and in turn providing appropriate reconfiguration recommendation for manufacturing systems.

4.3.2 Agent Architecture in DIMS

In DIMS, every agent is created on the basis of a generic agent architecture which is composed of three parts including a control unit, a common environment and children agents (as figure 4.3). However, as described above, children agents are independent agents. They are involved in the agent architecture only because there are hierarchical relationships between the manufacturing resources represented by these children agents and the

[4] The details about the restructuring agent can be referred from the thesis of Anosike (2005) who is one of the author's colleagues and studied the dynamic restructure mechanism in DIMS project.

manufacturing resource represented by a parent agent. In this context, the followings only focus on the introduction of the control unit and the common environment.

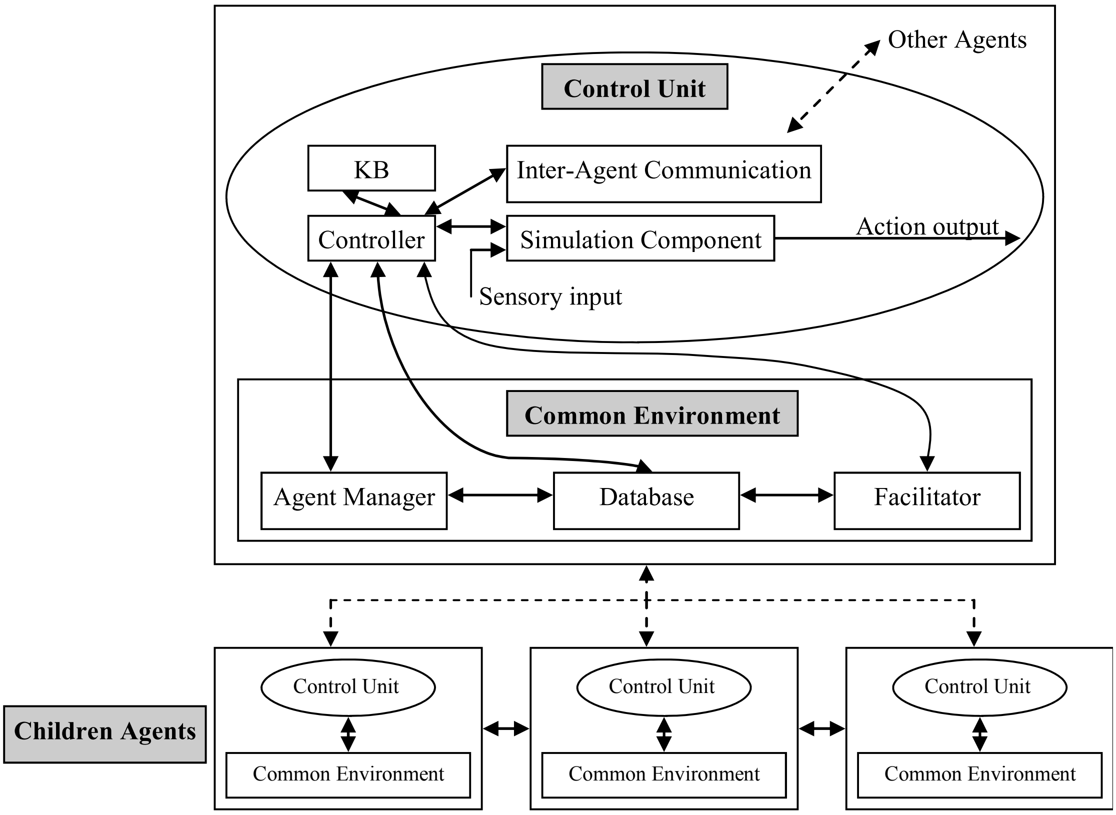

Figure 4.3 the Agent Architecture

4.3.2.1 The Control Unit

The control Unit of an agent contains four key parts including an inter-agent communication device, a knowledge base (KB), a controller and a simulation component.

The inter-agent communication device provides an agent with an ability to communicate with other agents. In DIMS, the agent communication is based on the Knowledge Query Manipulation Language KQML (Finin et al. 1994) due to its simplicity and extensibility. As for an agent, messages received from other agents are stored in a message queue and processed according to the First-In-First-Out (FIFO) rule.

The KB contains three major kinds of knowledge including task knowledge, problem-solving knowledge and cooperative knowledge which are represented as decision rules. In details, the task knowledge specifies tasks and local objectives of an agent. The problem-solving knowledge represents procedures along which an agent attempts to fulfil its tasks. The cooperative knowledge describes the negotiation rules and protocols based on which agents coordinate with each other.

The controller represents a rule-based system which contains agent's inference, reasoning and control mechanisms. In theory, control of a rule-based system can be achieved by using either forward-chaining or backward-chaining method. By the forward-chaining method, rules are used to determine what kind of reasonable behaviours or decisions can be obtained based on given data. However, by the backward-chaining method, rules are used to investigate whether system goals can be satisfied by the assumed behaviours or decisions. In DIMS, the controller uses the forward-chaining method to determine run-time behaviours or decisions of agents according to the knowledge contained in KB, existing data in the database (involved in common environment), and the knowledge extracted from incoming messages.

The simulation component provides an agent with a Petri Net (PN) model representing run-time activities of corresponding manufacturing resource based on the discrete event simulation mechanism. In DIMS, the simulation component of an agent can be dynamically connected with those of other agents to form a distributed simulation system which can be used to evaluate alternative system structures.

4.3.2.2 The Common Environment

The common environment of an agent is composed of three major parts, namely a database, an agent manager and a facilitator.

The database of an agent consists of information with respect to processing capability and dynamic state and status of the corresponding manufacturing resource, as well as the registration information about its children agents. The registration information of a child agent includes the name/identity, capability and physical location of the manufacturing resource associated with the child agent.

The agent manager takes charge of instantiating, initialising, registering/de-registering of children agents and stopping agents. In DIMS, agents are proposed to have the same architecture, which enables agents to be created as copies of agent prototypes with different initialising information. In turn, this facilitates model creations of manufacturing systems and product orders and also model modifications in response to dynamic changes in manufacturing systems such as introduction of new machines. In doing so, there is a prototype-database in the agent manager which consists of a set of agent prototypes (e.g., resource agents with respect to machines or sub-systems) pre-defined by users. When receiving a request from the agent controller to create a new agent, the agent manager selects an appropriate agent prototype from the prototype-database, creates an instance for the new agent as a copy of the prototype, and initialises the instance with particular information. After the new agent is instantiated and initialised, the agent manager will record detailed information about the new agent (e.g., name, capability and physical location) in database so that the new agent becomes a child to the owner agent.

The facilitator provides facilities for the easy communication between a parent agent and children agents. When receiving a request from the agent controller to send a message to children agents, the facilitator automatically checks the addresses of children agents in database and sends copies of the message to children agents. The reply messages from children agents will be firstly sent back to the facilitator which in turn conveys these messages directly to the agent controller rather than to the message queue of the inter-agent communication device.

4.4 Summary

This chapter at the beginning introduced the concept of DIMS and described the five decision options in DIMS which are proposed to be gradually considered so as to deal with changes in the business environment. Then, the major work of this chapter focused on the explanation of the agent-based modelling architecture in DIMS including how agents are used to form HAANs of manufacturing systems and product orders, which kinds of agents are involved in the modelling architecture, and how an individual agent is designed, namely the agent architecture. It was indicated that the HAAN is able to represent the hierarchical structures of manufacturing systems and meanwhile the parent-children relationships between agents enable system models based on HAANs to be dynamically changed as children agents register or deregister. Moreover, the generic agent architecture provides self-similarity to agents, which facilitates the easy creation and modification of system models.

CHAPTER 5

ITERATIVE AGENT BIDDING MECHANISM

5.1 Introduction

This chapter describes an iterative agent bidding mechanism based on Genetic Algorithm (GA) for solving one of the core problems in production planning and scheduling which involves the allocation (in space and time) of a production job containing a sequence of sub-jobs to a pool of resources that might be heterarchically distributed in a given system/sub-system or have sequencing constraints in terms of material handling, so that the entire job can be completed within a given time at the lowest production cost. The importance of this problem is that: the entire problem of production planning and scheduling is a hierarchical planning and scheduling problem due to the complex hierarchies of both product orders and manufacturing systems, whereas at each hierarchical level, a production job, in most cases, needs to be collectively produced by several resources at the same level; therefore, this problem forms the basis of the complex hierarchical planning problem. The rest of this chapter is organised into three sections. Section 5.2 discusses the fundamentality of this problem in production planning and scheduling, formulates the problem mathematically and reviews existing approaches in the literature to resource allocation in a distributed agent-based modelling environment. Section 5.3 is the major part of this chapter, which describes the GA-based iterative agent bidding mechanism including an iterative agent bidding process and a GA optimisation process. Section 5.4 provides a summary of this chapter.

5.2 Problem Identification

As discussed in Chapter 3, in order to provide an integrated decision platform on which decisions of manufacturing systems at both operational level and system restructure level can be considered concurrently, one of the critical issues is to have a mechanism for production planning and scheduling which enables product orders to be cost-efficiently and flexibly planned and scheduled within the structural constraints of manufacturing systems or across system boundaries of manufacturing systems when needed so that orders can be produced before their due dates at the lowest production costs. Basically, products are complex entities each of which consists of a hierarchy of parts. As for a product order, viewing the production jobs of parts[5] respectively from the top level down to the bottom level, the planning and scheduling activity with respect to the entire order in a manufacturing system can be decomposed into a hierarchy of common planning and scheduling activities each of which involves the allocation of a production job containing a set of sub-jobs to a pool of shared resources in a system/sub-system. As for a production job, sub-jobs contained are generally completed according to a specific sequence and planning and scheduling for this production job involves the determination of which sub-job should be performed on which resource at what time. For example, assuming a two-level product order PO and a two-level manufacturing system MS (see detailed hierarchy in *Figure 5.1*), planning and scheduling at the highest hierarchical level considers how to

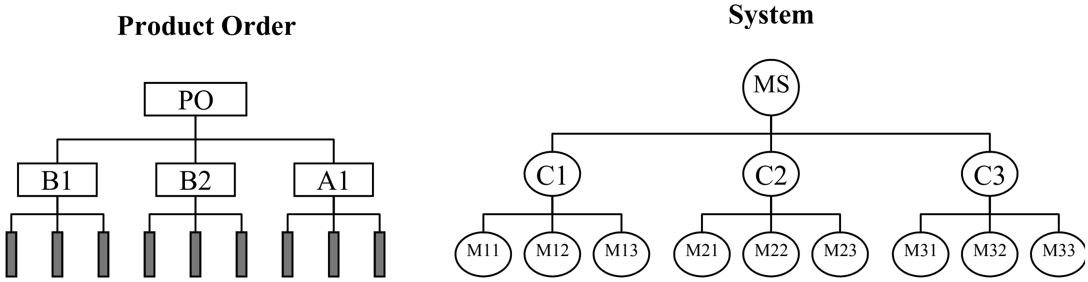

Figure 5.1 the Hierarchies of PO and MS

allocate the two parts (i.e., B1 and B2) and the assembly operation (i.e., A1) to manufacturing cells (i.e., C1, C2 and C3) based on the planning and scheduling options of these three cells. In turn, planning and scheduling at the next level is concerned with the allocation of operations contained in a part (B1 or B2) or an assembly operation (i.e., A1) to machines in a given cell (C1 or C2 or C3) based on the dynamic state and status of these machines. Therefore, in order to plan and schedule a product order for satisfying the order's due date at the minimal cost, the planning and scheduling at each of hierarchical level must

[5] A part could be an entire product, a component or an assembly operation

ensure sub-jobs are routed and scheduled on resources such that the due date is satisfied and the cost is minimised. In other words, the common planning and scheduling problem shared at each hierarchical level is to find the optimum allocation of a production job containing a sequence of sub-jobs to a pool of resources in a system/sub-system so that the entire job can be completed within a given due date at minimum production cost. From the above discussion, it is indicated that solving of the common problem shared at each hierarchical level is the basis to enable an entire product order to be produced cost-efficiently and timely. Hence, in the following of this chapter, the common planning and scheduling problem shared at each hierarchical level is termed as the basic problem in production planning and scheduling. As a result, it is imperative that the planning and scheduling mechanism needed for the integrated decision platform must firstly be able to solve the basic problem. Meanwhile, since manufacturing systems are modelled with heterarchically operating agents as described in the last chapter and also the basic problem considers the single level scenario (i.e., sub-jobs or resources are located at the same hierarchical level), the mechanism must also support the solving of the basic problem in a distributed agent-based modelling environment. In the following, the basic problem is formulated mathematically, which considers the planning and scheduling in the shop floor scenario in order to provide the generality (e.g., the sequence of sub-jobs etc).

5.2.1 Formulation of the Basic Problem

Considering a production job containing n operations ($O_1, O_2, \ldots, O_n$) and a system consisting of m resources ($r_1, r_2, \ldots, r_m$), the basic problem is concerned with the allocation of these operations to the resources so that the production of the entire job is able to satisfy a required due date D at the minimum production cost. These operations are assumed to be completed one at a time according to a linear sequence and every resource contained in the system is able to process more than one operation if possible. Meanwhile, for every resource, there is a job buffer containing a list of unprocessed jobs from previous orders and these jobs are sorted in the buffer according to a time order.

For each operation O_i ($i = 1, 2, \ldots, n$), there is a subset of resources R_k ($k \leq m$) which are technically able to carry out this operation. As for each resource $r_j (r_j \in R_k)$ contained in the subset, it could place the operation O_i at a specific position of its job buffer, which results in a scheduling option with a production cost ($C_{i,j}$) and a production lead time ($T_{i,j}$) represented as the following two equations, namely equation (1) and (2)

$$C_{i,j} = C_{i,j}^{T} + C_{i,j}^{S} + C_{i,j}^{P} + C_{i,j}^{W} + C_{i,j}^{R} \quad (1)$$

$$T_{i,j} = T_{i,j}^{T} + T_{i,j}^{S} + T_{i,j}^{P} + T_{i,j}^{W} \quad (2)$$

where

$C_{i,j}^{T}$ and $T_{i,j}^{T}$ = the transportation cost and time which depend on the location of the resource processing the previous operation (O_{i-1}), the location of current scheduling resource (r_j) and the material handling system.

$C_{i,j}^{S}$ and $T_{i,j}^{S}$ = the setup cost and time which depend on the previous unprocessed job in the job buffer of current scheduling resource (r_j).

$C_{i,j}^{P}$ and $T_{i,j}^{P}$= the processing cost and time to complete the operation O_i.

$C_{i,j}^{W}$and $T_{i,j}^{W}$= the waiting/holding cost and time which depend on how many unprocessed jobs are placed before the operation O_i in the job buffer and how long it takes for the current scheduling resource (r_j) to process these unprocessed jobs.

$C_{i,j}^{R}$= the rescheduling cost which is incurred when the operation O_i is placed before some of unprocessed jobs already existing in the job buffer because this may result in additional costs to process these unprocessed jobs. However, the rescheduling must ensure the due dates of these unprocessed jobs are not violated.

The basic problem concerned with the allocation of the operations ($O_1, O_2, \ldots, O_n$) to the set of resources ($r_1, r_2, \ldots, r_m$) can be formulated as following in (3) where C and T respectively represent the overall production cost and lead time for processing the entire production job; C_i and T_i are the production cost and lead time for the operation O_i ($O_1, O_2, \ldots, O_n$), which are the variables of the basic problem depending on which resource is selected for the operation and where the operation is placed in the job buffer of this resource.

$$Min\left(C=\sum_{i=1}^{n}C_i\right)$$

$$T=\sum_{i=1}^{n}T_i\leq D \qquad (3)$$

From the formulation of the basic problem especially equation (1) and (2), it is indicated that the performance of an operation (i.e., time and cost) is not only based on which resource is selected to perform this operation, but also depends on which resource is selected to carry out the preceding operation and how the resource performs the preceding operation. In other words, as for the basic problem, local decisions with respect to individual operations are correlated with each other. For example, the start time of an operation on a resource relies on when the job object arrives at this resource, which in turn is related to the finishing time of the preceding operation and the transportation time to move the job object from the resource performing the preceding operation to the current resource. Consequently, the change of the local decision with respect to an individual operation leads to the changes of performances of following operations on resources and in turn results in the change of the overall performance of the entire production job. As a result, different combination of resources for these operations and different scheduling options for operations on resources, generate alternative allocation plans with different performances (i.e., overall cost and time). In theory, as for the basic problem formulated above, the maximal number of possible allocation plans (i.e., for every operation, every resource has the technical capability and the operation can be put at any position in the job buffer of any resource) can be approximately represented as equation (4)

$$Z=(\sum_{j=1}^{m}S_j)^n \qquad (4)$$

where Z is the maximal number of possible allocation plans, S_j represents the scheduling options provided by the resource r_j for an operation which depends on how many unprocessed jobs exist in the job buffer of this resource, and n and m respectively represent the number of operations and resources in the basic problem. The reason why the equation provides an approximate representation for the maximal number of possible allocation plans is that it does not consider the influence of preceding operations on scheduling options of resources with respect to following operations. From this equation, it is indicated that the number of possible allocation plans for the basic problem grows exponentially with the increase of the number of operations. In this condition, the basic problem is NP-hard (Non-deterministic polynomial-time hard) and in turn to solve the basic problem by considering all of possible allocation plans through enumeration is unrealistic as the problem grows due to the huge searching space.

5.2.2 Approaches to Resource Allocation in Distributed Agent-based Modelling Environments

The basic problem identified above is a resource allocation problem. In the literature of distributed planning, existing approaches to resource allocation are mainly based on the use of bidding process between agents representing resources. In a bidding process, operations are released one at a time according to a specific sequence for agents to bid for or compete based on certain bidding criteria such as earliest finishing/starting time, the lowest production cost and sophisticated bidding functions combining multi-criteria (e.g., time, cost and etc). Operations are then assigned to resources providing the best performances at the bidding stages for the operations. In the literature, early approaches to resource allocation attempt to simply use the bidding process so as to quickly generate feasible and fault-tolerant allocation plans in real-time planning and scheduling situations, such as Duffie and Piper (1987), Duffie et al. (1988), Lin and Solberg (1992) and Gu et al. (1995). However, since only local objectives of operations are considered in the bidding process (Baker 1998), the entire allocation plan obtained through the bidding process may not be able to satisfy global objectives of the entire job due to the precedence constrains between operations. These early approaches based on the simple use of bidding process cannot be used to solve the basic problem which requires the entire job to be fulfilled within a given due date at the minimum overall cost. Currently, some approaches in the literature combine optimisation methods such as Genetic Algorithm (GA) with the bidding process so as to improve global performance of resource allocation on the shop floor. For example, Maione and Naso (2001; 2003) present a heterarchical scheme in which parts (i.e., production jobs) and resources are modelled as part agents and resources agents respectively. For each part type, there is a part agent which is given a weighted combination of multi-criteria such as processing cost, processing time and setup time etc to coordinate the bidding process amongst agents. When receiving an order for a part type, the allocation plan is obtained by using the bidding process in which the bidding criteria for selecting resources for operations are the weighted combination given to the part agent for the part type. However, the weights in the combination for each part type are dynamically adapted by a GA over different product orders, which aims at gradually improving the global planning and scheduling performance with respect to this part type. The similar GA optimisation scheme is presented in Deshpande and Cagan (2004) in which every resource is assigned with a selecting probability and whether an operation is allocated to a resource in the bidding process does not only depend on the technical performance of the resource, but also depend on the probability assigned to the resource. The improvement of the overall planning and scheduling performance is achieved through dynamic adaptation of selecting probabilities assigned to resources. The current approaches in the literature provide promising ways to improve global performance of resource allocation over a certain planning period and Maione and Naso (2001; 2003) denote such an approach also enables planning and scheduling on the shop floor to be adaptive to the dynamic changes in the marketplace. However, in terms of a production job in a specific product order, the allocation plan for the job is still obtained through the simple bidding process in these approaches, whereas one cannot ensure such an allocation plan is the optimum plan due to the precedence constraints between operations as discussed above.

From the above discussion, it is indicated that existing approaches to resource allocation cannot be used to solve the basic problem identified in this chapter satisfactorily. The major shortcoming of these approaches is that when planning and scheduling a production job, they only consider the allocation of operations to resources providing the best performance based on given criteria which may not result in a global optimum allocation plan for the entire job due to the precedence constraints between operations. In this sense, to find the optimum allocation plan for an entire job, alternative allocations of operations to resources have to be considered and evaluated simultaneously. However, the difficulty is that conventional bidding process is only able to involve one allocation plan in which the solution for every operation is locally optimised according to given criteria. Therefore, in order to obtain alternative allocation plans, the bidding amongst agents has to be implemented iteratively and meanwhile particular schemes (e.g., changing the bidding criteria or etc) must be used to control the bidding process so that allocation plans generated at different bidding iterations are distinguished with each other. Furthermore, as discussed above, the basic problem is NP-hard and to solve the basic problem by considering all of possible alternatives through enumeration is unrealistic. As a result, an optimisation method must be used so as to facilitate the determination of the optimum allocation plan for the basic problem.

5.3 The Iterative Agent Bidding Mechanism

In this work, to solve the basic problem in a distributed agent-based modelling environment, an iterative agent bidding mechanism based on Genetic Algorithm (GA) is presented, which consists of two critical processes including an iterative agent bidding process and a GA optimisation process. The former process facilitates the generation of alternative allocation plans through the bidding process, whereas the latter process enables the iterative bidding process to be able to generate better and better allocation plans towards the optimum one over iterations. In the following, these two processes are described respectively.

5.3.1 The Iterative Agent Bidding Process

In the iterative Agent bidding process, in order to support the generation of alternative allocation plans over different bidding iterations, two sets of parameters are introduced, including virtual prices for operations and the minimal virtual profits for resources which work together to regulate and control behaviours of individual agents in the bidding process. The use of these two sets of parameters is inspired by the economic model of human society. In a human society, there are a number of individuals or organisations which are able to perform specific economic activities. Every individual or organisation has its own objectives when participating in an economic activity. However, the behaviours of individuals or organisations with respect to economic activities are also influenced by some external factors such as tax rates, interest rates, political policies and etc. For example, when an organisation decides whether to invest in a project, the decision of this organisation does not only depend on if it can earn enough sales value from the project, but also depends on the interest rate for debt because the initial capital of this organisation may need to be funded by banks. Adjusting these external factors is able to control the individuals' behaviours for participating in economic activities. The virtual prices for operations and the minimal virtual profits for resources exert similar roles in bidding process as external factors in human societies so as to control agents' behaviours in the bidding environment. In the bidding process, every operation has a specific virtual price and every resource has a specific minimal virtual profit. When an agent representing a resource bids for an operation, it may have several scheduling options for this operation (i.e., placing the operation at different positions in the job buffer). Only when the virtual profit of a scheduling option (i.e., the margin between the virtual price of the operation and the production cost associated with the scheduling option) is more than or equal to the minimal virtual profit assigned to the corresponding resource, the agent submits the scheduling option as a bid. These two sets of parameters are able to regulate behaviours of individual agents in the bidding environment in that they determine which scheduling options of resources can be submitted as bids, whereas the submitted bids form the candidate domains for operations among which the allocation of operations to resources are determined based on certain criteria. As a result, the adjustment of virtual prices for operations and minimal virtual profits for resources exerts impact on the composition of candidate domains for operations and in turn results in alternative allocation plans.

The basic problem is to find the optimum allocation plan which is able to satisfy the due date of the entire production job at the lowest production cost. Among the entire domain of alternative allocation plans, the optimum allocation plan is located at the sub-domain which includes those plans satisfying the due date of the entire production job. As a result, to find the optimum allocation plan, it is imperative to ensure that the obtained allocation plans through the bidding process are able to meet the due date of the entire production job. Therefore, the bidding criteria for selecting resources for operations in the iterative bidding process is defined as the shortest lead-time to perform operations, so that every allocation plan obtained at every bidding iteration has a high possibility to meet the due date of the entire production job. The optimum plan with due date satisfaction and lowest production

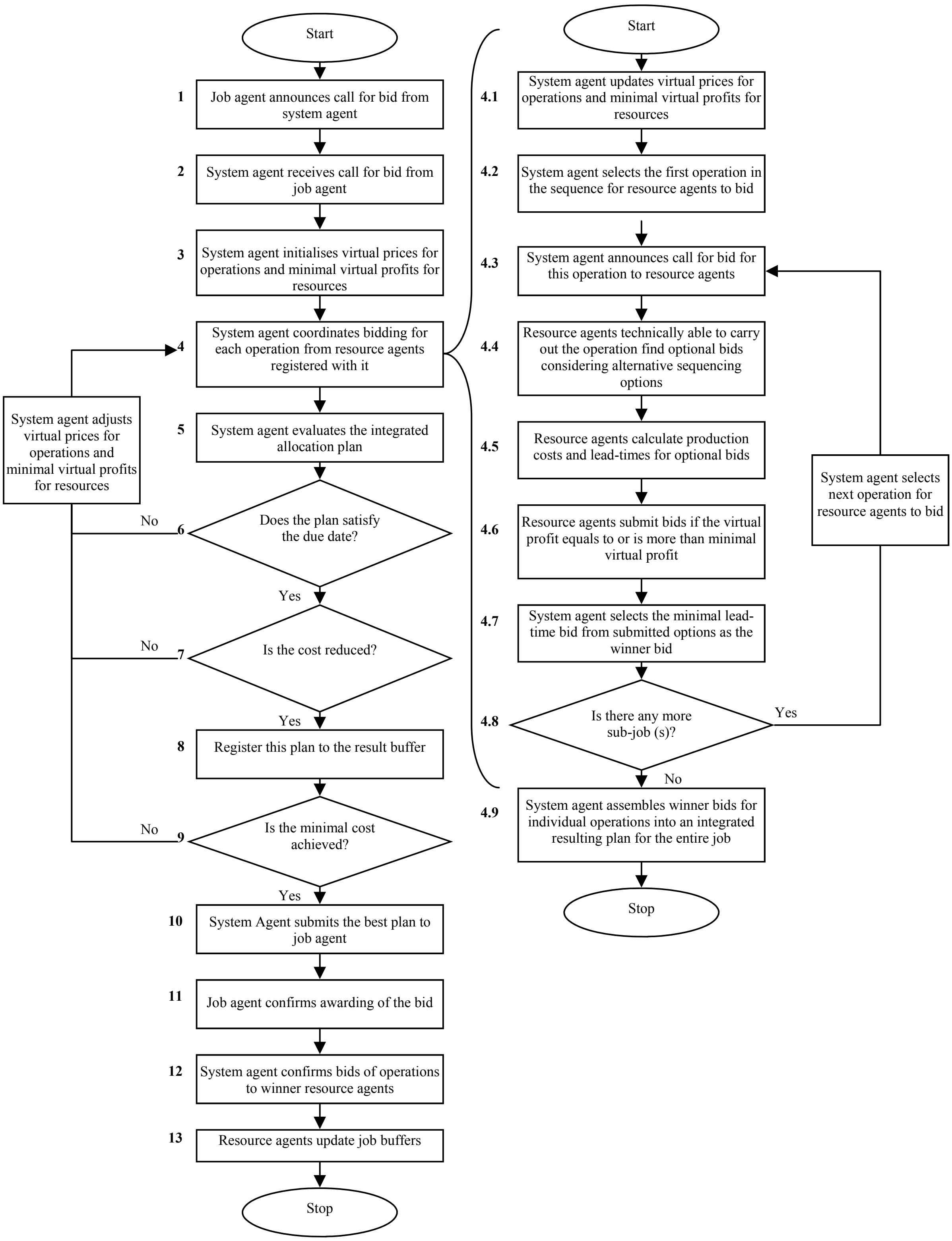

Figure 5.2 the Generic Procedures of the Iterative Bidding Process

cost is then found over bidding iterations by adjusting virtual prices for operations and minimal virtual profits for resources.

As for the basic problem formulated in section 5.2.1, the production job is modelled as a job agent and meanwhile the system and the m resources are represented as a system agent and resource agents as well. The iterative agent bidding process is started by the job agent announcing a call for bid for the entire job from the system agent which then launches the bidding process iteratively, as shown in figure 5.2. Within each bidding iteration, the system agent firstly creates a set of virtual prices $(P_1, P_2, \ldots, P_n)$ and a set of minimal virtual profits $(F_{min,1}, F_{min,2}, \ldots, F_{min,m})$. The P_i (i = *1, 2,…, n*) represents the virtual price assigned to operation O_i and the $F_{min,j}$ (*j = 1, 2,…, m*) is the minimal virtual profit assigned to resource r_j. The system agent then announces operations, one at a time according to the specific sequence between operations, for resource agents to bid for. For each operation O_i (i = *1, 2,…, n*), when a resource agent represents a resource r_j that is technically able to process this operation, the resource agent makes a scheduling option for the operation and calculates the corresponding production cost $(C_{i,j})$ and lead time $(T_{i,j})$ based on the equation of (1) and (2). In turn, a virtual profit $(F_{i,j})$ earned by the resource to carry out this scheduling option is computed as the margin between the virtual price for the operation and the production cost corresponding to the scheduling option, as shown in equation (5).

$$F_{i,j} = P_i - C_{i,j} \tag{5}$$

If based on the scheduling option the resource r_j is able to make a virtual profit greater than the minimal virtual profit assigned to it, the resource agent will submit the scheduling option as a bid to the system agent. In addition, since the rescheduling is allowed, resource r_j may be able to have several scheduling options for operation O_i by placing the operation in different buffer positions without violating the due dates of unprocessed jobs existing in the buffer. In turn, the resource agent may submit these scheduling options as bids simultaneously to the system agent as long as the virtual profits associated with these options are greater than or equal to the minimal virtual profit. When the system agent receives more than one bid for operation O_i from eligible resource agents, it selects the bid corresponding to the scheduling option which has the shortest lead-time as the winner bid, for this iteration as shown in (6)

$$B_i^{win} = B_i^{(l)}, \quad T_i^{win} = T_i^{(l)}, \quad C_i^{win} = C_i^{(l)}$$

$$T_i^{(l)} = Min\left(T_i^{(1)}, T_i^{(2)}, \dots, T_i^{(G)}\right) \quad (6)$$

where B_i^{win}, T_i^{win} and C_i^{win} represent the winner bid for operation O_i and the production lead time and cost corresponding to the winner bid, whereas G is the total number of bids for operation O_i received by the system agent. However, if there is not a bid for operation O_i, it means the system agent cannot find an appropriate resource for O_i under the given conditions (i.e., virtual prices for the operations and minimal virtual profits for resources) and in turn cannot find an allocation plan for the entire production job in the current bidding iteration. Under such circumstances, the system agent terminates the current bidding iteration immediately and starts the next bidding iteration. On the other hand, when winner bids for all operations in the current bidding iteration are found, the system agent then integrates these winner bids to form an allocation plan and calculates the planned cost (C) and lead time (T) for the entire production job as in (7)

$$C = \sum_{i=1}^{n} C_i^{win}, \quad T = \sum_{i=1}^{n} T_i^{win} \quad (7)$$

If the planned lead time does not satisfy the required due date, i.e., $T > D$, the system agent launches the next bidding iteration with adjusted virtual prices for operations and minimal virtual profits for resources. However, if the due date is satisfied, the system agent investigates whether the cost is reduced compared to the last iteration. If so, the system agent places the generated plan into a result buffer before next iteration is started. Otherwise, next bidding iteration is started subsequently. The iterative bidding process is ceased when the system agent considers the best plan in the result buffer is able to achieve the minimal or low enough cost.

In the iterative agent bidding process, different virtual prices for operations and minimal virtual profits for resources lead to different allocation plans. The higher virtual prices or lower minimal virtual profits encourage eligible resources to put forward more bids for operations (e.g., by the rescheduling process) so as to find allocation plans with short lead time. However, the lower virtual prices or higher minimal virtual profits reduce the attractiveness of operations for resources to submit high-cost/short-time bids and in turn lead to allocation plans with low production costs. In this context, when a set of virtual prices and a set of minimal virtual profits cannot result in an allocation plan meeting the due date, the system agent can attempt to increase virtual prices for operations or reduce minimal virtual for resources in the next iteration to encourage resources to submit more bids. On the other hand, if the allocation plan in a bidding iteration is able to satisfy the due date, the system agent can reduce virtual prices or increase minimal virtual profits so as to find a plan with a lower cost than the previous one.

5.3.2 The GA-based Optimisation Process

As described above, the iterative agent bidding process uses two set of parameters (i.e., the virtual prices for operations and minimal virtual profits for resources) to support the generation of alternative allocation plans. Therefore, another problem is how to dynamically tune the two sets of parameters so that allocation plans generated over bidding iterations can become better and better towards the optimum one. In doing so, a GA optimisation process is proposed in this work, as shown in figure 5.3. Like all GA applications, this optimisation process uses chromosomes to represent possible solutions and uses fitness function to evaluate these solutions. In this process, a chromosome represents a set of virtual prices for operations and a set of minimal virtual profits for resources based on which a unique allocation plan can be obtained through a bidding iteration. The fitness function for evaluating a chromosome is the production cost of the allocation plan corresponding to this chromosome. A lower production cost represents a higher fitness and vice versa. As a result, the optimisation problem based on this process is to find a set of virtual prices for operations and a set of minimal virtual profits for resources which are able to result in an allocation plan for the entire job that satisfies the due date with minimum production cost.

As for the basic problem formulated in section 5.2.1, when the system agent starts the iterative agent bidding process, the GA optimisation process is launched simultaneously with the generating of an initial population of chromosomes each of which is able to result in a feasible allocation plan (i.e., the planed lead time meets the due date). Within each GA iteration, a set of offspring chromosomes is produced through crossover and mutation processes. These offspring chromosomes are then used to coordinate the bidding process described previously for generating alternative allocation plans. For those offspring chromosomes which are able to result in feasible allocation plans (i.e., satisfying the due date of the entire job), they are evaluated through comparing their fitness with that of their

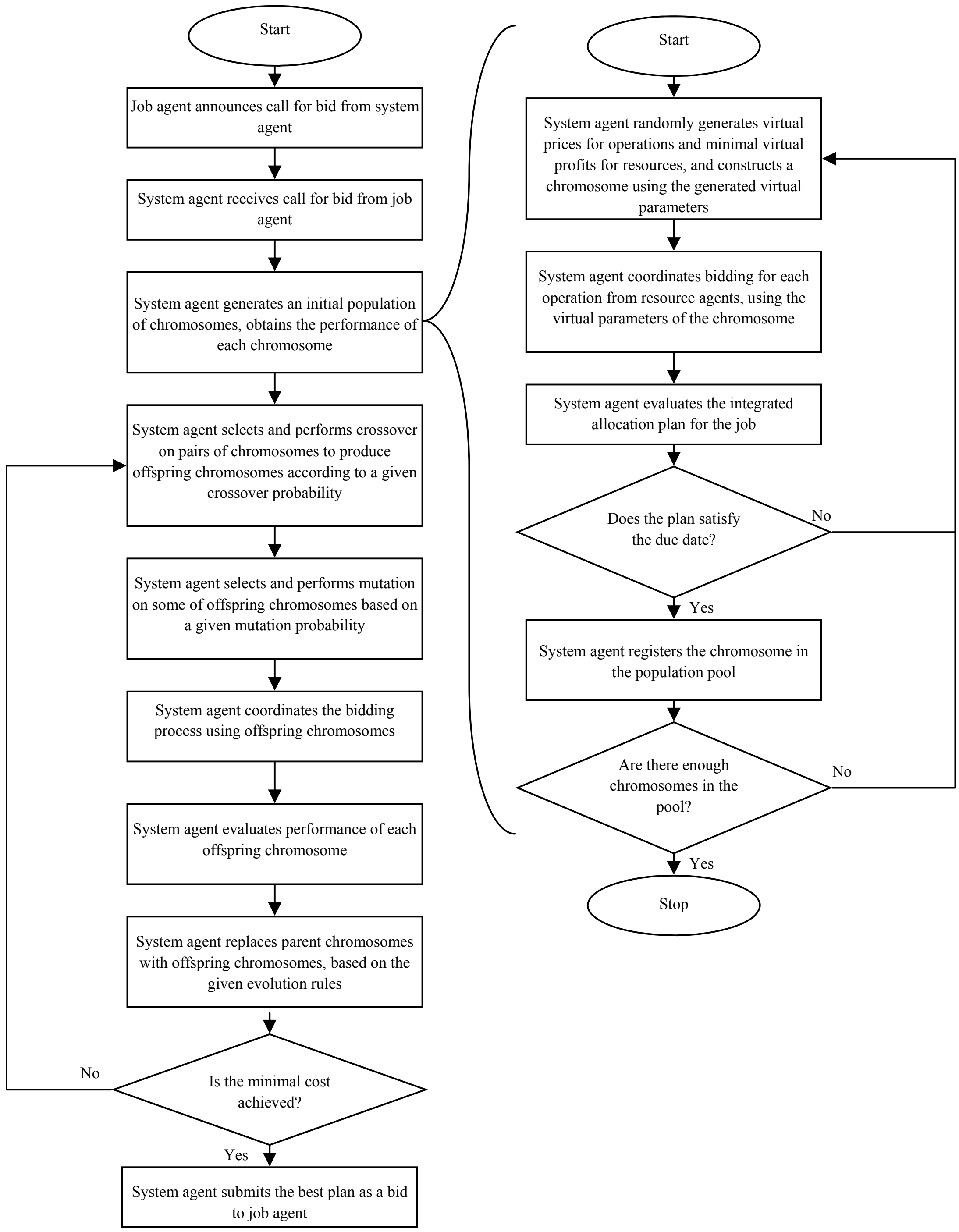

Figure 5.3 the GA Optimisation Process

parents chromosomes. Offspring chromosomes with better fitness (i.e., lower production cost) will be used to replace their parents chromosomes in the population, which then forms a new generation of chromosomes at the end of the GA iteration. The GA process iterates until the system agent ceases the iterative agent bidding process. In the following, the major issues involved in the GA process are illustrated, which include chromosome coding, initialisation of population, crossover and mutation.

5.3.2.1 Chromosome Coding

A chromosome is represented as a vector composed of a set of virtual prices for operations and a set of minimal virtual profits for resources, given in (8)

$$CH = \{P_1, P_2, \dots P_n,\ \ F_{min,1}, F_{min,2}, \dots, F_{min,m}\} \quad (8)$$

where P_i and (i = *1, 2,…, n*) is the virtual price for operation O_i and $F_{min,j}$ (j = *1, 2,…, m*) represents the minimal virtual profit for resource r_j. In order to facilitate the processes of crossover and mutation, the values of these two sets of parameters in the GA optimisation process are converted as binary numbers.

5.3.2.2 Initialisation of Population

In the GA optimisation process, the initial population of chromosomes is generated through a random process where virtual prices for operations and minimal virtual profits for resources in every initial chromosome are random values in a range of (0, *N*). The number of *N* could be any value greater than the total cost of any operation processed by any eligible resource. Once an initial chromosome is created, it is immediately used to coordinate the bidding process so as to investigate whether it is feasible to result in an allocation plan satisfying the due date for the entire production job. If the generated plan meets the due date, this chromosome is placed into the population pool. However, if not, it will be discarded and the next initial chromosome is created and evaluated. This process repeats until a predefined population size is achieved.

5.3.2.3 Crossover

The crossover consists of two major issues including selection of chromosomes and crossover of chromosomes both of which are carried out based on random techniques.

In order to randomly select a set of chromosomes from the population, a particular value P_c ($0 < P_c < 1$) is predefined, which can be regarded as a threshold of selecting chromosomes. In the selection process, every chromosome in the population is given a random number within the range of (0, 1). As for a chromosome, if the assigned random number is less than P_c, it is placed into a mating pool and waits for crossover and vice versa.

In order to perform crossover, chromosomes in the mating pool are firstly paired randomly with others. However, it has to be noted that if the size of the mating pool is odd, a chromosome must be randomly selected to be mated twice with the other two different chromosomes. Three kinds of crossover operators are used in order to generate unique and diversified offspring chromosomes, which include point-to-point, single cut-off point, and dual cut-off points. As for a pair of chromosomes, a particular operator is selected randomly from these three operators and the crossover is carried out based on this operator to generate two offspring chromosomes. If the two offspring chromosomes are different from their parents (i.e., the two original chromosomes), they are accepted and used to coordinate the bidding process. Otherwise, the crossover repeats until two unique offspring chromosomes distinguished from their parent are obtained. The detailed mechanisms of the three crossover operators are illustrated below.

Point-to-Point Crossover

$$Parent\ 1 = \{0\ 1\ 1\ \boxed{0}\ 1\ 0\ 0\ \boxed{1}\ 0\ 1\} \quad \rightarrow \quad Offspring\ 1\ \{0\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\}$$

$$Parent\ 2 = \{0\ 0\ 1\ \boxed{1}\ 0\ 1\ 0\ \boxed{0}\ 0\ 1\} \quad \rightarrow \quad Offspring\ 2\ \{0\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1\}$$

Single Cut-off Point Crossover

$$Parent\ 1 = \{0\ 1\ 1\ 0\ 1\ 0\ 0\ \vdots\ 1\ 0\ 1\} \quad \rightarrow \quad Offspring\ 1\ \{0\ 1\ 1\ 0\ 1\ 0\ 0\ 0\ 0\ 1\}$$

$$Parent\ 2 = \{0\ 0\ 1\ 1\ 0\ 1\ 0\ \vdots\ 0\ 0\ 1\} \quad \rightarrow \quad Offspring\ 2\ \{0\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 1\}$$

Dual Cut-off Points Crossover

$Parent\ 1 = \{0\ 1\ 1\ 0\ \vdots\ 1\ 0\ 0\ \vdots\ 1\ 0\ 1\} \quad \rightarrow \quad Offspring\ 1\ \{0\ 1\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1\}$

$Parent\ 2 = \{0\ 0\ 1\ 1\ \vdots\ 0\ 1\ 0\ \vdots\ 0\ 0\ 1\} \quad \rightarrow \quad Offspring\ 2\ \{0\ 0\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\}$

5.3.2.4 Mutation

The mutation is used to avoid local optimisation, which is carried out on some of offspring chromosomes created through the crossover process. This process uses the same technique as in the crossover process to select chromosomes for mutation. However, the predefined threshold parameter is represented as P_m ($0 < P_m < 1$).

When an offspring chromosome is selected to be mutated, the mutation to this chromosome is concerned with randomly changing the value of a gene (i.e., a virtual price for an operation or a minimal virtual profit for a resource) as shown in (9)

$$V_l^* = \mu \cdot V_l \tag{9}$$

where V_l represents the initial value of a gene randomly selected from genes contained in a offspring chromosome for mutation and the μ is a random number within a percentage range of $[Z^l, Z^u]$ predefined for the GA process. The V_l^* represents the new value for the selected gene after mutation, which is used to replace the V_l in the offspring chromosome.

5.4 Summary

This chapter at the beginning generalised the basic problem in production planning and scheduling as the allocation (in space and time) of a production job containing a sequence of sub-jobs to a pool of resources so that the production job can be completed within given time at the lowest production cost. By formulating the basic problem mathematically, it was found that the basic problem is NP-hard and to solve the basic problem by considering all of possible allocations through enumeration is unrealistic. Meanwhile, through reviewing the existing approaches to resource allocation in distributed agent-based modelling environments, it was found that these approaches are not able to solve the basic problem effectively. This chapter then described an iterative agent bidding mechanism based on GA for solving the basic problem. This mechanism includes two major processes including an iterative agent bidding process and a GA optimisation process. The iterative bidding process uses two sets of parameters (i.e., the virtual prices for sub-jobs and the minimal virtual profits for resources) to control the bidding process amongst agents so as to facilitate the generation of alternative allocation plans. The GA process provides an effective way to dynamically tune the two sets of parameters so that the allocation plan for the basic problem can be optimised over bidding iterations.

CHAPTER 6

HIERARCHICAL AGENT BIDDING MECHANISM

6.1 Introduction

As discussed in chapter 3, to assist manufacturing systems in dealing with changes in the business environment, an integrated decision platform is needed, on which operational decisions and restructuring decisions of manufacturing systems can be considered concurrently. In doing so, one of the critical issues is that production planning and scheduling of manufacturing systems must enable product orders to be firstly planned and scheduled to meet the orders' due dates at the minimum costs within the structural constraints of manufacturing systems as far as possible in order to reap the benefits of existing systems' structures (e.g., low material handling cost and etc). However, when orders cannot be fulfilled within structural constraints of existing system structures, manufacturing resources across system boundaries must be flexibly regrouped together with the minimum disturbances to the existing systems structures so as to enhance the operational flexibility of manufacturing systems to changes in the business environment and also facilitate the restructuring decision-makings of manufacturing systems under the changed business environment. This chapter provides a hierarchical agent bidding mechanism to help entire product orders to be planned and scheduled as required above in a distributed modelling environment. The detailed mechanism is described in section 6.3, which represents the generic procedures for distributed agents to make planning and scheduling decisions. The process of how an entire product order can be effectively planned and scheduled based on this mechanism is provided in section 6.4. Section 6.5 is a summary.

6.2 Problem Identification

In the last chapter, an iterative agent bidding mechanism based on Genetic Algorithm (GA) was described for solving one of the core problems in production planning and scheduling which is to find the optimum allocation (i.e., in space and time) of a production job containing a set of sub-jobs to a set of resources in a given system so that the production job can be completed within a given due date at the lowest production cost. This mechanism can be used to determine the best planning and scheduling decision that a given system can provide for a given production job when the job needs to be collectively produced by resources within the given system. However, both the production job and system considered in the iterative agent bidding mechanism are relatively simple in that only one level is involved in the job and system structures. Considering the complex hierarchical structures of both products and manufacturing systems, a product order always contains a multi-level hierarchy of production jobs each of which can be technically processed by different sub-systems that may be at the same or different levels in a multi-level system. Consequently, production planning and scheduling of an entire product order in a manufacturing system needs a mechanism to determine the optimum allocation of a hierarchy of production jobs contained in the order to a hierarchy of sub-systems/resources contained in the manufacturing system so that the overall due date of the entire order can be met at the lowest production cost. Meanwhile, this mechanism must enable a product order to be fulfilled within structural constraints of a manufacturing system as far as possible and however support resource regroupings across system boundaries with minimum disturbances to existing system structure when needed. In other words, when allocating a production job to sub-systems/resources, this mechanism must give priorities to those sub-systems which provide production plans based on which the job can be fulfilled within their structural constraints. For example, if a production job can be completed entirely within structural constraints of a single sub-system, the allocation of the production job to the sub-system should be preferred than the one that uses resources across several sub-systems. If there are several sub-systems which are all technically able to process the entire job, it is imperative to use a competitive method in the mechanism for selecting the most appropriate one based on the performances of these sub-systems in carrying out the production job. However, if any sub-systems cannot process the production job entirely but are only able to process one or more children/grandchildren jobs of this production job, the mechanism then needs to use a cooperative method to group resources across structural boundaries between these sub-systems so that the production job can be collectively processed by several sub-systems together. This will result in the problem for determining the optimum allocation of a set of children/grandchildren jobs contained in the entire job to several sub-systems. Such a problem can be solved by using the iterative agent bidding mechanism.

Similar to the iterative agent bidding mechanism, the mechanism discussed above should also be an agent-based distributed mechanism so as to support the compatibility with the former one and meanwhile support its implementation in the distributed agent-based modelling architecture described in chapter 4. However, from the literature review about the agent-based control of manufacturing systems in chapter 3, when considering the complex hierarchies of manufacturing systems, many of current approaches such as the Holonic Manufacturing System (HMS) are only able to use distributed methods to solve planning and scheduling problems in a single sub-system at the lowest level (e.g. a cell), whereas the planning and scheduling decisions at higher levels such as sequencing operations and allocating parts to cells/shops are determined by using centralized methods. In the literature, only few of scholars such as Shin et al. (2009[a], 2009[b]) propose distributed agent-based planning and scheduling mechanisms which enable product orders to be hierarchically decomposed and allocated to sub-systems/resources located at different hierarchical levels of manufacturing systems. However, these mechanisms only focus on finding feasible plans and schedules for product orders and however do not consider the cost optimisation in the planning and scheduling process. Furthermore, there is not a mechanism in the literature supporting coordinated resource regroupings across system boundaries of manufacturing systems. Due to the drawbacks of existing mechanisms in the literature, a novel agent-based mechanism has to be developed, which supports the coordinated allocation of a full hierarchy of production jobs of an entire order to a hierarchy of sub-systems/resources of a manufacturing system so that the entire order can be fulfilled cost-efficiently and timely within structural constraints of the system as far as possible or across system boundaries with fewer disturbances to the existing system structure when needed.

6.3 The Hierarchical Agent Bidding Mechanism

Recalling the agent-based distributed modelling architecture described in chapter 4, both of product orders and manufacturing systems are modelled as Hierarchical Autonomous Agent

Networks (HAANs) with heterarchically operating agents which are connected with each other through parent-children relationships. Agents in the HAAN of a product order are generally termed as part agents, whereas agents in the HAAN of a manufacturing system are referred to as resource agents. Production planning and scheduling of a product order in a manufacturing system is then achieved through the communication and coordination between part agents and resource agents, which involves part agents calling for bids from resource agents and resource agents making planning and scheduling decisions to compete for the call for bids. To enable an entire product order to be fulfilled within structural constraints of a manufacturing system as far as possible or when needed, to be fulfilled with resource regroupings across system boundaries but with fewer disturbances to the existing system structure, it is imperative for every resource agent representing a sub-system to follow the same strategy (as required for the order) to make planning and scheduling decision for every production job due to the similarity[6] between production jobs and entire product orders and the similarity between sub-systems and entire manufacturing systems. When a resource agent representing a sub-system receives a call for bid for a production job from a part agent, this resource agent should attempt to allocate the production job to a child system (represented by a child agent) in which the entire job can be processed completely. If there are several such children systems, the resource agent needs to let these children systems to compete for the job so as to select the optimum child to process the entire job. However, if there is not such a child system, the resource agent then should gradually relax structural boundaries between children systems so that the production job can be collectively processed by resources in different children systems. In this chapter, a hierarchical agent bidding mechanism is proposed, which represents the generic decision-making rules for resource agents to make planning and scheduling decisions for production jobs specified in call for bids. Assuming a resource agent (RA) representing a system receives a call for bid for a production job from a part agent (PA), the generic procedures of this mechanism are illustrated in the following and depicted in figure 6.1, which involve six major steps.

Step 1. If RA has no registered children agents, it means RA is a resource located at the bottom hierarchical level of a manufacturing system (e.g., a machine). Hence, if RA

[6] Similar to an entire product order or a entire manufacturing system, a production job or a sub-system may be also a multi-level entity where different sub-jobs and resources are located at different levels.

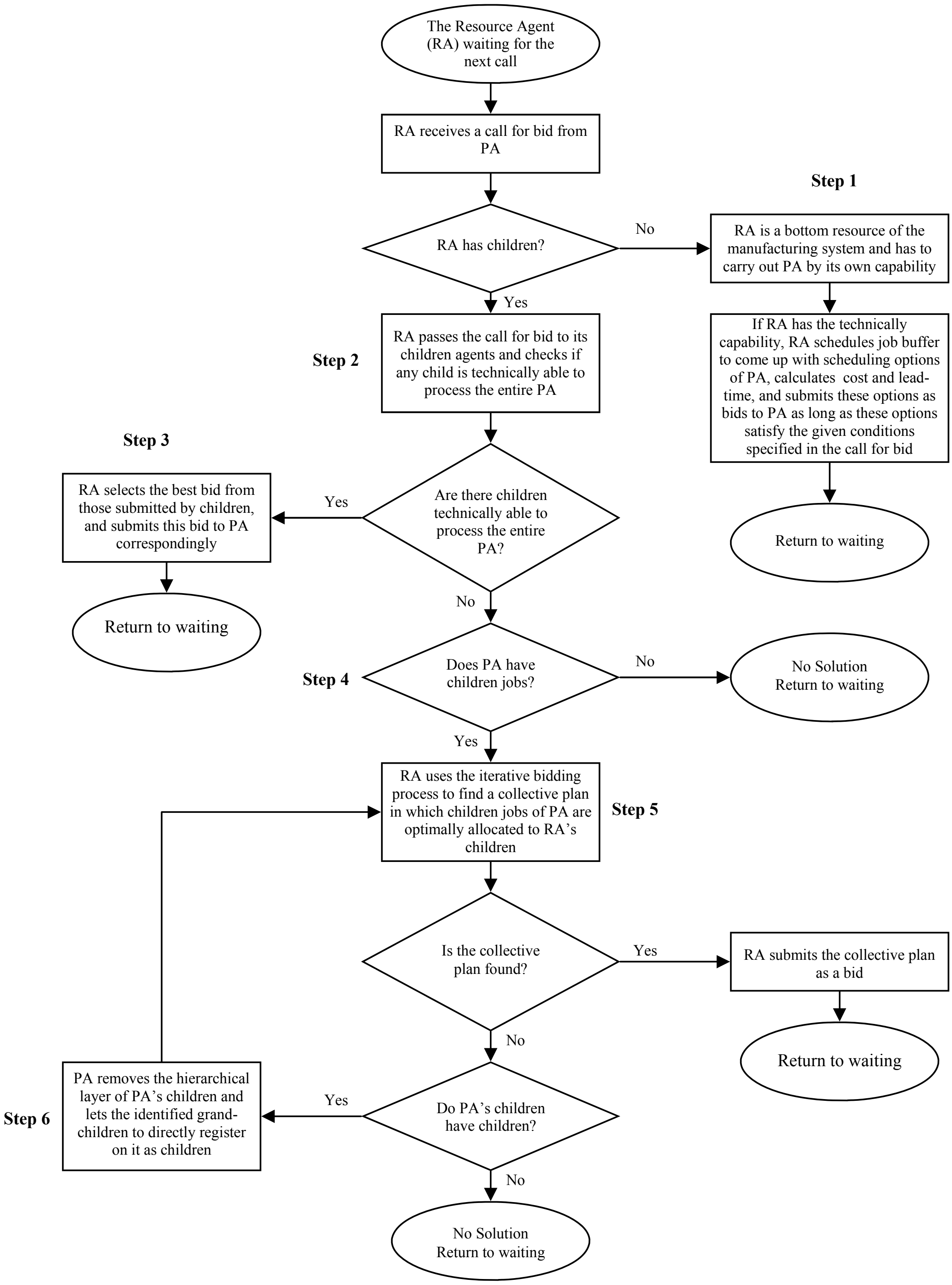

Figure 6.1 the Generic Procedures of the Hierarchical Agent Bidding Mechanism

is technically able to perform the production job, RA will schedule the production job based on its own capacity and status and submit the obtained schedule as a bid to PA as long as the bid satisfies bidding conditions required in the call for bid, such as due date or minimal virtual profit. RA then returns to waiting status.

Else, go to step 2.

Step 2. If RA has registered children agents, it means the system represented by RA has sub-systems or children resources. Therefore, RA should investigate whether there are sub-systems represented by children agents which are technically able to process the production job entirely so that the job could be fulfilled within structural constraints of the system as far as possible. In this sense, RA hands over the call for bid directly to its children agents and goes to step 3.

Step 3. If RA receives one or more bids from some of children agents, this means there are one or more sub-systems that can process the production job entirely and also meet the bidding conditions specified in the call. RA selects the optimal bid based on certain criteria and submits the bid to PA. RA then returns to waiting status.

Else, go to step 4.

Step 4. If RA does not receive any bids from children agents, this means current resource configurations in sub-systems do not enable any sub-systems to be able to complete the production job entirely or plan and schedule the job to meet the given conditions specified in the call for bid. In this context, resources within different sub-systems should be grouped together to process the production job. In order to result in fewer disturbances to the existing system structure, RA should firstly consider such a collective solution: sub-systems are grouped together to process the entire job and however every child job of the production job should be entirely processed within a single sub-system. In doing so, the feasibility for such a collective solution should be investigated firstly, namely whether the production job contains children jobs.

If PA has no children agents, it means the production job is at the bottom level of the product tree and cannot be collectively processed on different resources. As a result, it is indicated that the production job cannot be processed in the system represented by RA and no solution can be found. RA then returns to waiting status.

Else, go to step 5.

Step 5. If PA has children agents, it means the production job consists of children jobs. In this sense, RA has to determine the optimum allocation of these children jobs to sub-systems. The optimum allocation plan can be obtained by using the iterative agent bidding process based on GA described in the last chapter. This involves that RA initialises a set of virtual prices for children jobs and a set of minimal virtual profits for sub-systems and starts the iterative agent bidding process. Within each bidding iteration, RA announces call for bids for children jobs one at a time for its children resource agents to bid for.

If RA finds a collective plan for the entire job, it submits the plan as a bid when the plan is able to meet the bidding conditions specified in the call for bid. RA then returns to waiting status.

Else, go to step 6.

Step 6. If RA cannot find a collective plan in step 5 or the obtained collective plan cannot meet the given conditions specified in the call for bid, it means boundaries between sub-systems need to be further relaxed so that every child job can be also processed by the collective use of resources in different sub-systems. In doing so, the production job needs to be decomposed into smaller parts compared to that in step 5. As a result, the hierarchies of children jobs should be investigated firstly.

If PA has grandchildren agents, it means children jobs can be decomposed into grandchildren jobs. To facilitate the implementation of the iterative agent bidding process for finding the optimum allocation of grandchildren jobs to sub-systems so as to maintain the global performance of the system in processing the entire job, all grandchildren jobs have to be placed heterarchically. In doing so, PA is informed to remove children agents from its hierarchy and directly register all of grandchildren agents as new children agents. The iterative bidding process then is concerned with determining the optimum allocation of the new set of "children jobs" to sub-systems as in step 5.

Else, children jobs do not contain grandchildren jobs and in turn have to be entirely processed within single sub-systems. Due to the failures in previous steps, it can be concluded that the production job cannot be processed in the system represented by RA and no solution can be obtained. RA then returns to waiting status.

Based on the procedures of the hierarchical agent bidding mechanism, a resource agent in the HAAN of a manufacturing system is able to make planning and scheduling decisions which enable a production job to be fulfilled as far as possible within structural constraints of the system/sub-system represented. However, when the production job cannot be processed within the structural constraints, resource regroupings across system boundaries are supported and however the disturbances to the existing system/sub-system structure resulting from the resource regroupings are always attempted to be maintained at the lowest level. However, the hierarchical agent bidding mechanism only represents planning and scheduling procedures for individual resource agents. Since there are a hierarchy of resource agents in the HAAN of a manufacturing system, the next problem is how to effectively control the hierarchy of resource agents based on the implementation of the mechanism so that an entire product order can be planed and scheduled within structural constraints of the whole system as far as possible or across system boundaries with minimum disturbances to the existing system structure when needed.

6.4 The Hierarchical Agent Bidding Process

Based on the implementation of the hierarchical agent bidding mechanism, production planning and scheduling of a product order in a manufacturing system is achieved through a hierarchical agent bidding process. When a product order is placed in a manufacturing system, the order is modelled as a HAAN with part agents. The hierarchical agent bidding process is started by the top-level part agent (i.e., the order agent) in the HAAN of the order calling for bid from the top-level resource agent (i.e., the system agent) in the HAAN of the manufacturing system. When receiving the call for bid for the entire order, the system agent follows the generic procedures of the hierarchical agent bidding mechanism described above to process the call for bid. This may result in that the system agent directly passes the call for bid to its children agents and lets them to compete for the entire order or, the system agent gradually decomposes the order into a set of production jobs (e.g., children job, grandchildren jobs etc), announces call for bids for these jobs one at a time for children agents to bid for and coordinates children agents based on using the iterative agent bidding mechanism so as to find a collective plan for the entire order. Once receiving a call for bid from the system agent, every child agent of the system agent also follows the generic procedures of the hierarchical agent bidding mechanism to process the call for bid. In turn, the generic procedures are followed by resource agents at lower levels of the system HAAN to process call for bids passed over from their parent agents. It is indicated that the hierarchical agent bidding process involves a hierarchy of individual bidding processes which are operated respectively by the hierarchy of resource agents in the HAAN of the manufacturing system based on the implementation of the hierarchical agent bidding mechanism. The bidding processes at lower hierarchical levels are involved in those at higher hierarchical levels based on parent-children relationships between corresponding resource agents. The control decisions based on the hierarchical agent bidding process is made in a recursive way: the decision-makings in bidding processes at higher hierarchical levels rely on the decisions of those at lower hierarchical levels. By this way, planning and scheduling decisions from the sub-systems/resources at lower levels can be dynamically evaluated and/or coordinated by those at higher levels based on the consideration of global objectives, which enables product order to be planned and scheduled flexibly according to the dynamic situations of the manufacturing system and meanwhile maintains the global performance of manufacturing systems in fulfilling product orders. Moreover, since every resource agent follows the generic procedures of the hierarchical agent bidding mechanism to process call for bids, once receiving a call for bid for an order/job, resource agents at higher levels will firstly pass the call to children resource agents at lower levels and however consider resource regroupings (i.e., making collective plans) only when no children resources are able to process the order/job entirely. As a result, resource regroupings in the hierarchical agent bidding process firstly take place between sub-systems at lower levels (e.g., resource regroupings between cells of a shop), which are considered level by level from bottom to top along the system hierarchy until the order/job is fulfilled. This enables resource regroupings in the hierarchical agent bidding process to make minimum disturbances to existing system structures.

In order to provide a clarification for the hierarchical agent bidding process, an example is given in figure 6.2 which depicts a two-level product and a three-level manufacturing system. The product (i.e., PO) contains a set of components and assembly processes (e.g., CP_1, CP_2 etc) each of which involves a sequence of operations that need to be processed at machines. The manufacturing system (i.e., MS) is composed of several shops (e.g., S_1, S_2 etc) each of which contains a set of manufacturing cells (e.g., C_{11}, C_{21} etc). Machines in the

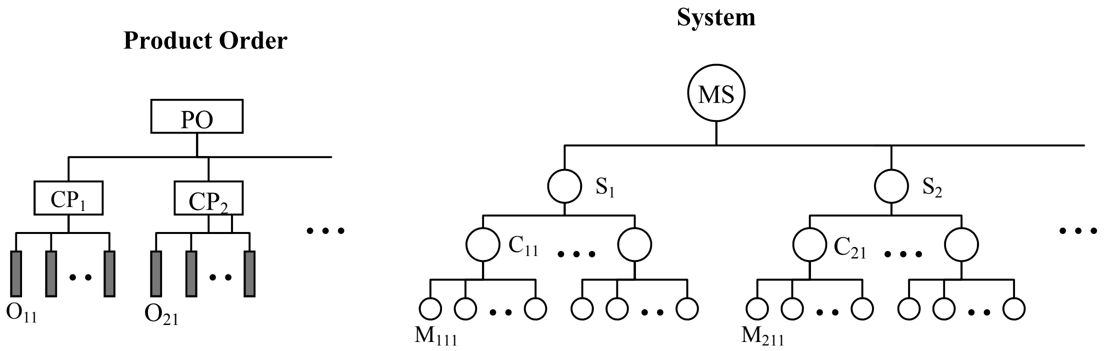

Figure 6.2 the Structure of the Product Order and Manufacturing System

manufacturing system are grouped and placed in different cells as shown in figure 6.2. When an order of product PO is placed in the manufacturing system, a HAAN of the order is created correspondingly. The hierarchical agent bidding process for planning and scheduling the order in the manufacturing system is then started by the order agent at the top-level of the order HAAN calling for bid from the system agent at the top-level of the system HAAN. The entire hierarchical agent bidding process for this example involves two major stages which are detailed in the following.

6.4.1 Stage 1

Once receiving the call for bid for the order, based on the generic procedures of the hierarchical agent bidding mechanism, the system agent passes the call directly to its children agents (i.e., shop agents) and aims at selecting the best shop within which the entire order can be completed cost-efficiently and timely. As for a shop agent in this example, to make a planning and scheduling decision for the entire order may need go through three steps which are clarified in the following.

6.4.1.1 Step 1.1

When receiving the call for bid for the entire order, following the hierarchical agent bidding mechanism, a shop agent firstly passes the call to cell agents contained each of which in turn hands over the call to machine agents contained as well. As for a machine agent, since it is at the bottom level of the system tree, it has to schedule the entire order based on its own capacity and status. However, an entire order normally cannot be completed entirely on a single machine and in turn no one machine agent contained in a cell agent can submit a feasible bid for processing the entire order. The cell agent therefore has to make a collective plan for the entire order, namely getting several machines together to produce the order. According to the hierarchical agent bidding mechanism, the cell agent firstly attempts to make a collective plan in which every component of the order is processed by a single machine entirely so as to make fewer disturbances to existing system structure. In doing so, the cell agent initialises virtual prices for components and minimal virtual profits for machines in the cell to start an iterative agent bidding process for finding the optimum allocation of components to machines. Within each bidding iteration, the cell agent announces call for bids for components one at a time for machine agents to bid, whereas machine agents schedule the released components based on their own capacity and status. However, in most cases, a single machine is still unable to produce an entire component, so no solution could be found. In this regard, for producing components in the order, the cell agent also needs to group different machines together. In doing so, following the hierarchical agent bidding mechanism, the cell agent informs the order agent to remove the hierarchical layer of existing component agents from the HAAN of the order and to let all of operation agents (i.e., children agents of component agents) to directly register as children in the order agent. After the modification of the order's hierarchy, the cell agent then starts an iterative agent bidding process again to find a collective plan for the entire order under the new condition under which machine agents bid for an individual operation at a time rather than bid for an entire component. Finally, if there is one or more cell agents which are able to find collective plans for the order, these plans will be submitted as bids to the shop agent. The shop agent then selects the best bid corresponding to the production plan and schedule which meet the order's due date at the lowest production cost, and in turn submits the bid to the system agent to compete with the optimal bids submitted by other shop agents.

6.4.1.2 Step 1.2

As for a shop, when no one cell contained is able to process the entire order completely, the shop needs to get several cells together to make a collective plan for the order. Following the generic procedures of the hierarchical agent bidding mechanism, the shop agent firstly finds such a collective plan for the order in which components are processed in single cells, so as to make fewer disturbances to the existing shop structure. In doing so, the shop agent decomposes the entire order into a set of components and initialises virtual prices for these components and minimal virtual profits for cells to start an iterative agent bidding process. Within each bidding iteration, the shop agent announces call for bids regarding components one at a time for cell agents to bid for. As for every cell agent, once receiving a call for bid for a component announced by the shop agent in a bidding iteration, it follows the procedures of the hierarchical agent bidding mechanism again to process the call. This means it still passes the call firstly to its children – machine agents. However, since a single machine is unable to process an entire component as mentioned above, machines in the cell must be grouped together to produce the component. Another iterative bidding process is then started by the cell agent to find a collective plan for the component. In doing so, the cell agent initialises a set of virtual prices for operations of the component and a set of minimal virtual profits for machines in the cell to start the bidding process. If the cell agent is able to find a collective plan for the component which meanwhile satisfies the minimal virtual profit assigned to the cell in the bidding iteration at the shop level, it submits the collective plan as a bid to the shop agent so that the bidding iteration at the shop level can be carried on. Similarly, when receiving call for bids for components in a bidding iteration at the shop level other cell agents will follow the same procedure to process these calls, which may result in other iterative agent bidding processes operated by these cell agents. As a result, planning and scheduling of the order in this step is based on a recursive bidding operation (as shown in figure 6.3) because each bidding iteration of the outer bidding process (i.e., the iterative agent bidding process at the shop level) relies on the entire completion of inner bidding processes (i.e., the iterative agent bidding processes at the cell level). It should be noted that in the recursive bidding operation, the outer bidding process is to find a collective plan for the order that is able to satisfy the due date of the order at the lowest production cost, whereas an inner bidding process controlled by a cell agent is to find a collective plan for a component that is able to satisfy the given minimal virtual profit

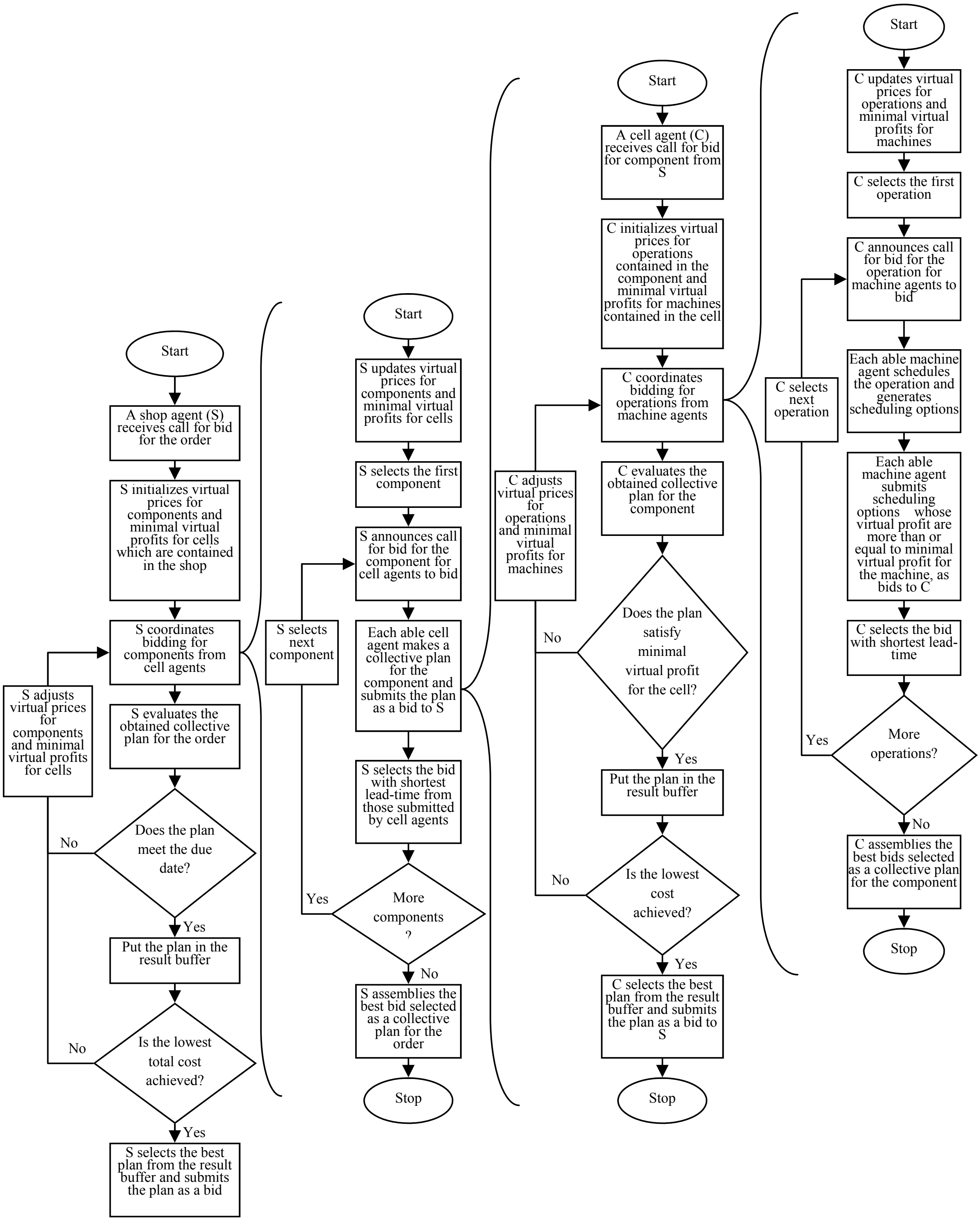

Figure 6.3 the Recursive Agent Bidding Operation

for the cell at the lowest production cost. This is because due date is only known for the entire product order and cannot be identified for a component in planning and scheduling period. However, since virtual prices for components and minimal virtual profits for cells are set as constraints for inner bidding processes, the adjustment of these two sets of parameters results in the adjustment of the criteria for evaluating whether a collective plan generated from an inner bidding iteration is feasible. This in turn enables a cell to submit alternative collective plans as bids after the completion of inner bidding processes. For example, when the virtual price for a component is very low or the minimal virtual profit for a cell is very high, a collective plan for this component in the cell with high cost and short lead-time may be discarded because it may not be able to meet the minimal virtual profit assigned to the cell. However, if the virtual price for the component is increased or the minimal virtual profit for the cell becomes very low, this plan may be kept and submitted as a bid. Therefore, the shop agent is able to adjust allocations of components to cells through iteratively adjusting virtual prices for components and minimal virtual profits for cells until an overall collective plan for the order that meets the order's due date at the minimum cost is achieved. If a shop agent is able to find a collective plan for the entire order that is able to satisfy the order's due date, it submits the plan as a bid to the system agent for competing with optimal bids submitted by other shop agents based on the production cost. However, compared to bids generated from the last step (i.e., step 1.2), the system agent will give bids from this step a lower priority since they lead to higher disturbances to the existing system structure of the manufacturing system than those from the previous step.

6.4.1.3 Step 1.3

If a shop agent cannot find a collective plan for the order by allocating components to cells, following the hierarchical agent bidding mechanism, the shop agent then needs to relax structural boundaries between cells so that resources within different cells can be flexibly regrouped together for fulfilling the order. According to the hierarchical agent bidding mechanism, this is achieved through the shop agent informing the order agent to remove the hierarchical layer of component agents and letting all of operation agents to directly register as children in the order agent. The shop agent then initialises virtual prices for operations and minimal virtual profits for cells to start an iterative agent bidding process. Within each bidding iteration, the shop agent announces call for bids for individual operations one at a time for cell agents to bid for. Once receiving a call for bid for an operation, a cell agent directly passes the call to machine agents contained which will schedule the operation based on their own capacities and statuses and submit scheduling options as bids to the cell agent as long as the options satisfy the minimal virtual profit assigned to the cell. The cell agent selects the bid with the shortest lead-time and submits the bid to the shop agent in order to compete with optimal bids submitted by other cell agents. Finally, if the shop agent finds a collective plan for the order, it submits the plan as a bid to the system agent. However, this bid will have a low priority if another shop agent is able to find a production plan for the order in previous steps (i.e., 6.4.1.1 and 6.4.1.2). This is because a collective plan from this step results in a higher disturbance to the existing system structure than that from previous steps.

6.4.2 Stage 2

After stage 1, if no one shop is able to process the entire product order either within structural constraints or across boundaries between cells contained, the system needs to consider resource regroupings between shops so that the order can be collectively produced across boundaries between shops. Following the hierarchical agent bidding mechanism, this stage may involve two steps as follows.

6.4.2.1 Step 2.1

According to the hierarchical agent bidding mechanism, the system agent firstly attempts to find a collective plan for the order in which a component is entirely produced in a shop so as to make fewer disturbances to the existing system structure. In doing so, the system agent decomposes the order into a set of production jobs with respect to components and starts an iterative agent bidding process to find such a collective plan. Within each bidding iteration, the system agent updates virtual prices for components and minimal virtual profits for shops and announces call for bids for components one at a time for shop agents to bid for. Once receiving a call for bid for a component in a bidding iteration operated by the system agent, a shop agent passes the call directly to cell agents contained which in turn passes the call to machine agents contained as well. However, since a single machine usually cannot process an entire component, a cell agent needs to start another iterative agent bidding process to find a collective plan for the component which is able to satisfy the minimal virtual profit assigned to its parent (i.e., a shop agent) at the lowest production cost. This results in a recursive bidding operation (as in 6.4.1.2) in which the outer bidding process is operated by the system agent, whereas the inner bidding processes are operated respectively by cell agents contained in shop agents. However, if no cells in a shop are able to process a component entirely or make collective plans satisfying the minimal virtual profit assigned to the shop, the shop then needs to regroup machines in different cells contained for fulfilling the component. In doing so, the shop agent initialises virtual prices for operations of the component and minimal virtual profits for cells to start another iterative agent bidding process. Similarly, this also results in a recursive bidding operation in which the outer bidding process is still controlled by the system agent, whereas the inner bidding processes are controlled by shop agents respectively.

6.4.2.2 Step 2.2

If based on the above steps, the system agent still cannot find a collective plan for the entire order, it means that letting components to be produced within single shops does not enable the entire order to be fulfilled within the order's due date. Therefore, boundaries between shops need to be relaxed further so that every component can be also collectively produced by using resources in different shops. In doing so, the system agent informs the order agent to remove the hierarchical layer of component agents and lets all of operation agents to register in the order agent as children. The system agent then uses an iterative agent bidding process to determine the optimum allocation of operations to shops. Within each bidding iteration, the system agent updates virtual prices for operations and minimal virtual profits for shops and announces call for bids for individual operations one at a time for shop agents to bid for. When receiving a call for bid for an operation from the system agent, a shop agent passes the call directly to cell agents contained which in turn hands over the call to machine agents contained as well. A machine agent will then schedule the operation specified in the call for bid and submit scheduling options as bids to its parent agent as long as they are able to satisfy the minimal virtual profit assigned to the shop. In turn, bids submitted by machine agents will be evaluated and filtered hierarchically from the cell level to the system level so as to select the bid with the shortest lead-time. Finally, if the system agent finds a collective plan for the entire order through the iterative bidding process, it will submit the plan to the order agent. However, if not, it means the product order cannot be fulfilled within the manufacturing system.

6.4.3 Discussions

In the hierarchical agent bidding process for planning and scheduling the product order in the given example, stage 1 represents a process in which the system agent attempts to select the best sub-system to produce the entire order from a set of candidates located at the same or different hierarchical levels so that the order can be fulfilled within structural constraints of the manufacturing system as far as possible. Stage 2 depicts a process of how resources in the whole system can be flexibly used and regrouped in order to complete the product order.

In stage 1, shop agents may theoretically submit three types of bids for the entire order to the system agent. According to where the bids are originated, these three types of bids are concerned with production plans for the product order at machine level, cell level and shop level.

- The bids at machine level correspond to production plans in which the product order is produced by single machines entirely.
- The bids at cell level correspond to production plans in which the product order is produced by the collective use of machines in single cells.
- The bids at shop level correspond to production plans in which the product order is produced by the collective use of machines of different cells in single shops.

Since bids at different levels are given different priorities (e.g., bids at machine level are given the highest priority and the bids at shop level are given the lowest priority), when making planning and scheduling decision for the product order based on submitted bids, the system agent firstly considers bids at machine level, then considers bids at cell level and finally considers bids at shop level. In this context, the hierarchical agent bidding process in this stage can be regarded as an equivalent biding scenario where: the system agent firstly lets all of machines with technical abilities (theoretically) to bid for the entire order in order to select the best machine on which the entire order can be fulfilled to meet the order's due date at the lowest cost. Secondly, if in the system there are no machines that are able to process the entire order or are able to produce the entire order to meet the order's due date, the system agent lets all of cells with technical ability to compete for the entire order so as to select the best cell in which the order can be collectively produced by several machines together to meet the order's due date at the lowest cost. Additionally, if in the system there are no such cells, the system agent then informs shop agents with technical ability to make collective plans for the order by regrouping resources across cells and in turn bid for the product order. In general, the hierarchical agent bidding process firstly forms a process where the top-level resource agent in the system HAAN attempts to select the optimal sub-system/resource for entirely producing the product order along the system tree from bottom level to top level (i.e., the stage 1). Only when there are no such sub-systems/resources, the collective use of resources across the whole system is considered (i.e., stage 2). This enables product orders to be cost-efficiently produced within structural constraints of manufacturing systems as far as possible.

Resource regroupings occur in both stages 1 and 2. However, resource regroupings in stage 1 are concerned with regrouping internal resources in single sub-systems. Since the hierarchical agent bidding process in stage 1 is equivalent to a bidding process which is implemented from the bottom level to the top level along the system tree as aforementioned above, resource regroupings within sub-systems at lower hierarchical levels are firstly considered for fulfilling the product order, which are then considered gradually from the bottom level to the top level. This enables the hierarchical agent bidding process to make fewer disturbances to existing system structures when considering resource regroupings. In the entire process for planning and scheduling the product order in the given example, there are four resource regroupings which are described in the following:

<u>*Resource regrouping I*</u>: The *resource regrouping I* comes out in step 1.3 when shop agents make collective plans for the product order by the collective use of machines across cells

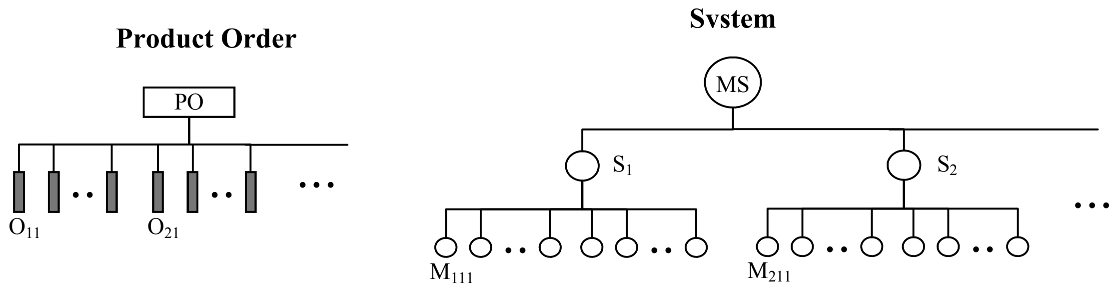

Figure 6.4 (a) the Relaxation of Structural Constraints in *Resource Regrouping I*

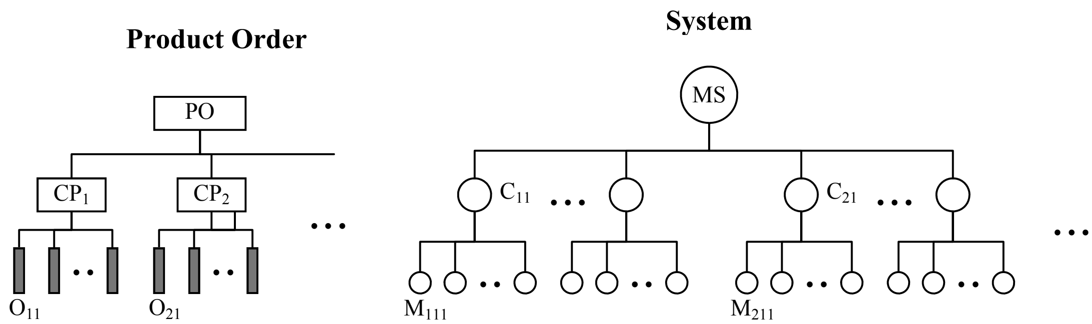

Figure 6.4 (b) the Relaxation of Structural Constraints in *Resource Regrouping II*

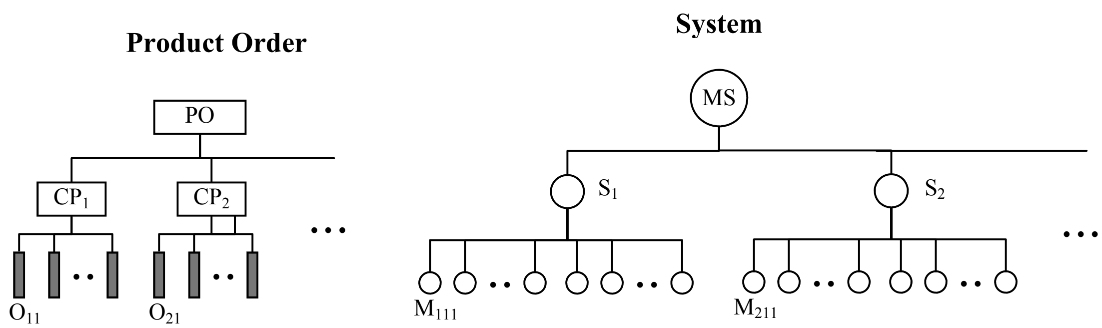

Figure 6.4 (c) the Relaxation of Structural Constraints in *Resource Regrouping III*

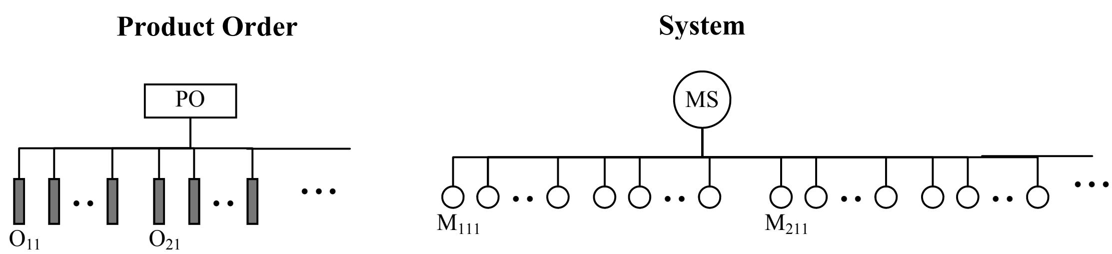

Figure 6.4 (d) the Relaxation of Structural Constraints in *Resource Regrouping IV*

contained. In this resource regrouping process, a shop agent informs the order agent to remove the hierarchical layer of component agents and directly register operation agents as children in the order agent. It then announces call for bids of individual operations for cell agents to bid for. Once receiving calls passed over from shop agents, cell agents will in turn directly pass the calls to machine agents contained according to the hierarchical agent bidding mechanism. This is equivalent to a situation where a shop agent announces call for bids of operations directly for a set of machine agents to bid for. The shop, in this context, is equivalent to a job shop where boundaries between cells are removed and any machines could bid for any operations in the order (as shown in figure 6.4 (a)).

<u>*Resource regrouping II*</u>: The *resource regrouping II* takes place in step 2.1 where the system agent decomposes the order into components and announces call for bids for components one at a time for shop agents to bid for. Once receiving calls from system agent, shop agents will directly pass the calls to cell agents contained[7] to bid for. This is similar to the scenario where the boundaries between shops in the manufacturing system are removed and all cells are placed heterarchically in the system and could bid for any components in an order (as shown in figure 6.4 (b)).

<u>*Resource regrouping III*</u>: The *resource regrouping III* occurs in step 2.1. As in a shop, when no cells are able to produce the released component entirely, the shop needs to make a collective plan for the component. In doing so, the shop agent breaks the component into a set of operations and announces call for bids for individual operations for cell agents to bid for. Once receiving calls for operations, cell agents will pass the calls to machine agents contained to bid for. This makes the shop to be similar to a job shop where all machines are placed heterarchically and could bid for any operations in the component (as shown in figure 6.4 (c)).

<u>*Resource regrouping IV*</u>: The *resource regrouping IV* is in step 2.2 where components are removed from the order's hierarchy. The system agent announces call for bids for individual operations which are then passed along the system hierarchy top-bottom to machine agents to bid for. The manufacturing system, in this context, is equivalent to a flat

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[7] Since it is assumed that a single machine is unable to produce an entire component, cell agents passing calls for components to machines agents is not considered in *resource regrouping II*.

factory (as shown in figure 6.4 (d)) where machines are placed heterarchically and can be grouped with maximal flexibility for manufacturing the product order.

6.5 Summary

This chapter at the beginning discussed the needs for a distributed agent-based mechanism which should enable a product order to be cost-efficiently planned and scheduled within structural constraints of manufacturing systems or across system boundaries with lowest disturbances to the existing system structures. Then a hierarchical agent bidding mechanism was described in this chapter, which represents the generic decision-making procedures for resource agents in the HAAN of a manufacturing system. This mechanism enables every resource agent to make planning and scheduling decisions with resource utilisations within structural constraints as far as possible. However, when it is not possible, the mechanism also enables resource agents to consider resource regroupings across system boundaries but with fewer disturbances to the existing system structure. Based on the implementation of the hierarchical agent bidding mechanism, production planning and scheduling of product orders is achieved through a hierarchical agent bidding process which enables a product order to be hierarchically decomposed and allocated to sub-systems/resources in a manufacturing system. The decision-making in the hierarchical agent bidding process is achieved through a recursive way which enables planning and scheduling decisions to be evaluated and coordinated hierarchically from bottom to top along the hierarchies of manufacturing systems in order to maintain performances of manufacturing systems and achieve global objectives (i.e., due dates and costs) for fulfilling product orders. In the hierarchical agent bidding process, resource regroupings occur when a resource agent attempts to find a collective plan for an order/job. Since every resource agent follows the generic procedures of the hierarchical agent bidding mechanism to process call for bids, once receiving a call for bid for an order/job, resource agents at higher levels will firstly pass the call to children resource agents at lower levels and however consider resource reconfigurations only when any children resources are unable to complete the order/job entirely. This makes resource regroupings occur gradually from the bottom sub-systems to the top system, which in turn maintains the minimum level of disturbances to existing system structures of manufacturing systems when considering resource regroupings.

CHAPTER 7

NUMERICAL TESTS OF AGENT BIDDING MECHANISMS

7.1 Introduction

In the previous two chapter, an iterative agent bidding mechanism and a hierarchical agent bidding mechanism were described, which work together to support production planning and scheduling in a distributed agent-based modelling environment. In details, the iterative agent bidding mechanism is used to determine the cost-efficient collective plan for a production job within a given system when the job needs to be decomposed and allocated to resources in the system so that it can be collectively processed. Coupled with the iterative agent bidding mechanism, the hierarchical agent bidding mechanism enables an entire product order to be planned and scheduled to meet the order's due date at the lowest production cost. Meanwhile, based on the hierarchical agent bidding mechanism, the overall production planning and scheduling considers resource utilisations within structural constraints of manufacturing systems as far as possible and however supports resource regroupings across system boundaries when needed so as to enhance the operational flexibility of manufacturing systems to changes in the business environment. Therefore, this chapter provides numerical tests to verify the capabilities of these two mechanisms. In doing so, a test case is provided in the next section (i.e., section 7.2), which includes a test manufacturing system and two test products. Section 7.3 describes how the numerical tests are designed and implemented based on the test case and discusses the test results. Section 7.4 concludes findings from the numerical tests and a summary is provided in the last section, namely section 7.5.

7.2 Test Case

The test case in this chapter is a cellular manufacturing system in which two kinds of products are manufactured. In the following, the layout and setup parameters of the manufacturing system are illustrated in sub-section 7.2.1, whereas the structures and processing parameters of the two products are given in sub-section 7.2.2.

7.2.1 The Layout and Setup Parameters of the Test Manufacturing System

The test manufacturing system consists of two workshops (Shop A and Shop B) each of which contains three manufacturing cells (as shown in figure 7.1). In shop A, three manufacturing cells contained are respectively Cell A1, Cell A2 and Cell A3 among which the former two are both normal production cells, whereas Cell A3 is an assembly and test cell. Similarly, Shop B also contains two normal production cells (Cell B1 and Cell B2) and an assembly and test cell (Cell B3) as well. Machines contained in different cells are shown in figure 7.2 and 7.3 and setup parameters of these machines are illustrated in Appendix A of the thesis. As for the test manufacturing system, there are three assumptions about the layout and material handling which are suggested in the following.

Firstly, except assembly machines, every machine in the manufacturing system is able to process any operation related to the functionality/functionalities it can provide. For example, the machine LatheA11 in Cell A1 has two functionalities including turning and drilling.

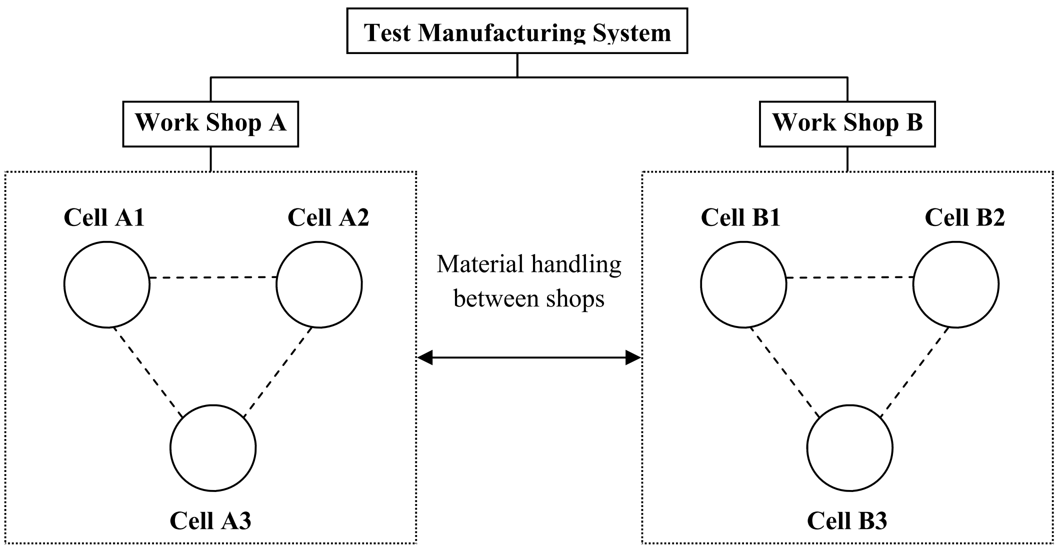

Figure 7.1 the Layout of the Test Manufacturing System

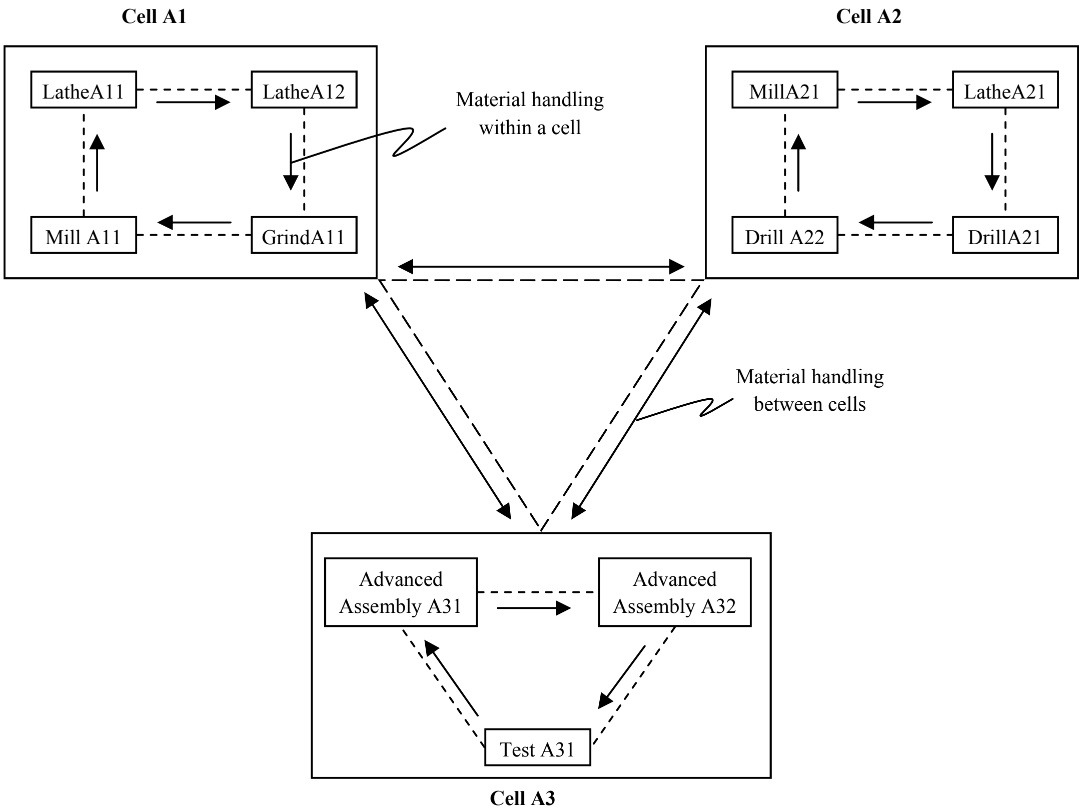

Figure 7.2 the Layout of Shop A

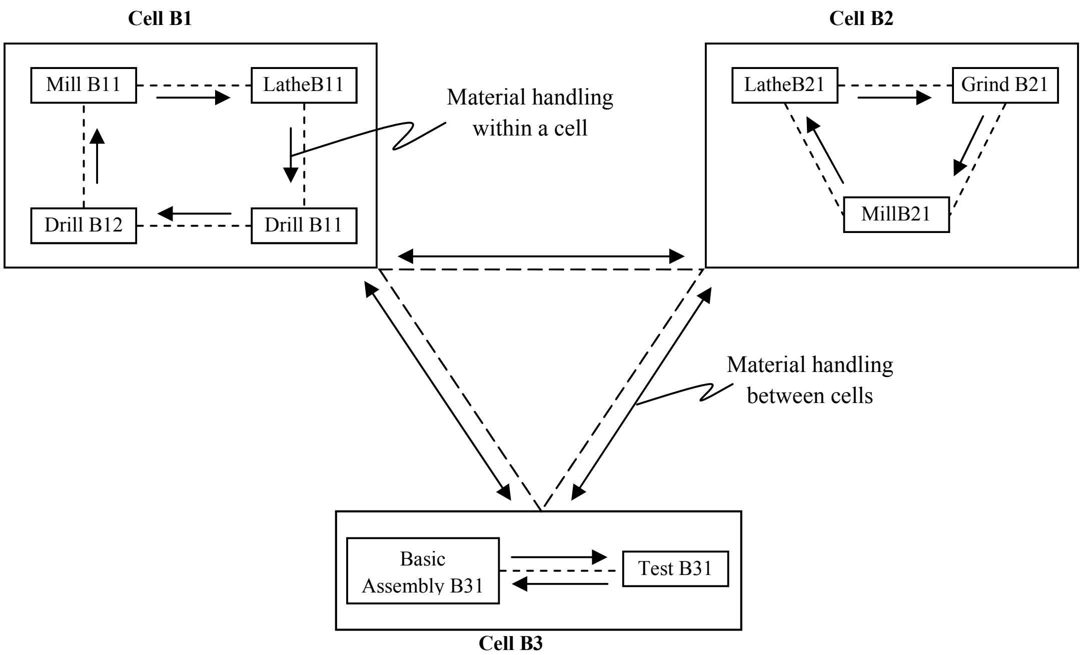

Figure 7.3 the Layout of Shop B

Lathe A11 therefore can perform any turning or drilling operations on any product or component. In the test manufacturing system, there are two kinds of assembly operations including the advanced assembly and the basic assembly. Only advanced assembly machines (i.e., the advanced assembly A31 and A32) are able to process both of the operations. However, the basic assembly machine (i.e., the basic assembly B31) is only able to process the basic assembly operation but cannot be used for the advanced assembly.

Secondly, machines contained in a particular cell are located at different apexes of a regular polygon whose type depends on the number of machines in the cell. For example, since there are four machines in Cell A1, these machines are respectively located at four apexes of a square. Similarly, machines contained in Cell A3 are at three apexes of an equilateral triangle. However, whatever the type of a polygon is, the length of each side of each polygon is the same for all of polygons which define the arrangements of machines in all of cells. This length represents the distance (i.e., the "*distance 1*" in table 7.1) between two next machines in a cell. In the test manufacturing system, the same approach to the arrangement of machines in a cell is used for arranging cells in a shop as shown in figure 7.1. The reason for using such a layout in the test manufacturing system is to facilitate the comparison between different restructuring options during the decision-making process of the system restructuring[8] and also to ease the computation of material handling cost and time resulting from the transportation of materials between manufacturing resources as discussed in the following.

Table 7.1 the Parameters of Material Transportation for the Test Manufacturing System

Parameter	Value
Distance 1	5 units
Distance 2	20 units
Distance 3	40 units
Material transportation time/distance unit	1.5 time unit
Material transportation cost/distance unit	0.5 cost unit

Thirdly, the material handling resources in the test manufacturing system are assumed to be always available for manufacturing resources. In other words, when a machine completes an operation of a component, materials for manufacturing the component are immediately transported by a material handling resource to the machine which will carry out the next

[8] The implementation and test about the system restructuring referred from the thesis of Anosike (2005)

operation of the component. In the test manufacturing system, the distance for transporting materials between any two machines in different shops is the same, which is represented as "*distance 3*" in table 7.1. The distance for transporting materials between any two machines in different cells of a shop is also a constant, which is represented as "*distance 2*" in table 7.1. However, the transportation of materials between machines in a particular cell follows a clockwise route along the sides of the polygon which defines the arrangement of machines in the cell. Consequently, the distance for transporting materials between two machines in a cell may be different. For example, the distance for material transportation from MillA11 to Lathe A11 equals to the length of "*distance 1*", namely 5 distance units. However, the distance for material transportation from LatheA11 to MillA11 becomes three times of "*distance 1*", namely 15 distance units. The detailed parameters regarding the material handling cost and time in the test manufacturing system are also shown in table 7.1.

In the numerical tests, in order to facilitate the description of machines in results discussion, abbreviated names of machines are used. For example, the LatheA11 is abbreviated as LA11. The MillA21 is notated as MA21. The GrillA11 and Drill A21 are represented as GA11 and DA21 respectively. The AssemblyA31 is abbreviated as AA31.

7.2.2 The Structures and Processing Parameters of the Test Products

In the test case, two products are designed to be produced within the test manufacturing system, which include Product PA and Product PB. Every product is assembled from two basic components each of which needs a sequence of operations to be processed at machines. The structures of these two products are illustrated in figure 7.4 (a) and 7.4 (b) respectively in which the sequence between operations needed for a component or

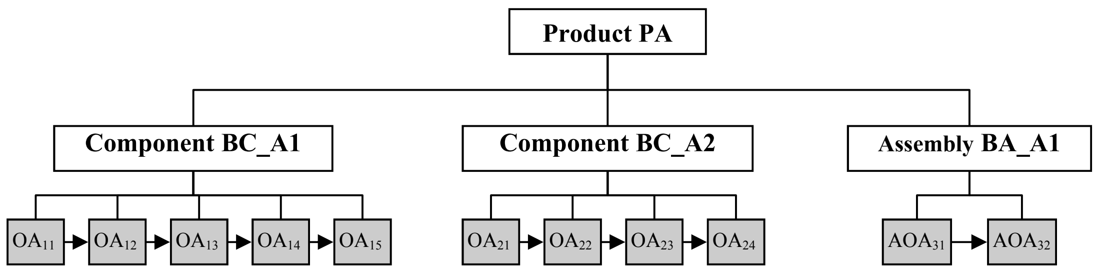

Figure 7.4 (a) the Structure of Product PA

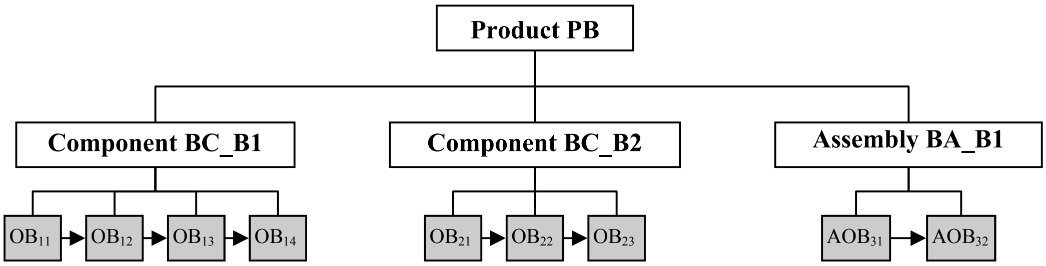

Figure 7.4 (b) the Structure of Product PB

Table 7.2 (a) Operations of BC_A1

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
OA11	Turning	170	0.75
OA12	Turning	143	0.75
OA13	Turning	86	1.00
OA14	Grinding	30	0.25
OA15	Milling	62	0.75

Table 7.2 (b) Operations of BC_A2

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
OA21	Milling	80	0.75
OA22	Milling	80	0.75
OA23	Drilling	54	0.4
OA24	Drilling	26	0.2

Table 7.2 (c) Operations of BA_A1

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
AOA31	Advanced Assembly	120	1.00
AOA32	Test	50	1.00

Table 7.2 (d) Operations of BC_B1

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
OB11	Milling	120	0.75
OB12	Turning	30	0.2
OB13	Drilling	6	0.2
OB14	Drilling	20	0.4

Table 7.2 (e) Operations of BC_B2

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
OB21	Turning	6	0.3
OB22	Milling	46	0.3
OB23	Grinding	32	0.25

Table 7.2 (f) Operations of BA_B1

Operations	Process Required	Material Volume (cm^3)	Tolerance (+/- mm)
AOB31	Basic Assembly	70	1.00
AOB32	Test	30	1.00

assembly is described by arrows between operations. The detailed data regarding the operations of components and assemblies are provided in table 7.2 (a) – (f).

7.3 The Numerical Tests and Result Discussions

Based on the test case described above, two tests are implemented in this chapter. The first test is concerned with the validation of the effectiveness of the iterative agent bidding mechanism to finding optimum collective plans for production jobs, whereas the second test is to verify the proposed capabilities of the hierarchical agent bidding mechanism in planning and scheduling product orders within manufacturing systems. Both tests are implemented on a software platform which is developed by the author based on the use of Java Development Kit (JDK) 1.6. The followings describe the details about the tests' designs and results discussions.

7.3.1 Test I

Test Aims

This test aims at investigating whether the GA-based iterative agent bidding mechanism is able to find the optimum collective plans for allocating production jobs containing a sequence of sub-jobs to a set of resources in a given system so that the entire job can be completed before a given due date at the lowest production cost.

Test Design

In this test, a production job for the Component A1 (BC_A1) of product PA is created with a preferred lead-time[9] at 1 day[10], which will be allocated in Cell A1 of the test manufacturing system. In order to provide a standard for evaluating the optimality of the iterative agent bidding mechanism, the absolute optimum plan for allocating operations of the production job to machines contained in Cell A1 is already determined by using a centralized method in which the absolute optimum plan is found through the enumerated

[9] The preferred lead-time represents the time period between the required due date and the current time.
[10] One day includes 1000 time units.

evaluation of all possible plans for the production job. To facilitate the process for searching the absolute optimum plan based on the centralized method, this test assumes that there are no unprocessed jobs for machines in Cell A1 so as to reduce the number of possible scheduling options for operations that can be provided by machines and in turn reduce the total number of possible plans for the entire production job. The absolute optimum plan for the entire job determined by the centralized method is illustrated in table 7.3 where it is shown that the optimum processing route for this job on machines is LA11 – LA11 – LA11 – GA11 – MA11 and the total lead-time and cost of the absolute optimum plan is 121 time units and 855 cost units respectively.

Table 7.3 the Absolute Optimum Plan for the Production Job of BC_A1

Processing Route	LA11- LA11- LA11- GA11- MA11
Total lead-time for the order	121 time units
Total cost for the order	855 cost units

Since a Genetic Algorithm (GA) is embedded in the agent bidding mechanism to control the process for searching the optimum collective plan, the results based on the bidding mechanism may be, to some extent, influenced by the random nature of GA. To have an accurate investigation on the effectiveness of the iterative agent bidding mechanism, this test involves an experiment with 10 replications which are conducted under the same running environment of GA as shown in table 7.4.

Table 7.4 Setup Parameters of GA

Setup Parameters	Values
Population Size	6
Number of GA Iterations	50
Crossover Probability	0.5
Mutation Probability	0.35

Test Results and Discussions

The collective plans obtained by using the iterative agent bidding mechanism in the 10 replications are illustrated in table 7.5 which indicates that the solution of every experiment replication is consistent with the absolute optimum plan shown above. This demonstrates that the iterative agent bidding mechanism is able to find the optimum collective plan for the given test case and in turn validates the optimality of the iterative agent bidding

Table 7.5 the Collective Plans for the Production Job of BC_A1 Based on the Iterative Agent Bidding Mechanism

Number of Replication	Processing Route	Cost (units)	Lead-Time (units)
1	LA11- LA11- LA11- GA11- MA11	855	121
2	LA11- LA11- LA11- GA11- MA11	855	121
2	LA11- LA11- LA11- GA11- MA11	855	121
4	LA11- LA11- LA11- GA11- MA11	855	121
5	LA11- LA11- LA11- GA11- MA11	855	121
6	LA11- LA11- LA11- GA11- MA11	855	121
7	LA11- LA11- LA11- GA11- MA11	855	121
8	LA11- LA11- LA11- GA11- MA11	855	121
9	LA11- LA11- LA11- GA11- MA11	855	121
10	LA11- LA11- LA11- GA11- MA11	855	121

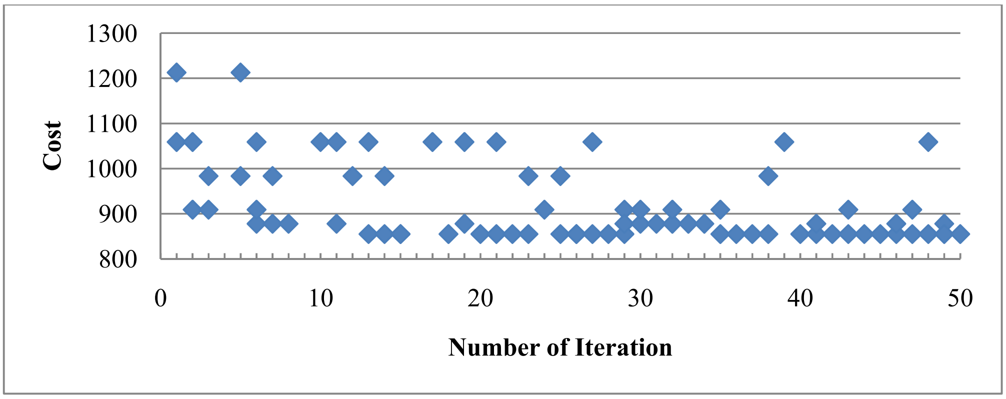

Figure 7.5 (a) Bids Received at each GA Iteration in the Bidding Process

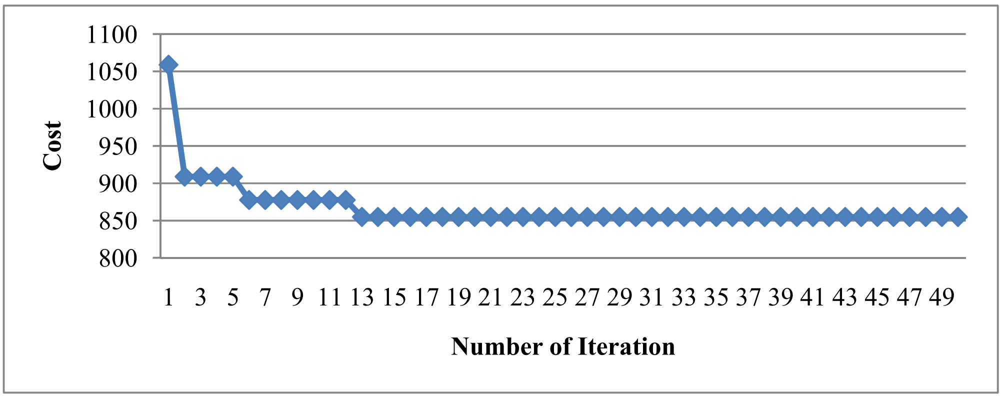

Figure 7.5 (b) the Optimal Bids after each GA Iteration in the Bidding Process

mechanism. Figures 7.5 (a) and 7.5 (b) depict the detailed process of using the bidding mechanism for searching the optimum collective plan for the production job of BC_A1 in the seventh replication, among which figure 7.5 (a) shows the bids generated from the bidding process at each GA iteration[11] and figure 7.5 (b) shows the optimum bid recorded by the GA after each GA iteration. From figure 7.5 (a), it is observed that the adjustment of the control parameters for the bidding process (i.e., the virtual prices for operations and minimal virtual profits for resources) enables the bidding process to find alternative allocation plans for the entire job because at each GA iteration, different offspring chromosomes representing different control parameters results in distinguished allocation plans. For example, at the sixth GA iteration shown in figure 7.5 (a), three alternative bids with different costs are generated through the bidding process. Meanwhile, these two figures also show that the GA optimises the searching domain gradually over iterations towards the area where the optimum allocation plan is located.

7.3.2 Test II

This test aims at validating the proposed capabilities of the hierarchical agent bidding mechanism in planning and scheduling entire product orders within manufacturing systems. Two sub-tests are involved in this section, namely Test 2-1 and Test 2-2 among which the former one is to verify the ability of the hierarchical agent bidding mechanism in firstly considering cost-efficient resource utilisations within structural constraints of manufacturing systems when planning and scheduling entire orders, whereas the second one is to demonstrate whether the hierarchical agent bidding mechanism is able to support resource regroupings across system boundaries in order to enhance the operational flexibility of manufacturing systems to dynamic changes in the business environment.

7.3.2.1 Test 2-1

Test Aims

This test is to investigate that in the process for planning and scheduling product orders, whether the hierarchical agent bidding mechanism is able to firstly consider cost-efficient production plans and schedules within structural constrains of manufacturing systems.

[11] At a GA iteration, crossover and mutation of chromosomes in the population are conducted, which may generate several offspring chromosomes each of which will be used to coordinate the bidding process at a bidding iteration.

Test Design

In this test, an order for product PB is created with a batch quantity at 1 and a preferred lead-time at 1 day unit as well. Meanwhile, in order to create a scenario so that there is no necessity to fulfil the order by resource regroupings across system boundaries of the test manufacturing system, this test assumes that there are no unprocessed orders for the test manufacturing system to provide enough capacity for the system to fulfil the order within its structural constraints. From the structure and composition of product PB, it is observed that both shops in the test manufacturing system have technical abilities to produce the order entirely and also to manufacture the order within their structural constraints (i.e., every component or assembly is processed within a single cell). To have an absolute standard for evaluating the effectiveness of the hierarchical agent bidding mechanism, the optimum production plans and schedules for the order within the two shops' structures are determined through the use of a centralized enumeration scheme (i.e., all possible plans within the structural constraints of a shop are considered, among which the one satisfying the order's due date at the lowest production cost is selected as the optimum one for the shop), which are illustrated in table 7.6 where it is shown that both shops are able to fulfil the order of PB within their structural constraints to satisfy the given due date and however the optimum plan of Shop B for this order results in a lower total production cost (641 cost units) than that of Shop A (675 cost units). As a result, when planning and scheduling the created order, if the hierarchical agent bidding mechanism is able to firstly consider cost-

Table 7.6 the Optimal Production Plans for the Order of PB in Shop A and B

The Optimal Production Plan for the Order for PB in Shop A		
Component/Assembly	Processing Route	Lead-time/Cost (in unit)
BC_B1	MA21 – LA21 – DA21 – DA21	145 / 305
BC_B2	LA11 – MA11 – GA11	109 / 131
BA_B1	AA31 – TA31	177 / 239
Total Lead-time/Cost		**222 / 675**
The Optimal Production Plan for the Order for PB in Shop B		
Component/Assembly	Processing Route	Lead-time/Cost (in unit)
BC_B1	MB11 – LB11 – DB11 – DB11	129 / 277
BC_B2	LB21 – MB21 – GB21	93 / 151
BA_B1	A B31 – TB31	73 / 213
Total Lead-time/Cost		**202 / 641**

efficient production plans and schedules within structural constraints of manufacturing systems, the created order should be entirely produced in Shop B and also the components and product assembly of the order should be processed in such a way: BC_B1 to CellB1, BC_B2 to CellB2 and BA_B1 to CellB3.

Since the iterative agent bidding mechanism is always used in the hierarchical agent bidding process to find collective plans for orders or production jobs, to avoid possible noise caused by the random-based searching scheme in the former bidding mechanism and have an accurate investigation about the effectiveness of the hierarchical agent bidding mechanism, this test also conducts an experiment with 10 replications for planning and scheduling the created order. Setup parameters of GA in this test are the same with that in the last test as shown in table 7.4.

Table 7.7 the Production Plans for the Order of PB based on the Hierarchical Agent Bidding Mechanism

Number of Replication	Components / Assembly	Processing Route	Lead-time / Cost (in units)	Total Lead time / Cost (in units)
1	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
2	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
3	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
4	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
5	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
6	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
7	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
8	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
9	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	
10	BC_B1	LB11 – LB11 – DB11 – DB11	121 / 280	202 / 641
	BC_B2	LB21 – MB21 – GB21	93 / 151	
	BA_B1	BA31 – TB31	73 / 213	

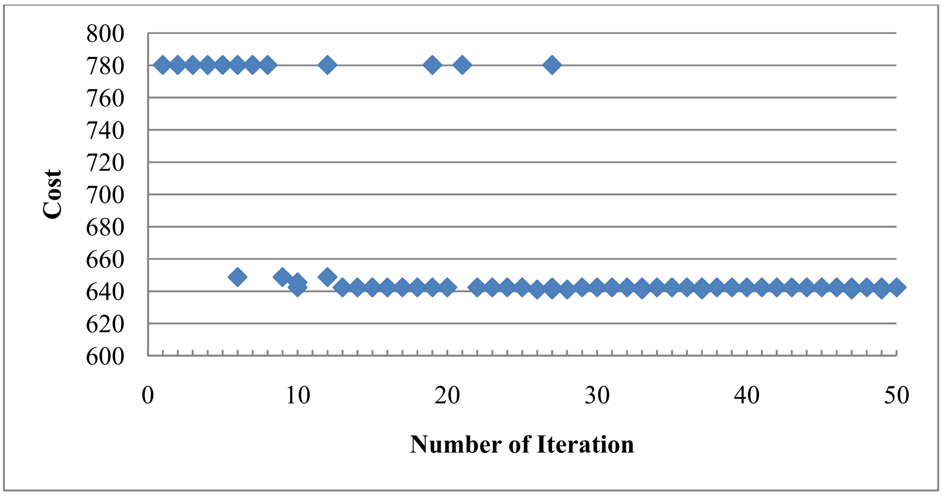

Figure 7.6 (a) Bids Received at each GA Iteration in the Iterative Bidding Process Operated by Shop B

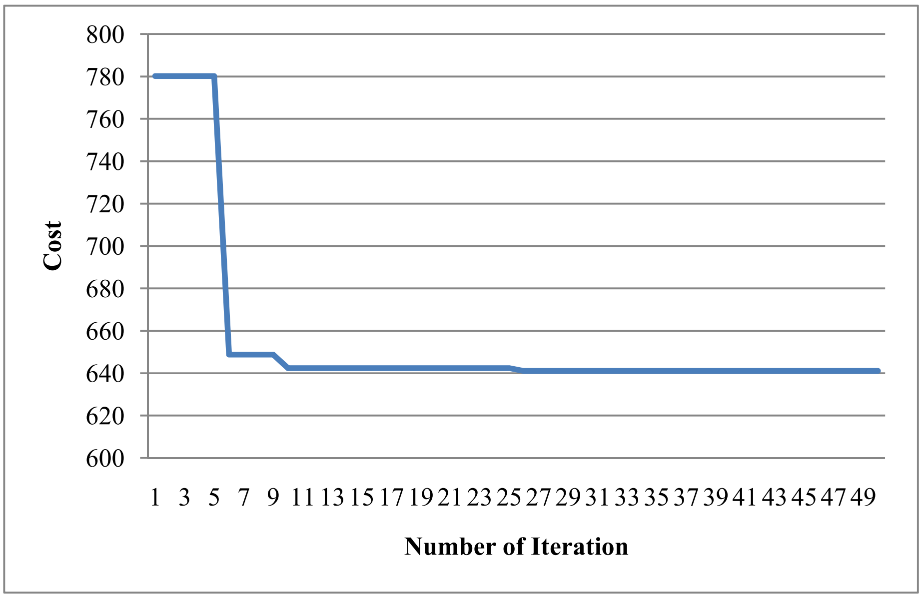

Figure 7.6 (b) the Optimal Bid after each GA Iteration in the Iterative Bidding Process Operated by Shop B

Test Results and Discussions

Table 7.7 shows the production plans and schedules for the created order which are derived from the implementation of the hierarchical agent bidding mechanism in the 10 replications. From this table, it is observed that in all of replications, the order of PB is entirely produced within Shop B and also manufacturing of components and assembly of PB are also consistent with the anticipated way mentioned previously (BC_B1—CellB1, BC_B2—CellB2 and BA_B1—CellB3). Moreover, the hierarchical agent bidding mechanism in every replication finds the production plan and schedule for the order which is absolutely the same with the optimum plan shown in table 7.6 (i.e., the optimum production plan for PB in Shop B). In conclusion, this demonstrates that when planning and scheduling product orders, the hierarchical agent bidding mechanism is able to firstly consider the cost-efficient production plans and schedules within structural constraints of manufacturing systems.

In the hierarchical agent bidding process, when planning and scheduling the order of PB in Shop B, due to the existence of product assembly, the order cannot be entirely produced by any cells of Shop B. In this condition, Shop B needs to find a collective plan for the order by allocating components and the assembly to cells based on the use of the iterative agent bidding mechanism. Recursively, when receiving a released component in a bidding iteration operated by Shop B, a cell with technical ability also needs to start another iterative agent bidding process to find a collective plan for the component. Thus, planning and scheduling the order in Shop B based on the implementation of the hierarchical agent bidding mechanism results in a recursive bidding process. Figures 7.6 (a) and 7.6 (b) depict the top-level of the recursive bidding process namely the process of Shop B finding the optimum production plan and schedule for the entire order. From these two figures, it is indicated that coupled with the recursive implementation of the iterative agent bidding process at multiple levels, the hierarchical agent bidding mechanism is able to result in alternative production plans for the entire order iteratively and also able to optimise the production plans over iteration towards the optimum one.

7.3.2.2 Test 2-2

Test Aims

This test aims at investigating whether the hierarchical agent bidding mechanism is able to consider resource regroupings so as to enhance the operational flexibility of manufacturing systems to changes in the business environment, especially change in customer demands.

Test Design

In the test, in order to provide a benchmark for evaluating the operational flexibility to changes in the business environment supported by the hierarchical agent bidding mechanism, two manufacturing systems are designed in this test, which have the same structure and machine composition with the test manufacturing system. The test then focuses on comparing the performances of these two systems when facing a demand fluctuation.

- *System I*

  The *System I* is designed as a conventional cellular manufacturing system wherein every shop is responsible for producing a specific product and every cell is to manufacture a specific component/assembly. As for product PA, since it needs an advanced assembly operation which can be only processed by the assembly cell (Cell A3) of Shop A, PA in *System I* is dedicatedly produced within Shop A. As for product PB, since it is shown in Test 2-1 that Shop B is able to provide it with a lower cost than Shop A, PB in *System I* then is dedicatedly produced within Shop B. The detailed specification of which cell is responsible for producing which component in *System I*, is given in table 7.8, which is designed based on the lowest cost criteria. For such a manufacturing system, when it receives an order for a product, the system passes the order directly to the assigned shop for the product. The shop then decomposes the order into components and assemblies and hands over them to specific cells for scheduling. As for each cell, the planning and scheduling for a component or assembly is performed by a cell manager which makes all of possible planning and scheduling

Table 7.8 the Dedicated Shops and Cells for PA and PB in *System I*

Shops/Cells	Products / Components or Assembly
Shop A	PA
CellA1	Component BC_A1
CellA2	Component BC_A2
CellA3	Assembly BA_A1
Shop B	PB
CellB1	Component BC_B1
CellB2	Component BC_B2
CellB3	Assembly BA_B1

options for the component or assembly and submits all these options to the shop. The shop then concurrently considers all of options submitted by different cells for different components so as to find the optimum production plan and schedule for the entire order (i.e., satisfying the due date at the lowest production cost).

- *System II*

In *System II*, production planning and scheduling for product orders is controlled based on the hierarchical agent bidding mechanism.

To simulate the change in customer demand, orders for both PA and PB are assumed to be placed with a unique pattern: batch quantity for every order must be at 20 and preferred lead-time for every order must be 2 day units. Around the two products PA and PB, this test creates 11 sets of orders each of which covers orders for 5 simulation days (as shown in Appendix B). In the first set of orders, the numbers of daily orders for PA and PB are 6 and 4 respectively, whereas each set in the following increases the number of daily orders for PA by 1 based on that in the previous set (as shown in table 7.9). In each order set, orders at each simulation day are issued in a random sequence and the rule for processing these orders in both *System I* and *System II* is based on the First Come and First Served (FCFS) rule. In the test, the assumption of the unique pattern for product orders is to facilitate the data analysis regarding systems' performances under the demand fluctuation. For example, due to the same batch quantity of orders, machine utilisation in a manufacturing system can be approximately evaluated by the number of operations processed by machines. Meanwhile, the same batch quantity and preferred lead-time for orders enable analyzers to use the maximum number of processed orders to evaluate the capacity of a system/sub-

Table 7.9 the Created Order Sets

Order Set	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Number of Daily Orders for PA	6	7	8	9	10	11	12	13	14	15	16
Number of Daily Orders for PB	4	4	4	4	4	4	4	4	4	4	4
Total Number of Orders for PA in an Order Set	30	35	40	45	50	55	60	65	70	75	80
Total Number of Orders for PB in an Order Set	20	20	20	20	20	20	20	20	20	20	20

system and to use the number of non-accepted[12] orders to roughly evaluate the operational flexibly of a manufacturing system to the demand fluctuation. For example, if under the same condition (i.e., the same market and manufacturing conditions), one manufacturing system has a lower number of non-accepted orders than another, it is implied that this manufacturing system has a higher operational flexibility to the demand fluctuation than the other and vice versa.

Test Results and Discussions

For the 11 sets of orders, the detailed production plans and schedules of *System I* and *System II* are illustrated in Appendix C. Table 7.10 and figures of 7.7 (a) and (b) depict the overall performances of *System I* and *System II* in dealing with the 11 sets of orders.

From table 7.10, it is shown that in *System I*, when the number of daily orders for PA equals to or is more than 9 (i.e., 4th – 11th order sets), there are non-accepted orders for PA whose number is respectively 2, 6, 11, 16, 20, 25, 30 and 35. Since for each order set, the total number of orders for PA is increased by 5 (the number of increase orders for PA per day is 1 and each set covers 5 simulation days) compared to the previous set, it is implied that *System I* basically rejects all of increased orders when the number of daily orders for PA is more than 9. As a result, the maximum capacity of Shop A in *System I* is approximately enough to fulfil 9 orders of PA per day. In turn, this reflects that at every simulation day, only 9 orders of PA can be fulfilled within the structural constraints of Shop A (i.e., every component and assembly of PA is produced in a single cell of Shop A). As for *System II*, although the daily demand of PA is increased gradually over the 11 sets of orders, all of orders in each set are accepted by the manufacturing system, which means that all of orders can be effectively planned and scheduled in *System II* to meet the orders' due dates. This reflects that *System II* has a higher operational flexibility to the demand

Table 7.10 Number of Non-Accepted Orders in *System I* and System *II*

Order Set	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Number of Non-accepted Orders in ***System I***	0	0	0	2	6	11	16	20	25	30	35
Number of Non-accepted Orders in ***System II***	0	0	0	0	0	0	0	0	0	0	0

[12] The non-acceptation of an order means this order cannot be effectively planned and scheduled to meet the order's due date.

fluctuation than *System I* and in turn, reflects that implementation of the hierarchical agent bidding mechanism is able to enhance the operational flexibility of a manufacturing system to demand fluctuations.

Figures 7.7 (a) and (b) depict the average number of operations processed by machines per day in the two systems which can be used to evaluate machine utilisations in the two systems as discussed in the test design. From 7.7 (a), it is observed that since in *System I*, PA and PB are dedicatedly produced in Shop A and B respectively, the machine utilisation of Shop B in *System I* is always maintained at a low level (3.3), whereas the machine utilisation of Shop A in *System I* is gradually increased from 5.0 with the demand increase of PA and finally maintained at a certain level of 7.5 as reaching the maximum capacity. Comparing to the performance of *System I*, the performance of *System II* shown in figure 7.7 (b) can be classified into three stages listed in the following.

- Firstly, when the daily demand of PA is between 6 to 9 orders, the performance of *System II* is quite similar to that of *System I*, i.e., machine utilisation of Shop B is maintained at a low level (3.0 – 3.3) and machine utilisation of Shop A grows from 5.3 gradually up to 7.5 with the demand increase of PA. This reflects that in this stage, orders of PA in *System II* are mainly produced in Shop A and orders of PB are mainly processed in Shop B. Meanwhile, the overall performance of *System I* in this stage indicates that orders of PA can be fulfilled entirely within structural constraints of Shop A (i.e., components and assembly are processed within single cells) and also orders of PB can be fulfilled entirely within the structural constraints of Shop B. A hypothesis is made for the overall performance of *System II* at this stage, which is suggested as following:

  Hypothesis 1: at the first stage, orders of PA are produced within structural constraints of Shop A and orders of PB are completed within structural constraints of Shop B.

- Secondly, when the daily demand of PA is between 10 to 12 orders, unlike *System I* where machine utilisations in Shop A and Shop B are both maintained at certain levels (7.3 and 3.3 respectively), the machine utilisation of Shop A in *System II* keeps growing to 9.9 with the demand increase of PA but the machine utilisation of Shop B in *System II* is still maintained at around 3.3. This implies that in this stage, orders of PA are still

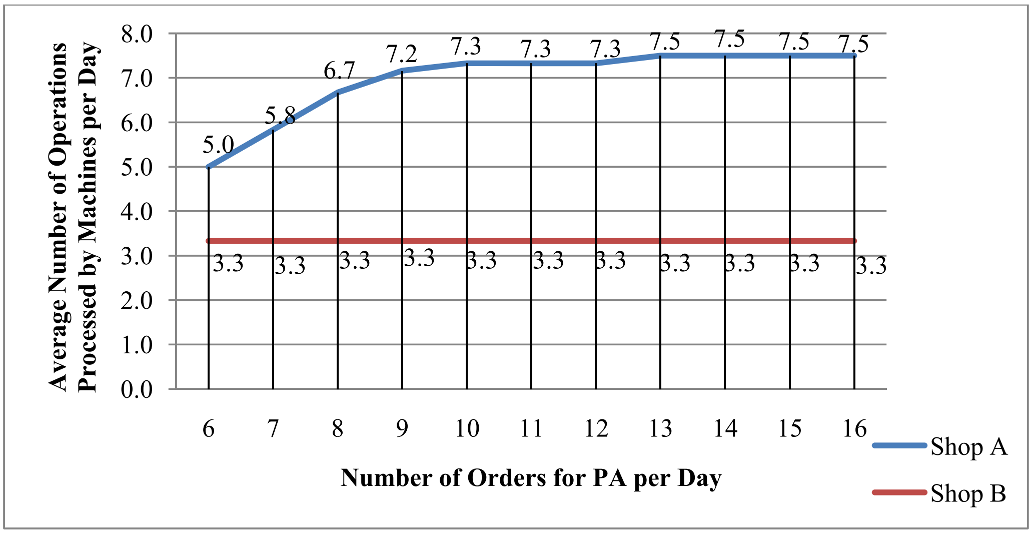

Figure 7.7 (a) the Average Number of Operations Processed by Machines in *System I*

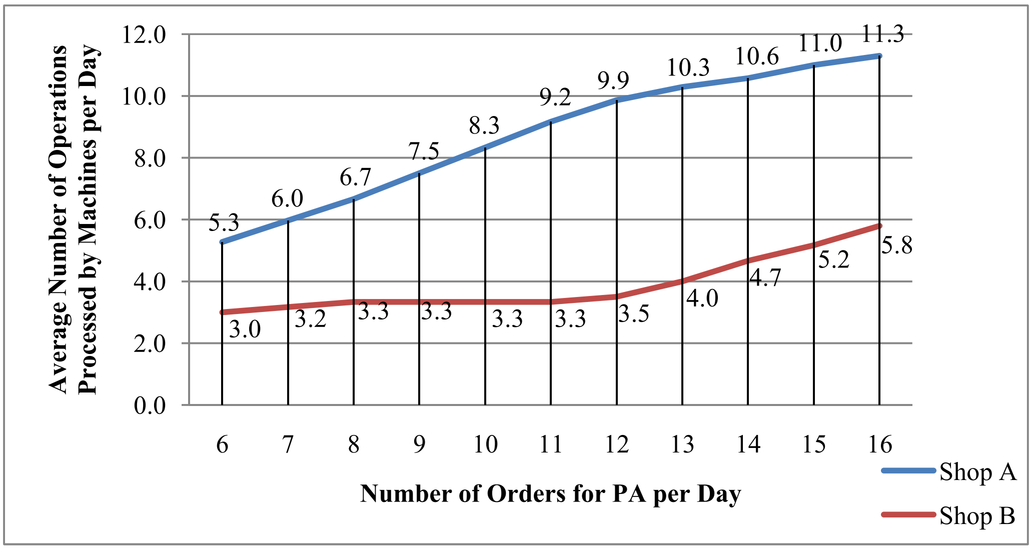

Figure 7.7 (b) the Average Number of Operations Processed by Machines in *System II*

produced in Shop A and, Shop B is also primarily responsible for producing PB. However, as discussed previously, only 9 orders of PA can be fulfilled within the structural constraints of Shop B per day according to the planning and scheduling performance of *System I* and also Shop B cannot entirely produce PA due to the lack of advanced assembly machines. The only one explanation for the increasing machine utilisation of Shop A in *System II* at this stage is that increased orders of PA at this stage are produced based on the resource regrouping between cells in Shop A so as to enhance the operational flexibility to the demand increase and meanwhile lead to fewer disturbances to existing system structure. As a result, for the overall performance of *System II* at this stage, a hypothesis is made as following:

Hypothesis 2: at the second stage, orders of PA are still produced entirely within Shop A. However, for some of orders of PA, resource regroupings between cells of Shop A are used to fulfil these orders and meanwhile the proportion of such orders grows with the demand increase of PA.

- Thirdly, when the number of daily orders of PA is more than 12, the growth pace of machine utilisation of Shop A in *System II* is gradually decreased with the demand growth of PA. However, the machine utilisation of Shop B in *System II* at this stage is no longer unchanged at a certain level but gradually increased from 3.5 to 5.8. The only reason for this phenomenon is that when the daily demand of PA excesses 12 orders, resources of Shop B are flexibly utilised to fulfil some of orders of PA. Since the assembly of product PA must be processed in Shop A, this results in resource regroupings across shops. In this sense, for the overall performance of *System II* at this stage, there is another hypothesis as following:

  Hypothesis 3: at the third stage, some of orders of PA are processed across Shop A and Shop B (i.e., the resource regrouping across shops). Meanwhile, implied from the increasing machine utilisation of Shop B, the percentage of such orders grows gradually with the demand increase of PA.

In the following, the detailed planning and scheduling performance in *System II* over the three stages are analysed, which aims at validating the three hypotheses and also providing detailed investigation on how resource regroupings are incurred over the 11 sets of orders based on the implementation of the hierarchical agent bidding mechanism.

Table 7.11 illustrates the planning and scheduling performance of *System II* in the first stage (i.e., the daily demand of PA is between 6 and 9 orders). The results in this table shows that at the first stage, orders of PA are all produced in Shop A and 97.5% PB orders are processed entirely in Shop B. Meanwhile, 98.3% orders of PA are fulfilled in Shop A with such a plan: BC_A1 – CellA1, BC_A2 – CellA2 and BA_A1 – CellA3. Also, 97.5% orders of PB are produced in Shop B with such a plan: BC_B1 – CellB1, BC_B2 – CellB2

Table 7.11 the Planning and Scheduling Performance of System *II* at the first Stage

Products		Number of daily Orders of PA				
		6	7	8	9	Average
PA made in Shop A		100%	100%	100%	100%	100%
PA made in Shop A with such a plan:	BC_A1 made in CellA1 BC_A2 made in CellA2 BA_A1 made in CellA3	100%	100%	100%	93%	98.3%
PA made in Shop A with other plans		0	0	0	7%	1.7%
PB made in Shop B		90%	95%	100%	100%	97.5%
PB made in Shop B with such a plan:	BC_B1 made in CellB1 BC_B2 made in CellB2 BA_B1 made in CellB3	90%	95%	100%	100%	97.5%
PB made in Shop B with other plans		0	0	0	0	0

and BA_B1 – CellB3. This validates the *hypothesis 1* for the overall performance of *System II* at the first stage. Furthermore, recalling the dedicated production design for *System I* as shown in table 7.8, it is implied that the implementation of the hierarchical agent bidding mechanism makes *System II* at the first stage to perform as a conventional cellular manufacturing system where products and components are produced rigidly within dedicated shops and cells so as to reap the benefits resulting from the existing system structure such as high manufacturing efficiency and low production costs. Moreover, it also demonstrates the point discussed in the last test (i.e., Test 2-1), namely the hierarchical agent bidding mechanism is able to firstly consider the cost-efficient resource utilisations within structural constraints for fulfilling customer orders.

Table 7.12 illustrates the planning and scheduling performance of *System II* at the second (i.e., the daily demand of PA is between 10 and 12 orders) and third (i.e., the daily demand of PA is more than 12 orders) stages. From this table, it is observed that at these two stages, orders of PB (95% - 100%) are still mainly processed in Shop B and also produced within the structural constraints of Shop B (i.e., every component/assembly is completed within a single cell). At the second stage, almost all of orders of PA (98.3% - 100%) are entirely produced in Shop A and meanwhile the percentage of PA orders fulfilled with resource regroupings across cells of Shop A is increased gradually from 16% to 25%. This validates the *hypothesis 2* for the overall performance of *System II* at the second stage. In the third stage, the portion of PA orders fulfilled with resource regrouping across cells of Shop A is maintained at 27% approximately. However, the proportion of PA orders produced based on resource regrouping across the two shops grows dramatically from 6.2% to 20%, which

Table 7.12 the Planning and Scheduling Performance of System *II* at the second and third Stages

Products	Number of daily Orders of PA						
	10	11	12	13	14	15	16
PA made within Shop A's structure*	84%	78%	73.3%	66.1%	61.4%	54.6%	52.5%
PA made with resource regroupings across cells of Shop A	16%	22%	25%	27.7%	27.2%	30.7%	27.5%
PA made with resource regroupings across Shop A and B	0	0	1.7%	6.2%	11.4%	14.7%	20%
PB made within Shop B's structure*	100%	100%	100%	100%	100%	100%	95%
PB made with resource regroupings across cells of Shop B	0	0	0	0	0	0	0
PB made with resource regroupings across Shop A and B	0	0	0	0	0	0	0

* *A product is made within a shop's structure means that the product is entirely produced within the shop and also every component/assembly is entirely processed within a single cell of this shop*

verifies the *hypothesis 3* for the overall performance of *System II* and confirms the explanation that the increase of machine utilisation of Shop B in *System II* at the third stage is caused by the resource regrouping between shops.

The results in table 7.12 demonstrate the ability of the hierarchical agent bidding mechanism in supporting resource regroupings across system boundaries and in turn enhancing the operational flexibility of manufacturing systems to changes in the business environment especially change in customer demand. Meanwhile, it is also shown in this table that with the demand increase of PA, resource regrouping between cells of Shop A occur before that across shops, which demonstrates another issue of the hierarchical agent bidding mechanism, namely when orders need to be fulfilled with resource regroupings across system boundaries, the hierarchical agent bidding mechanism is able to firstly consider resource regroupings between sub-systems at lower levels (e.g., between cells of Shop A) so as to result in lower disturbances to the existing system structure. This issue can be also verified by the results shown in table 7.13 which illustrates the production plans and schedules based on using the hierarchical agent bidding mechanism for some orders in the 8th order set (i.e., the order set with 13 orders of PA and 4 orders of PB per day). From this table, it is illustrated that in order to fulfil the last five orders (44th to 48th orders) received at the late time of the simulation day, resource regroupings are considered. However, among these orders, the former four orders are all produced with resource regrouping

Table 7.13 the Production Plans and Schedules for some of Orders in the 8th Order Set in *System II*

Order Number	Product	Component / Assembly	Processing Routes	Is Resource Regrouping incurred?
34	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	No
35	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
36	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
37	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
38	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
39	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
40	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA12 - GA11 - MA11 MA21 - MA21 - DA22 - DA21 AA31 - TA31	No
41	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	No
42	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB12 - DB11 LB21 - MB21 - GB21 AB31 - TB31	No
43	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	No
44	PA	BC_A1 BC_A2 BA_A1	LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - LA12 - LA12 AA32 - TA31	Yes(1)
45	PA	BC_A1 BC_A2 BA_A1	LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - DA22 - DA22 AA32 - TA31	Yes(1)
46	PA	BC_A1 BC_A2 BA_A1	LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - DA22 - DA21 AA32 - TA31	Yes(1)
47	PA	BC_A1 BC_A2 BA_A1	LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - DA22 - DA21 AA32 - TA31	Yes(1)
48	PA	BC_A1 BC_A2 BA_A1	LB21 - LB21 - LB21 - GB21 - MB21 MB21 - MB21 - LB21 - LB21 AA31 - TA31	Yes(2)

* *Yes (1): the resource regroupings between cells in a shop*
Yes (2): the resource regroupings between shops

across cells in Shop A and only the last one is processed with the collective use of resources across Shop A and B.

7.4 Discussions

Test I investigates the capability of the iterative agent bidding mechanism in finding optimum collective plans for production jobs within given systems. In doing so, a production job of BC_A1 of product PA is allocated in Cell A1 of Shop A. In order to avoid the possible influence resulting from the random-based searching scheme (i.e., GA), this test conducts an experiment with 10 replications. The experiment result shows that in each replication, the allocation plan obtained from the implementation of the iterative agent bidding mechanism is the same with the absolute optimum plan determined by using a centralized method, which proves the ability of the iterative agent bidding in finding the optimum plans for allocating production jobs to resources in a given system.

Test 2-1 investigates whether the hierarchical agent bidding mechanism is able to firstly consider the cost-efficient resource utilisations within structural constraints of manufacturing systems for planning and scheduling product orders. In doing so, this test creates a customer order for the test product PB and assumes the test manufacturing system has enough capacity. Through comparing the absolute optimum plan which is obtained based on the resource utilisations within structural constraints of the test manufacturing system and has the lowest production cost, the test demonstrates that the hierarchical agent bidding mechanism is able to firstly consider cost-efficient resource utilisations within structural constraints of manufacturing systems for planning and scheduling product orders.

Test 2-2 investigates the capability of the hierarchical agent bidding mechanism in supporting resource regroupings across system boundaries of manufacturing systems so as to enhance the operational flexibility of manufacturing systems to dynamic changes in the business environment. In this test, the change in customer demand is considered, which is simulated as the increase of average daily numbers of orders. The test results show that under normal market conditions, the hierarchical agent bidding mechanism enables manufacturing systems to be able to utilise resources within structural constraints as far as possible so as to reap the benefits resulting from the existing system structures. For example, under normal market condition, the hierarchical agent bidding mechanism enables the test manufacturing system to perform as a conventional cellular manufacturing system where products and components are rigidly produced within dedicated shops and cells. However, when the demand fluctuation is detected, the bidding mechanism enables product orders to be produced with flexible resource utilisations across system boundaries of manufacturing systems, which balances the resource utilisations throughout manufacturing systems and in turn enhances operational flexibility of manufacturing systems to the demand fluctuation. Meanwhile, this test also demonstrates that when considering resource regroupings across system boundaries of manufacturing systems, the bidding mechanism always attempts to make fewer disturbances to the existing system structures. For example, the resource regrouping between cells of a shop is firstly considered to fulfil customer orders. If it is not possible, the resource regrouping between shops is then considered.

7.5 Summary

This chapter provided numerical tests to verify the capabilities of the two agent bidding mechanisms (i.e., the GA-based iterative agent bidding mechanism and the hierarchical agent bidding mechanism) described in the previous two chapters. Three numerical tests were designed and implemented in this chapter. Test I verifies the capability of the iterative agent bidding mechanism for finding optimum collective plans for production jobs within given systems. Test 2-1 demonstrates the capability of the hierarchical agent bidding mechanism in firstly considering cost-efficient resource utilisations within structural constraints of manufacturing systems when planning and scheduling customer orders. Test 2-2 demonstrates the ability of the hierarchical agent bidding mechanism in supporting resource regroupings across system boundaries of manufacturing systems for planning and scheduling product orders and also proves that this mechanism is able to enhance the operational flexibility of manufacturing systems to changes in customer demands.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Introduction

This chapter summarises the conclusions of this PhD research, clarifies the major contributions of this PhD research and also presents the possible future work based on this PhD research.

8.2 Research Conclusions

As aforementioned in the introduction chapter, this PhD research is a part of the DIMS research whose aim is to develop a systematic manufacturing system modelling and control architecture wherein operational decisions can be integrated with the dynamic system restructure so as to enable manufacturing systems to optimally and flexibly utilise and organise manufacturing resources for dealing with changes in the business environment. Motivated by the advantages of the Multi-agent System (MAS) technology, DIMS investigates the applicability of MAS technology in achieving its overall aim. Three research questions are involved in DIMS research, which are restated in the following:

Question 1: How to model manufacturing systems based on MAS technology so that the established system models are able to represent the complex hierarchies of manufacturing systems and avoid the centralized control of manufacturing systems and most importantly, can be used to provide operational and restructuring controls of manufacturing systems?

Question 2: How to control the production planning and scheduling of manufacturing systems based on the established agent-based models for making the optimally and flexibly coordinated operational decisions which enable product orders to be cost-efficiently fulfilled within structural constraints of manufacturing systems and also to be fulfilled with flexible resource regroupings across system boundaries when orders cannot be fulfilled within the structural constraints.

Question 3: How to control the system restructure based on the established agent-based models so that manufacturing systems structures can be continuously evaluated and dynamically reconfigured at the right time with the right decisions.

Among the three research questions of DIMS, the first and third questions have been answered by the author's colleagues who developed an agent-based distributed modelling architecture which models manufacturing systems with Hierarchical Autonomous Agent Networks (HAAN) and developed an agent-based dynamic system restructure method enabling manufacturing systems to dynamically adapt their structures to changes in the business environment. Based on the developed agent-based modelling architecture, this PhD study investigates the control of production planning and scheduling in DIMS so as to answer the second question of DIMS.

Since both products and manufacturing systems are complex entities with complex hierarchies, the entire problem of planning and scheduling a product order in a manufacturing system is a hierarchical problem which involves the allocation of a hierarchy of production jobs of the order to a hierarchy of resources in the manufacturing system. Therefore, to develop a production planning and scheduling method as required in question 2 based on the agent-based modelling architecture in DIMS, this research identifies two technical requirements for the method. Firstly, in order to solve the entire hierarchical problem in a distributed agent-based modelling environment, this method must have an agent-based mechanism to solve a common problem shared at each hierarchical level of planning and scheduling entire product orders in manufacturing systems. The common problem involves the allocation of a production job containing a sequence of sub-jobs to a set of resources in a given system so that the entire job can be fulfilled within a given due date at the lowest production cost. Secondly, for enabling a hierarchy of production jobs of an order to be optimally allocated to a hierarchy of resources in a manufacturing system, this method must have another agent-based mechanism which is able to find the optimum sub-system/resource for every production job from a hierarchy of candidates in the manufacturing system so that every job and in turn the entire product order can be optimally fulfilled within structural constraints of the manufacturing system as far as possible. However, this mechanism must also enable resources in manufacturing systems to be flexibly regrouped together across system boundaries but with lowest disturbances to the existing system structures when orders cannot be fulfilled within structural constraints of manufacturing systems.

Based on the identified two technical requirements, this research develops two agent-based bidding mechanisms which work together to enable agents in the established modelling architecture to be coordinated through bidding processes so as to make optimal and flexible planning and scheduling decisions for product orders. The first mechanism is the iterative agent bidding mechanism based on a Genetic Algorithm (GA) which aims at solving the common problem as mentioned above, namely determining the optimum allocation of a production job containing a sequence of sub-jobs to a set of resources within a given system/sub-system so that the entire job can be completed within a given time at the lowest cost. In this mechanism, the bidding amongst agents is carried out iteratively. Within each bidding iteration, two sets of parameters are used, including virtual prices for sub-jobs and minimal virtual profits for resources, for regulating and controlling behaviours of individual agents in the bidding iteration in order to generate alternative allocation plans different from those from other bidding iterations. The GA is used for optimising these two sets of parameters over bidding iterations to result in better and better allocation plans for the entire job. The second mechanism is the hierarchical agent bidding mechanism which is equipped in every resource agent of a HAAN of a manufacturing system as a generic rule for making planning and scheduling decisions. Based on this mechanism, when a resource agent representing a system makes the planning and scheduling decision for a production job, this agent firstly attempts to find the best sub-system represented by a child agent (if possible) to perform the entire job so that the job can be cost-efficiently fulfilled within structural constraints of the system. This is achieved through the resource agent letting all of eligible children agents to bid for the entire job. However, when it is not possible, this mechanism enables the resource agent to gradually relax the boundaries between sub-systems represented by children agents and find the cost-efficiently collective plan for the entire job based on the use of the iterative agent bidding mechanism. The entire production planning and scheduling of a product order in a manufacturing system is determined through a hierarchical agent bidding process. This process is started by the top-level part agent in the HAAN of the order calling for bid from the top-level resource agent in the HAAN of the manufacturing system. Once receiving calls for bids, every resource agent follows the hierarchical agent bidding mechanism to process the calls. The applicability of these two agent bidding mechanisms is validated by numerical tests in Chapter 7 of this thesis.

In conclusion, based on the successful developments of these two agent bidding mechanisms, the two technical requirements for the planning and scheduling method are achieved and in turn the second question in DIMS is successfully answered.

8.3 Research Contributions

The major research contributions of this PhD research include:

- The identification of technical requirements for the control of production planning and scheduling in a hierarchically structured distributed modelling environment.
- The development of an iterative agent bidding mechanism for solving one of the core problems in production planning and scheduling which involves the allocation of a production job containing a set of sub-jobs to a set of resource in a given system so that the job can be completed within a given due date at the lowest or near lowest cost.
- The development of a hierarchical agent bidding mechanism for making cost-efficient and flexible production plans and schedules for entire orders so that the orders can be fulfilled within structural constraints of manufacturing systems as far as possible and also fulfilled with resource regroupings across system boundaries when needed.

8.4 Future Work

Although this PhD research developed a modelling and control method enabling product orders to be planed and scheduled cost-efficiently and flexibly, this method does not consider material supplies of manufacturing systems. As a result, future work based on this PhD research can update the modelling architecture and planning and scheduling mechanisms developed so as to involve material supplies of manufacturing systems in the planning and scheduling process. A possible way to achieve that is to design a Material Inventory and Procurement Agent (MIPA) in the modelling architecture for monitoring the up-to-date material inventory and procurement information of a manufacturing system and also add an Inventory Monitoring Component (IMC) in the generic agent architecture for supervising and updating the information of material buffers of resources. At the beginning of a day, MIPA updates the current material information of the entire system and also creates a material procurement plan for the next several days and then, informs all of resource agents to update their IMCs information. When receiving calls for bids for production jobs, resource agents acquire the material supply information from their IMCs and set the information as constraints for making planning and scheduling decisions. For those resource agents which are eventually confirmed to carry out production jobs, information of IMCs is correspondingly updated.

APPENDIX A

SETUP PARAMETERS OF MACHINES IN THE TEST MANUFACTURING SYSTEM

Table A1. Setup Parameters of Machines in Cell A_1

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
Lathe A11	Turning/Milling	23	2.0	1.8	35	0.35
Lathe A12	Turning/Drilling	30	3.0	2.3	44	0.35
Grind A11	Grinding	18	1.9	1.0	18	0.2
Mill A11	Milling	28	2.8	1.5	45	0.4

Table A2. Setup Parameters of Machines in Cell A_2

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
MillA21	Milling	28	2.6	1.6	38	0.28
Lathe A21	Turning/Milling	34	3.2	1.85	46	0.35
Drill A21	Drilling	28	2.5	1.5	34	0.28
Drill A21	Drilling	35	2.7	1.65	42	0.4

Table A3. Setup Parameters of Machines in Cell A_3

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
Advanced Assembly A31	Advanced/Basic Assembly	20	1.7	2.2	28	0.15
Advanced Assembly A32	Advanced/Basic Assembly	28	2.3	3.0	40	0.2
Test A31	Test	16	1.7	1.8	30	0.25

Table A4. Setup Parameters of Machines in Cell B_1

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
Mill B11	Milling	28	2.6	1.45	38	0.35
Lathe B11	Turning/Milling	26	2.2	1.5	32	0.3
Drill B11	Drilling	24	2.7	1.55	32	0.35
Drill B12	Drilling	32	2.4	1.85	36	0.4

Table A5. Setup Parameters of Machines in Cell B_2

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
Lathe B21	Turning/Drilling	28	3.0	2.3	44	0.35
GrindB21	Grinding	20	2.0	1.3	22	0.28
Mill B21	Milling	30	2.8	1.8	45	0.4

Table A6. Setup Parameters of Machines in Cell B_3

Name of Machine	Functionality	Setup time	Setup cost	Processing cost/material unit	Material removal rate	Holding cost/time unit
Basic Assembly B31	Basic Assembly	16	1.5	1.8	28	0.2
Test B31	Test	16	1.7	1.8	30	0.25

APPENDIX B

PRODUCT ORDERS IN TEST 2-2

Table B.1 the 1st Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PB	20	0	2
1	PA	20	0	2
2	PA	20	0	2
3	PB	20	0	2
4	PB	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PA	20	0	2
8	PA	20	0	2
9	PB	20	0	2
10	PB	20	1	3
11	PB	20	1	3
12	PA	20	1	3
13	PA	20	1	3
14	PB	20	1	3
15	PA	20	1	3
16	PB	20	1	3
17	PA	20	1	3
18	PA	20	1	3
19	PA	20	1	3
20	PB	20	2	4
21	PB	20	2	4
22	PA	20	2	4
23	PA	20	2	4
24	PA	20	2	4
25	PB	20	2	4
26	PA	20	2	4
27	PA	20	2	4
28	PB	20	2	4
29	PA	20	2	4
30	PB	20	3	5
31	PA	20	3	5
32	PA	20	3	5
33	PB	20	3	5
34	PA	20	3	5
35	PB	20	3	5
36	PA	20	3	5
37	PA	20	3	5
38	PA	20	3	5
39	PB	20	3	5
40	PB	20	4	6
41	PA	20	4	6
42	PA	20	4	6
43	PB	20	4	6

44	PB	20	4	6
45	PB	20	4	6
46	PA	20	4	6
47	PA	20	4	6
48	PA	20	4	6
49	PA	20	4	6

Table B.2 the 2nd Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PA	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PB	20	0	2
5	PB	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PA	20	0	2
9	PA	20	0	2
10	PB	20	0	2
11	PB	20	1	3
12	PA	20	1	3
13	PA	20	1	3
14	PB	20	1	3
15	PB	20	1	3
16	PA	20	1	3
17	PA	20	1	3
18	PA	20	1	3
19	PB	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PB	20	2	4
23	PB	20	2	4
24	PB	20	2	4
25	PA	20	2	4
26	PA	20	2	4
27	PA	20	2	4
28	PB	20	2	4
29	PA	20	2	4
30	PA	20	2	4
31	PA	20	2	4
32	PA	20	2	4
33	PA	20	3	5
34	PB	20	3	5
35	PA	20	3	5
36	PB	20	3	5
37	PA	20	3	5
38	PA	20	3	5
39	PA	20	3	5
40	PA	20	3	5
41	PB	20	3	5
42	PA	20	3	5
43	PB	20	3	5
44	PB	20	4	6
45	PA	20	4	6
46	PB	20	4	6
47	PA	20	4	6
48	PB	20	4	6
49	PA	20	4	6

50	PB	20	4	6
51	PA	20	4	6
52	PA	20	4	6
53	PA	20	4	6
54	PA	20	4	6

Table B.3 the 3rd Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PA	20	0	2
2	PB	20	0	2
3	PB	20	0	2
4	PA	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PA	20	0	2
9	PB	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PB	20	1	3
13	PA	20	1	3
14	PA	20	1	3
15	PA	20	1	3
16	PA	20	1	3
17	PA	20	1	3
18	PB	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PB	20	1	3
23	PB	20	1	3
24	PB	20	2	4
25	PA	20	2	4
26	PB	20	2	4
27	PA	20	2	4
28	PA	20	2	4
29	PA	20	2	4
30	PA	20	2	4
31	PA	20	2	4
32	PB	20	2	4
33	PA	20	2	4
34	PB	20	2	4
35	PA	20	2	4
36	PA	20	3	5
37	PB	20	3	5
38	PB	20	3	5
39	PA	20	3	5
40	PA	20	3	5
41	PB	20	3	5
42	PA	20	3	5
43	PA	20	3	5
44	PA	20	3	5
45	PA	20	3	5
46	PA	20	3	5
47	PB	20	3	5
48	PA	20	4	6
49	PB	20	4	6

50	PA	20	4	6
51	PA	20	4	6
52	PB	20	4	6
53	PB	20	4	6
54	PA	20	4	6
55	PA	20	4	6
56	PA	20	4	6
57	PA	20	4	6
58	PB	20	4	6
59	PA	20	4	6

Table B.4 the 4th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PA	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PA	20	0	2
5	PB	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PA	20	0	2
9	PB	20	0	2
10	PA	20	0	2
11	PB	20	0	2
12	PA	20	0	2
13	PA	20	1	3
14	PA	20	1	3
15	PA	20	1	3
16	PB	20	1	3
17	PA	20	1	3
18	PB	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PB	20	1	3
23	PB	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PA	20	2	4
27	PA	20	2	4
28	PA	20	2	4
29	PB	20	2	4
30	PA	20	2	4
31	PB	20	2	4
32	PB	20	2	4
33	PA	20	2	4
34	PA	20	2	4
35	PA	20	2	4
36	PA	20	2	4
37	PA	20	2	4
38	PB	20	2	4
39	PB	20	3	5
40	PA	20	3	5
41	PB	20	3	5
42	PB	20	3	5
43	PA	20	3	5
44	PA	20	3	5
45	PA	20	3	5
46	PA	20	3	5
47	PB	20	3	5
48	PA	20	3	5
49	PA	20	3	5

50	PA	20	3	5
51	PA	20	3	5
52	PA	20	4	6
53	PA	20	4	6
54	PA	20	4	6
55	PB	20	4	6
56	PB	20	4	6
57	PB	20	4	6
58	PA	20	4	6
59	PA	20	4	6
60	PA	20	4	6
61	PA	20	4	6
62	PB	20	4	6
63	PA	20	4	6
64	PA	20	4	6

Table B.5 the 5th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PB	20	0	2
1	PA	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PA	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PB	20	0	2
9	PA	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PA	20	0	2
13	PB	20	0	2
14	PA	20	1	3
15	PA	20	1	3
16	PB	20	1	3
17	PA	20	1	3
18	PB	20	1	3
19	PA	20	1	3
20	PB	20	1	3
21	PB	20	1	3
22	PA	20	1	3
23	PA	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PA	20	1	3
27	PA	20	1	3
28	PA	20	2	4
29	PA	20	2	4
30	PA	20	2	4
31	PB	20	2	4
32	PA	20	2	4
33	PB	20	2	4
34	PA	20	2	4
35	PA	20	2	4
36	PA	20	2	4
37	PB	20	2	4
38	PA	20	2	4
39	PB	20	2	4
40	PA	20	2	4
41	PA	20	2	4
42	PA	20	3	5
43	PB	20	3	5
44	PB	20	3	5
45	PB	20	3	5
46	PA	20	3	5
47	PA	20	3	5
48	PA	20	3	5
49	PA	20	3	5

50	PA	20	3	5
51	PA	20	3	5
52	PA	20	3	5
53	PB	20	3	5
54	PA	20	3	5
55	PA	20	3	5
56	PB	20	4	6
57	PA	20	4	6
58	PB	20	4	6
59	PA	20	4	6
60	PA	20	4	6
61	PA	20	4	6
62	PB	20	4	6
63	PA	20	4	6
64	PA	20	4	6
65	PA	20	4	6
66	PA	20	4	6
67	PB	20	4	6
68	PA	20	4	6
69	PA	20	4	6

Table B.6 the 6th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PB	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PB	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PA	20	0	2
8	PA	20	0	2
9	PA	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PB	20	0	2
13	PB	20	0	2
14	PA	20	0	2
15	PA	20	1	3
16	PA	20	1	3
17	PA	20	1	3
18	PB	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PA	20	1	3
23	PB	20	1	3
24	PB	20	1	3
25	PA	20	1	3
26	PA	20	1	3
27	PB	20	1	3
28	PA	20	1	3
29	PA	20	1	3
30	PA	20	2	4
31	PA	20	2	4
32	PA	20	2	4
33	PA	20	2	4
34	PB	20	2	4
35	PB	20	2	4
36	PA	20	2	4
37	PB	20	2	4
38	PB	20	2	4
39	PA	20	2	4
40	PA	20	2	4
41	PA	20	2	4
42	PA	20	2	4
43	PA	20	2	4
44	PA	20	2	4
45	PA	20	3	5
46	PA	20	3	5
47	PB	20	3	5
48	PA	20	3	5
49	PA	20	3	5

50	PB	20	3	5
51	PA	20	3	5
52	PA	20	3	5
53	PA	20	3	5
54	PB	20	3	5
55	PA	20	3	5
56	PA	20	3	5
57	PB	20	3	5
58	PA	20	3	5
59	PA	20	3	5
60	PA	20	4	6
61	PB	20	4	6
62	PA	20	4	6
63	PB	20	4	6
64	PA	20	4	6
65	PB	20	4	6
66	PA	20	4	6
67	PA	20	4	6
68	PA	20	4	6
69	PB	20	4	6
70	PA	20	4	6
71	PA	20	4	6
72	PA	20	4	6
73	PA	20	4	6
74	PA	20	4	6

Table B.7 the 7th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PB	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PA	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PB	20	0	2
9	PB	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PA	20	0	2
13	PA	20	0	2
14	PA	20	0	2
15	PA	20	0	2
16	PA	20	1	3
17	PA	20	1	3
18	PB	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PB	20	1	3
22	PA	20	1	3
23	PB	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PA	20	1	3
27	PA	20	1	3
28	PB	20	1	3
29	PA	20	1	3
30	PA	20	1	3
31	PA	20	1	3
32	PB	20	2	4
33	PA	20	2	4
34	PA	20	2	4
35	PA	20	2	4
36	PA	20	2	4
37	PA	20	2	4
38	PA	20	2	4
39	PB	20	2	4
40	PA	20	2	4
41	PB	20	2	4
42	PA	20	2	4
43	PA	20	2	4
44	PB	20	2	4
45	PA	20	2	4
46	PA	20	2	4
47	PA	20	2	4
48	PA	20	3	5
49	PA	20	3	5

50	PA	20	3	5
51	PA	20	3	5
52	PA	20	3	5
53	PA	20	3	5
54	PB	20	3	5
55	PA	20	3	5
56	PB	20	3	5
57	PA	20	3	5
58	PA	20	3	5
59	PA	20	3	5
60	PB	20	3	5
61	PA	20	3	5
62	PB	20	3	5
63	PA	20	3	5
64	PA	20	4	6
65	PB	20	4	6
66	PA	20	4	6
67	PB	20	4	6
68	PB	20	4	6
69	PA	20	4	6
70	PB	20	4	6
71	PA	20	4	6
72	PA	20	4	6
73	PA	20	4	6
74	PA	20	4	6
75	PA	20	4	6
76	PA	20	4	6
77	PA	20	4	6
78	PA	20	4	6
79	PA	20	4	6

Table B.8 the 8th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PA	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PB	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PA	20	0	2
8	PA	20	0	2
9	PA	20	0	2
10	PA	20	0	2
11	PB	20	0	2
12	PA	20	0	2
13	PB	20	0	2
14	PA	20	0	2
15	PA	20	0	2
16	PB	20	0	2
17	PB	20	1	3
18	PA	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PA	20	1	3
23	PA	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PA	20	1	3
27	PA	20	1	3
28	PA	20	1	3
29	PA	20	1	3
30	PB	20	1	3
31	PA	20	1	3
32	PB	20	1	3
33	PB	20	1	3
34	PB	20	2	4
35	PA	20	2	4
36	PA	20	2	4
37	PA	20	2	4
38	PA	20	2	4
39	PA	20	2	4
40	PA	20	2	4
41	PA	20	2	4
42	PB	20	2	4
43	PB	20	2	4
44	PA	20	2	4
45	PA	20	2	4
46	PA	20	2	4
47	PA	20	2	4
48	PA	20	2	4
49	PB	20	2	4

50	PA	20	2	4
51	PA	20	3	5
52	PA	20	3	5
53	PA	20	3	5
54	PA	20	3	5
55	PA	20	3	5
56	PB	20	3	5
57	PA	20	3	5
58	PB	20	3	5
59	PA	20	3	5
60	PB	20	3	5
61	PB	20	3	5
62	PA	20	3	5
63	PA	20	3	5
64	PA	20	3	5
65	PA	20	3	5
66	PA	20	3	5
67	PA	20	3	5
68	PA	20	4	6
69	PA	20	4	6
70	PA	20	4	6
71	PA	20	4	6
72	PA	20	4	6
73	PA	20	4	6
74	PA	20	4	6
75	PB	20	4	6
76	PA	20	4	6
77	PA	20	4	6
78	PA	20	4	6
79	PB	20	4	6
80	PA	20	4	6
81	PA	20	4	6
82	PB	20	4	6
83	PB	20	4	6
84	PA	20	4	6

Table B.9 the 9th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PA	20	0	2
2	PB	20	0	2
3	PB	20	0	2
4	PA	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PA	20	0	2
8	PA	20	0	2
9	PA	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PB	20	0	2
13	PA	20	0	2
14	PA	20	0	2
15	PB	20	0	2
16	PA	20	0	2
17	PA	20	0	2
18	PB	20	1	3
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PB	20	1	3
23	PA	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PB	20	1	3
27	PA	20	1	3
28	PA	20	1	3
29	PA	20	1	3
30	PA	20	1	3
31	PA	20	1	3
32	PA	20	1	3
33	PA	20	1	3
34	PB	20	1	3
35	PA	20	1	3
36	PA	20	2	4
37	PB	20	2	4
38	PA	20	2	4
39	PA	20	2	4
40	PB	20	2	4
41	PA	20	2	4
42	PA	20	2	4
43	PA	20	2	4
44	PA	20	2	4
45	PB	20	2	4
46	PA	20	2	4
47	PB	20	2	4
48	PA	20	2	4
49	PA	20	2	4

50	PA	20	2	4
51	PA	20	2	4
52	PA	20	2	4
53	PA	20	2	4
54	PA	20	3	5
55	PB	20	3	5
56	PA	20	3	5
57	PA	20	3	5
58	PA	20	3	5
59	PB	20	3	5
60	PA	20	3	5
61	PA	20	3	5
62	PA	20	3	5
63	PB	20	3	5
64	PB	20	3	5
65	PA	20	3	5
66	PA	20	3	5
67	PA	20	3	5
68	PA	20	3	5
69	PA	20	3	5
70	PA	20	3	5
71	PA	20	3	5
72	PA	20	4	6
73	PA	20	4	6
74	PB	20	4	6
75	PA	20	4	6
76	PA	20	4	6
77	PB	20	4	6
78	PA	20	4	6
79	PA	20	4	6
80	PB	20	4	6
81	PA	20	4	6
82	PA	20	4	6
83	PA	20	4	6
84	PA	20	4	6
85	PA	20	4	6
86	PB	20	4	6
87	PA	20	4	6
88	PA	20	4	6
89	PA	20	4	6

Table B.10 the 10th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PB	20	0	2
2	PA	20	0	2
3	PB	20	0	2
4	PA	20	0	2
5	PB	20	0	2
6	PA	20	0	2
7	PB	20	0	2
8	PA	20	0	2
9	PA	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PA	20	0	2
13	PA	20	0	2
14	PA	20	0	2
15	PA	20	0	2
16	PA	20	0	2
17	PA	20	0	2
18	PA	20	0	2
19	PA	20	1	3
20	PA	20	1	3
21	PA	20	1	3
22	PA	20	1	3
23	PB	20	1	3
24	PA	20	1	3
25	PB	20	1	3
26	PA	20	1	3
27	PA	20	1	3
28	PA	20	1	3
29	PA	20	1	3
30	PA	20	1	3
31	PA	20	1	3
32	PA	20	1	3
33	PA	20	1	3
34	PA	20	1	3
35	PB	20	1	3
36	PB	20	1	3
37	PA	20	1	3
38	PA	20	2	4
39	PA	20	2	4
40	PA	20	2	4
41	PA	20	2	4
42	PA	20	2	4
43	PA	20	2	4
44	PA	20	2	4
45	PA	20	2	4
46	PA	20	2	4
47	PA	20	2	4
48	PA	20	2	4
49	PA	20	2	4

50	PB	20	2	4
51	PA	20	2	4
52	PB	20	2	4
53	PA	20	2	4
54	PA	20	2	4
55	PB	20	2	4
56	PB	20	2	4
57	PB	20	3	5
58	PA	20	3	5
59	PA	20	3	5
60	PB	20	3	5
61	PA	20	3	5
62	PA	20	3	5
63	PA	20	3	5
64	PA	20	3	5
65	PA	20	3	5
66	PA	20	3	5
67	PA	20	3	5
68	PA	20	3	5
69	PA	20	3	5
70	PA	20	3	5
71	PB	20	3	5
72	PA	20	3	5
73	PA	20	3	5
74	PB	20	3	5
75	PA	20	3	5
76	PA	20	4	6
77	PB	20	4	6
78	PB	20	4	6
79	PA	20	4	6
80	PA	20	4	6
81	PB	20	4	6
82	PA	20	4	6
83	PA	20	4	6
84	PA	20	4	6
85	PA	20	4	6
86	PA	20	4	6
87	PA	20	4	6
88	PA	20	4	6
89	PB	20	4	6
90	PA	20	4	6
91	PA	20	4	6
92	PA	20	4	6
93	PA	20	4	6
94	PA	20	4	6

Table B.11 the 11th Set of Orders

Order ID	Product	Quantity	Arrival Time	Due Date
0	PA	20	0	2
1	PB	20	0	2
2	PA	20	0	2
3	PA	20	0	2
4	PA	20	0	2
5	PA	20	0	2
6	PA	20	0	2
7	PA	20	0	2
8	PA	20	0	2
9	PB	20	0	2
10	PA	20	0	2
11	PA	20	0	2
12	PA	20	0	2
13	PA	20	0	2
14	PA	20	0	2
15	PA	20	0	2
16	PA	20	0	2
17	PB	20	0	2
18	PB	20	0	2
19	PA	20	0	2
20	PB	20	1	3
21	PA	20	1	3
22	PB	20	1	3
23	PA	20	1	3
24	PA	20	1	3
25	PA	20	1	3
26	PA	20	1	3
27	PA	20	1	3
28	PB	20	1	3
29	PA	20	1	3
30	PA	20	1	3
31	PA	20	1	3
32	PA	20	1	3
33	PA	20	1	3
34	PA	20	1	3
35	PA	20	1	3
36	PA	20	1	3
37	PB	20	1	3
38	PA	20	1	3
39	PA	20	1	3
40	PA	20	2	4
41	PB	20	2	4
42	PA	20	2	4
43	PA	20	2	4
44	PA	20	2	4
45	PA	20	2	4
46	PA	20	2	4
47	PA	20	2	4
48	PB	20	2	4
49	PA	20	2	4

50	PA	20	2	4
51	PA	20	2	4
52	PA	20	2	4
53	PA	20	2	4
54	PA	20	2	4
55	PA	20	2	4
56	PA	20	2	4
57	PA	20	2	4
58	PB	20	2	4
59	PB	20	2	4
60	PA	20	3	5
61	PA	20	3	5
62	PA	20	3	5
63	PB	20	3	5
64	PA	20	3	5
65	PA	20	3	5
66	PA	20	3	5
67	PA	20	3	5
68	PB	20	3	5
69	PA	20	3	5
70	PA	20	3	5
71	PA	20	3	5
72	PA	20	3	5
73	PA	20	3	5
74	PA	20	3	5
75	PB	20	3	5
76	PA	20	3	5
77	PA	20	3	5
78	PB	20	3	5
79	PA	20	3	5
80	PA	20	4	6
81	PB	20	4	6
82	PA	20	4	6
83	PA	20	4	6
84	PA	20	4	6
85	PA	20	4	6
86	PA	20	4	6
87	PB	20	4	6
88	PB	20	4	6
89	PA	20	4	6
90	PA	20	4	6
91	PA	20	4	6
92	PA	20	4	6
93	PA	20	4	6
94	PB	20	4	6
95	PA	20	4	6
96	PA	20	4	6
97	PA	20	4	6
98	PA	20	4	6
99	PA	20	4	6

APPENDIX C

PRODUCTION PLANS AND SCHEDULES FOR PRODUCT ORDERS IN TEST 2-2

Table C.1 the Production Plans and Schedules for the 1st set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
4	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
7	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
8	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
9	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
10	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
11	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MA21 - LA21 - DA22 - DA21	1238	No
		BC_B2	LB21 - MB21 - GB21	1171	LA12 - LA11 - GA11	1188	
		BA_B1	AB31 - TB31	1396	AA31 - TA31	1385	

12	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1495	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1237	MA21 - MA21 - DA22 - DA21	1302	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1671	
13	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	1769	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1340	MA21 - MA21 - DA21 - DA21	1405	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	1925	
14	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1396	
15	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA12 - LA12 - LA12 - GA11 - MA11	1357	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1443	LA21 - LA21 - DA22 - DA22	1329	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	1534	
16	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1446	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA11 - LA11 - LA11 - GA11 - MA11	2043	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1546	MA21 - MA21 - DA22 - DA21	1442	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2199	
18	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1324	LA12 - LA12 - LA12 - GA11 - MA11	1598	No
		BC_A2	MA21 - MA21 - DA22 - DA21	1562	MA21 - MA21 - DA21 - DA21	1553	
		BA_A1	AA31 - TA31	1718	AA31 - TA31	1757	
19	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1566	LA11 - LA11 - LA11 - GA11 - MA11	2317	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1665	MA21 - MA21 - DA21 - DA21	1656	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2473	
20	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
21	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MA21 - LA21 - DA21 - DA21	2231	No
		BC_B2	LB21 - MB21 - GB21	2171	LA12 - MA11 - GA11	2161	
		BA_B1	AB31 - TB31	2396	AA31 - TA31	2359	
22	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2591	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA22 - DA21	2301	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	2747	
23	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA12 - LA12 - LA12 - GA11 - MA11	2357	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2404	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	2561	
24	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA11 - LA11 - LA11 - GA11 - MA11	2865	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA21 - DA21	2507	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	3021	
25	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2396	
26	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2324	LA12 - LA12 - LA12 - GA11 - MA11	2624	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	LA21 - LA21 - DA22 - DA22	2329	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	2833	
27	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2575	LA11 - LA11 - LA11 - GA11 - MA11	3139	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA22 - DA21	2526	
		BA_A1	AA31 - TA31	2869	AA31 - TA31	3295	
28	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2446	

29	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2849	LA12 - LA12 - LA12 - GA11 - MA11	2898	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2637	
		BA_A1	AA31 - TA31	3058	AA31 - TA31	3107	
30	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
31	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3911	LA11 - LA11 - LA11 - GA11 - MA11	3413	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3237	
		BA_A1	AA31 - TA31	4068	AA31 - TA31	3569	
32	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4185	LA11 - LA11 - LA11 - GA11 - MA11	3687	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3340	
		BA_A1	AA31 - TA31	4342	AA31 - TA31	3843	
33	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
34	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4459	LA12 - LA12 - LA12 - GA11 - MA11	3324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA21 - LA21 - DA22 - DA22	3219	
		BA_A1	AA31 - TA31	4616	AA31 - TA31	3481	
35	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
36	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4733	LA11 - LA11 - LA11 - GA11 - MA11	3961	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA22 - DA21	3379	
		BA_A1	AA31 - TA31	4890	AA31 - TA31	4117	
37	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3324	LA12 - LA12 - LA12 - GA11 - MA11	3566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3490	
		BA_A1	AA31 - TA31	3880	AA31 - TA31	3722	
38	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3566	LA11 - LA11 - LA11 - GA11 - MA11	4235	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3593	
		BA_A1	AA31 - TA31	3965	AA31 - TA31	4391	
39	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
40	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
41	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5007	LA11 - LA11 - LA11 - GA11 - MA11	4509	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4237	
		BA_A1	AA31 - TA31	5164	AA31 - TA31	4665	
42	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5281	LA11 - LA11 - LA11 - GA11 - MA11	4783	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4340	
		BA_A1	AA31 - TA31	5438	AA31 - TA31	4939	
43	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
44	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
45	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	

46	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5555	LA12 - LA12 - LA12 - GA11 - MA11	4324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	LA21 - LA21 - DA22 - DA22	4219	
		BA_A1	AA31 - TA31	5712	AA31 - TA31	4481	
47	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5829	LA11 - LA11 - LA11 - GA11 - MA11	5057	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA22 - DA21	4379	
		BA_A1	AA31 - TA31	5986	AA31 - TA31	5213	
48	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4324	LA12 - LA12 - LA12 - GA11 - MA11	4566	No
		BC_A2	MA21 - MA21 - DA22 - DA21	4562	MA21 - MA21 - DA21 - DA21	4490	
		BA_A1	AA31 - TA31	4718	AA31 - TA31	4751	
49	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4566	LA12 - LA12 - LA12 - GA11 - MA11	4816	No
		BC_A2	MA21 - MA21 - DA22 - DA21	4596	MA21 - MA21 - DA21 - DA21	4593	
		BA_A1	AA31 - TA31	4804	AA31 - TA31	5025	

Table C.2 the Production Plans and Schedules for the 2nd set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
4	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
5	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
7	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
8	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
9	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
10	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
11	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
12	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1445	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1237	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1602	
13	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	1719	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1340	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	1876	
14	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	

15	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
16	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA12 - LA12 - LA12 - GA11 - MA11	1324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1443	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	1481	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA11 - LA11 - LA11 - GA11 - MA11	1993	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1546	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2150	
18	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1324	LA12 - LA12 - LA12 - GA11 - MA11	1566	No
		BC_A2	MA21 - MA21 - DA22 - DA21	1562	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1718	AA31 - TA31	1722	
19	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
20	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1566	LA11 - LA11 - LA11 - GA11 - MA11	2267	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1665	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2424	
21	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1807	LA12 - LA12 - LA12 - GA11 - MA11	1807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1768	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2047	AA31 - TA31	1964	
22	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
23	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
24	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MA21 - LA21 - DA22 - DA21	2238	No
		BC_B2	LB21 - MB21 - GB21	2200	LA12 - LA11 - GA11	2284	
		BA_B1	AB31 - TB31	2446	AA31 - TA31	2481	
25	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2591	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA22 - DA21	2302	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	2767	
26	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA11 - LA11 - LA11 - GA11 - MA11	2865	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2405	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	3021	
27	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA12 - LA12 - LA12 - GA11 - MA11	2357	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA22 - DA21	2420	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	2600	
28	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2446	
29	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2324	LA12 - LA12 - LA12 - GA11 - MA11	2624	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA21	2553	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	2853	
30	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2575	LA11 - LA11 - LA11 - GA11 - MA11	3139	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	LA21 - LA21 - DA22 - DA22	2329	
		BA_A1	AA31 - TA31	2869	AA31 - TA31	3295	
31	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2849	LA12 - LA12 - LA12 - GA11 - MA11	2898	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2656	
		BA_A1	AA31 - TA31	3058	AA31 - TA31	3107	

32	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3048	LA12 - LA12 - LA12 - GA11 - MA11	3081	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	MA21 - MA21 - DA21 - DA21	2759	
		BA_A1	AA31 - TA31	3332	AA31 - TA31	3381	
33	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3911	LA11 - LA11 - LA11 - GA11 - MA11	3413	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3237	
		BA_A1	AA31 - TA31	4068	AA31 - TA31	3569	
34	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
35	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4185	LA11 - LA11 - LA11 - GA11 - MA11	3687	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3340	
		BA_A1	AA31 - TA31	4342	AA31 - TA31	3843	
36	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
37	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4459	LA12 - LA12 - LA12 - GA11 - MA11	3324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA21 - LA21 - DA22 - DA22	3219	
		BA_A1	AA31 - TA31	4616	AA31 - TA31	3481	
38	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4733	LA11 - LA11 - LA11 - GA11 - MA11	3961	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA22 - DA21	3379	
		BA_A1	AA31 - TA31	4890	AA31 - TA31	4117	
39	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3324	LA12 - LA12 - LA12 - GA11 - MA11	3566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3490	
		BA_A1	AA31 - TA31	3880	AA31 - TA31	3722	
40	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3566	LA11 - LA11 - LA11 - GA11 - MA11	4235	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3593	
		BA_A1	AA31 - TA31	3965	AA31 - TA31	4391	
41	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
42	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3807	LA12 - LA12 - LA12 - GA11 - MA11	3807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	LA21 - LA21 - DA22 - DA21	3356	
		BA_A1	AA31 - TA31	4154	AA31 - TA31	3964	
43	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
44	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
45	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5007	LA11 - LA11 - LA11 - GA11 - MA11	4509	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4237	
		BA_A1	AA31 - TA31	5164	AA31 - TA31	4665	
46	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
47	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5281	LA11 - LA11 - LA11 - GA11 - MA11	4783	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4340	
		BA_A1	AA31 - TA31	5438	AA31 - TA31	4939	
48	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	

49	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5555	LA12 - LA12 - LA12 - GA11 - MA11	4324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	LA21 - LA21 - DA22 - DA22	4219	
		BA_A1	AA31 - TA31	5712	AA31 - TA31	4481	
50	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
51	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5829	LA11 - LA11 - LA11 - GA11 - MA11	5057	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA22 - DA21	4379	
		BA_A1	AA31 - TA31	5986	AA31 - TA31	5213	
52	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4324	LA12 - LA12 - LA12 - GA11 - MA11	4566	No
		BC_A2	MA21 - MA21 - DA22 - DA21	4562	MA21 - MA21 - DA21 - DA21	4490	
		BA_A1	AA31 - TA31	4718	AA31 - TA31	4751	
53	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4566	LA12 - LA12 - LA12 - GA11 - MA11	4816	No
		BC_A2	MA21 - MA21 - DA22 - DA21	4596	MA21 - MA21 - DA21 - DA21	4593	
		BA_A1	AA31 - TA31	4804	AA31 - TA31	5025	
54	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4807	LA11 - LA11 - LA11 - GA11 - MA11	5330	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4743	LA21 - LA21 - DA22 - DA21	4356	
		BA_A1	AA31 - TA31	4975	AA31 - TA31	5487	

Table C.3 the Production Plans and Schedules for the 3rd set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
2	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
3	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA21 - DA22	435	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	475	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
7	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
8	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	578	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
9	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA22	327	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	681	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
12	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
13	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1445	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1237	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1602	
14	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	1719	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1340	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	1876	

15	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA12 - LA12 - LA12 - GA11 - MA11	1324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1443	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	1481	
16	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA11 - LA11 - LA11 - GA11 - MA11	1993	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1546	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2150	
17	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1324	LA12 - LA12 - LA12 - GA11 - MA11	1566	No
		BC_A2	MA21 - MA21 - DA22 - DA21	1562	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1718	AA31 - TA31	1722	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
19	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1566	LA11 - LA11 - LA11 - GA11 - MA11	2267	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1665	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2424	
20	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1807	LA12 - LA12 - LA12 - GA11 - MA11	1807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1768	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2047	AA31 - TA31	1964	
21	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2048	LA12 - LA12 - LA12 - GA11 - MA11	2048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1871	MA21 - MA21 - DA21 - DA21	1696	
		BA_A1	AA31 - TA31	2236	AA31 - TA31	2236	
22	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
23	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
24	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
25	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2541	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2237	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	2698	
26	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
27	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA11 - LA11 - LA11 - GA11 - MA11	2815	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2340	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	2972	
28	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA12 - LA12 - LA12 - GA11 - MA11	2324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	LA21 - LA21 - DA22 - DA22	2219	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	2510	
29	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2324	LA12 - LA12 - LA12 - GA11 - MA11	2575	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA22 - DA21	2379	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	2784	
30	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2575	LA11 - LA11 - LA11 - GA11 - MA11	3089	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2490	
		BA_A1	AA31 - TA31	2869	AA31 - TA31	3246	
31	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2849	LA12 - LA12 - LA12 - GA11 - MA11	2849	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2593	
		BA_A1	AA31 - TA31	3058	AA31 - TA31	3058	

32	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
33	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3048	LA11 - LA11 - LA11 - GA11 - MA11	3363	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	LA21 - LA21 - DA22 - DA21	2356	
		BA_A1	AA31 - TA31	3332	AA31 - TA31	3520	
34	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
35	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3290	LA12 - LA12 - LA12 - GA11 - MA11	3048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA21 - MA21 - DA21 - DA21	2696	
		BA_A1	AA31 - TA31	3606	AA31 - TA31	3332	
36	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3911	LA11 - LA11 - LA11 - GA11 - MA11	3637	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3237	
		BA_A1	AA31 - TA31	4068	AA31 - TA31	3794	
37	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
38	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
39	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4185	LA12 - LA12 - LA12 - GA11 - MA11	3324	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3340	
		BA_A1	AA31 - TA31	4342	AA31 - TA31	3606	
40	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4459	LA11 - LA11 - LA11 - GA11 - MA11	3911	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA21 - LA21 - DA22 - DA22	3219	
		BA_A1	AA31 - TA31	4616	AA31 - TA31	4068	
41	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
42	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4733	LA12 - LA12 - LA12 - GA11 - MA11	3566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA21 - DA21	3443	
		BA_A1	AA31 - TA31	4890	AA31 - TA31	3880	
43	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3531	LA11 - LA11 - LA11 - GA11 - MA11	4185	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA22 - DA21	3463	
		BA_A1	AA31 - TA31	3880	AA31 - TA31	4342	
44	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3772	LA12 - LA12 - LA12 - GA11 - MA11	3807	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3574	
		BA_A1	AA31 - TA31	3965	AA31 - TA31	3965	
45	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4014	LA12 - LA12 - LA12 - GA11 - MA11	4048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	LA21 - LA21 - DA22 - DA22	3327	
		BA_A1	AA31 - TA31	4170	AA31 - TA31	4205	
46	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4255	LA11 - LA11 - LA12 - GA11 - MA11	4456	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	3677	
		BA_A1	AA31 - TA31	4427	AA31 - TA31	4613	
47	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
48	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5007	LA11 - LA11 - LA11 - GA11 - MA11	4638	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4237	
		BA_A1	AA31 - TA31	5164	AA31 - TA31	4795	

49	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
50	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5281	LA11 - LA11 - LA11 - GA11 - MA11	4912	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4340	
		BA_A1	AA31 - TA31	5438	AA31 - TA31	5069	
51	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5555	LA11 - LA11 - LA11 - GA11 - MA11	5186	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	LA21 - LA21 - DA22 - DA22	4219	
		BA_A1	AA31 - TA31	5712	AA31 - TA31	5343	
52	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
53	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
54	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5829	LA12 - LA12 - LA12 - GA11 - MA11	4698	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA22 - DA21	4379	
		BA_A1	AA31 - TA31	5986	AA31 - TA31	4880	
55	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4496	LA12 - LA12 - LA12 - GA11 - MA11	4945	No
		BC_A2	MA21 - MA21 - DA22 - DA21	4562	MA21 - MA21 - DA21 - DA21	4490	
		BA_A1	AA31 - TA31	4718	AA31 - TA31	5154	
56	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4767	LA12 - LA12 - LA12 - GA11 - MA11	5219	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4665	MA21 - MA21 - DA21 - DA21	4593	
		BA_A1	AA31 - TA31	4975	AA31 - TA31	5428	
57	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5041	LA11 - LA11 - LA12 - GA11 - MA11	5457	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4768	LA21 - LA21 - DA22 - DA21	4356	
		BA_A1	AA31 - TA31	5249	AA31 - TA31	5614	
58	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
59	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5221	LA11 - LA11 - LA12 - GA11 - MA11	5636	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4871	MA21 - MA21 - DA21 - DA21	4696	
		BA_A1	AA31 - TA31	5523	AA31 - TA31	5792	

Table C.4 the Production Plans and Schedules for the 4th set of Orders

Order No.	Product	Comp.	System I Processing Route	System I Finishing time (time units)	System II Processing Route	System II Finishing time (time units)	System II Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
5	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
7	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
8	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
9	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
11	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
13	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1624	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1237	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1781	
14	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	1898	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1340	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	2055	

15	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA11 - LA11 - LA11 - GA11 - MA11	2172	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1443	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	2329	
16	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA12 - LA12 - LA12 - GA11 - MA11	1684	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1546	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	1866	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
19	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1324	LA12 - LA12 - LA12 - GA11 - MA11	1932	No
		BC_A2	MA21 - MA21 - DA22 - DA21	1562	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1718	AA31 - TA31	2140	
20	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1566	LA12 - LA12 - LA12 - GA11 - MA11	2206	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1665	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2414	
21	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1807	LA11 - LA11 - LA12 - GA11 - MA11	2443	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1768	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2047	AA31 - TA31	2600	
22	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
23	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
24	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2048	LA11 - LA11 - LA12 - GA11 - MA11	2622	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1871	MA21 - MA21 - DA21 - DA21	1696	
		BA_A1	AA31 - TA31	2236	AA31 - TA31	2779	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2301	LA11 - LA11 - LA12 - GA11 - MA11	2801	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1974	LA21 - LA21 - DA22 - DA22	1429	
		BA_A1	AA31 - TA31	2510	AA31 - TA31	2957	
26	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2983	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2237	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	3139	
27	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA12 - LA12 - LA12 - GA11 - MA11	2482	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2340	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	2685	
28	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA11 - LA11 - LA11 - GA11 - MA11	3257	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	LA21 - LA21 - DA22 - DA22	2219	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	3413	
29	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
30	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2575	LA12 - LA12 - LA12 - GA11 - MA11	3016	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA22	2435	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	3225	
31	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	

32	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
33	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2772	LA12 - LA12 - LA12 - GA11 - MA11	3206	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2475	
		BA_A1	AA31 - TA31	3058	AA31 - TA31	3499	
34	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3014	LA11 - LA11 - LA12 - GA11 - MA11	3528	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2578	
		BA_A1	AA31 - TA31	3332	AA31 - TA31	3684	
35	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3255	LA11 - LA11 - LA12 - GA11 - MA11	3706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	LA21 - LA21 - DA22 - DA22	2327	
		BA_A1	AA31 - TA31	3417	AA31 - TA31	3863	
36	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3496	LA12 - LA12 - LA12 - GA11 - MA11	3448	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA21 - MA21 - DA21 - DA21	2681	
		BA_A1	AA31 - TA31	3653	AA31 - TA31	3770	
37	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3814	LA21 - LA21 - LA21 - GA11 - MA11	2516	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2959	MA11 - MA11 - DA22 - DA22	2447	
		BA_A1	AA31 - TA31	3971	AA31 - TA31	2864	
38	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
39	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
40	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4088	LA11 - LA11 - LA11 - GA11 - MA11	3888	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3237	
		BA_A1	AA31 - TA31	4245	AA31 - TA31	4045	
41	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
42	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
43	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4362	LA11 - LA11 - LA11 - GA11 - MA11	4162	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3340	
		BA_A1	AA31 - TA31	4519	AA31 - TA31	4319	
44	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4636	LA12 - LA12 - LA12 - GA11 - MA11	3922	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA21 - LA21 - DA22 - DA22	3219	
		BA_A1	AA31 - TA31	4793	AA31 - TA31	4131	
45	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3847	LA12 - LA12 - LA12 - GA11 - MA11	4112	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA22 - DA21	3379	
		BA_A1	AA31 - TA31	4056	AA31 - TA31	4405	
46	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4121	LA11 - LA11 - LA12 - GA11 - MA11	4433	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3490	
		BA_A1	AA31 - TA31	4330	AA31 - TA31	4590	
47	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
48	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4298	LA11 - LA11 - LA12 - GA11 - MA11	4612	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3593	
		BA_A1	AA31 - TA31	4604	AA31 - TA31	4769	

49	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4813	LA11 - LA11 - LA12 - GA11 - MA11	4791	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	LA21 - LA21 - DA22 - DA21	3356	
		BA_A1	AA31 - TA31	4969	AA31 - TA31	4948	
50	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4669	LA12 - LA12 - LA12 - GA11 - MA11	4353	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	3696	
		BA_A1	AA31 - TA31	4878	AA31 - TA31	4676	
51	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3589	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3429	
		BA_A1			AA32 - TA31	3803	
52	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5087	LA11 - LA11 - LA11 - GA11 - MA11	4973	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4237	
		BA_A1	AA31 - TA31	5243	AA31 - TA31	5129	
53	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5361	LA11 - LA11 - LA11 - GA11 - MA11	5247	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4340	
		BA_A1	AA31 - TA31	5517	AA31 - TA31	5403	
54	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5635	LA12 - LA12 - LA12 - GA11 - MA11	4830	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	LA21 - LA21 - DA22 - DA22	4219	
		BA_A1	AA31 - TA31	5791	AA31 - TA31	5033	
55	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
56	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
57	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
58	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4858	LA12 - LA12 - LA12 - GA11 - MA11	5071	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA22 - DA21	4379	
		BA_A1	AA31 - TA31	5055	AA31 - TA31	5228	
59	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5120	LA11 - LA11 - LA12 - GA11 - MA11	5518	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4490	
		BA_A1	AA31 - TA31	5329	AA31 - TA31	5674	
60	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5394	LA11 - LA11 - LA12 - GA11 - MA11	5697	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA21 - DA21	4593	
		BA_A1	AA31 - TA31	5603	AA31 - TA31	5853	
61	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5812	LA12 - LA12 - LA12 - GA11 - MA11	5313	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	LA21 - LA21 - DA22 - DA21	4356	
		BA_A1	AA31 - TA31	5968	AA31 - TA31	5489	
62	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
63	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5668	LA12 - LA12 - LA11 - GA11 - MA11	5730	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA21 - MA21 - DA21 - DA21	4696	
		BA_A1	AA31 - TA31	5877	AA31 - TA31	5939	
64	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	4512	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4429	
		BA_A1			AA32 - TA31	4709	

Table C.5 the Production Plans and Schedules for the 5th set of Orders

Order No.	Product	Comp.	System I Processing Route	System I Finishing time (time units)	System II Processing Route	System II Finishing time (time units)	Resource Regrouped?
0	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
7	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
8	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
9	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
13	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
14	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1803	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1237	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1960	

15	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	2077	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1340	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	2234	
16	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA12 - LA12 - LA12 - GA11 - MA11	1836	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1443	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	2045	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
19	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA11 - LA11 - LA11 - GA11 - MA11	2351	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1546	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2508	
20	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
21	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
22	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1324	LA12 - LA12 - LA12 - GA11 - MA11	2027	No
		BC_A2	MA21 - MA21 - DA22 - DA21	1562	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1718	AA31 - TA31	2319	
23	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1566	LA11 - LA11 - LA12 - GA11 - MA11	2622	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1665	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2779	
24	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1807	LA11 - LA11 - LA12 - GA11 - MA11	2801	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1768	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2047	AA31 - TA31	2957	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2048	LA12 - LA12 - LA12 - GA11 - MA11	2268	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1871	MA21 - MA21 - DA21 - DA21	1696	
		BA_A1	AA31 - TA31	2236	AA31 - TA31	2593	
26	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2301	LA12 - LA12 - LA12 - GA11 - MA11	2509	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1974	LA21 - LA21 - DA22 - DA22	1429	
		BA_A1	AA31 - TA31	2510	AA31 - TA31	2679	
27	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2575	LA21 - LA21 - LA21 - GA11 - MA21	1610	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2077	MA11 - MA11 - DA22 - DA22	1537	
		BA_A1	AA31 - TA31	2784	AA32 - TA31	1811	
28	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2983	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2237	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	3139	
29	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA11 - LA11 - LA11 - GA11 - MA11	3257	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2340	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	3413	
30	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA12 - LA12 - LA12 - GA11 - MA11	3016	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	LA21 - LA21 - DA22 - DA22	2219	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	3225	
31	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	

32	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2772	LA12 - LA12 - LA12 - GA11 - MA11	3206	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA22	2435	
		BA_A1	AA31 - TA31	3058	AA31 - TA31	3499	
33	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
34	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3014	LA11 - LA11 - LA12 - GA11 - MA11	3528	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2475	
		BA_A1	AA31 - TA31	3332	AA31 - TA31	3684	
35	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3255	LA11 - LA11 - LA12 - GA11 - MA11	3706	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2578	
		BA_A1	AA31 - TA31	3417	AA31 - TA31	3863	
36	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3496	LA12 - LA12 - LA12 - GA11 - MA11	3448	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	LA21 - LA21 - DA22 - DA22	2327	
		BA_A1	AA31 - TA31	3653	AA31 - TA31	3770	
37	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
38	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3814	LA21 - LA21 - LA21 - GA11 - MA21	2570	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA11 - MA11 - DA22 - DA22	2447	
		BA_A1	AA31 - TA31	3971	AA32 - TA31	2737	
39	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
40	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2782	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	2460	
		BA_A1			AA32 - TA31	2920	
41	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3077	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	2568	
		BA_A1			AA32 - TA31	3258	
42	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4088	LA11 - LA11 - LA11 - GA11 - MA11	3888	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3287	
		BA_A1	AA31 - TA31	4245	AA31 - TA31	4045	
43	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
44	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
45	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
46	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4362	LA11 - LA11 - LA11 - GA11 - MA11	4162	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3390	
		BA_A1	AA31 - TA31	4519	AA31 - TA31	4319	
47	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4636	LA12 - LA12 - LA12 - GA11 - MA11	3922	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA21 - LA21 - DA22 - DA22	3219	
		BA_A1	AA31 - TA31	4793	AA31 - TA31	4131	
48	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3847	LA12 - LA12 - LA12 - GA11 - MA11	4112	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA22 - DA21	3428	
		BA_A1	AA31 - TA31	4056	AA31 - TA31	4405	

49	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4121	LA11 - LA11 - LA12 - GA11 - MA11	4433	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3539	
		BA_A1	AA31 - TA31	4330	AA31 - TA31	4590	
50	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4298	LA11 - LA11 - LA12 - GA11 - MA11	4612	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	LA21 - LA21 - DA22 - DA22	3327	
		BA_A1	AA31 - TA31	4604	AA31 - TA31	4769	
51	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4813	LA11 - LA11 - LA12 - GA11 - MA11	4791	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA21 - DA21	3642	
		BA_A1	AA31 - TA31	4969	AA31 - TA31	4948	
52	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4669	LA12 - LA12 - LA12 - GA11 - MA11	4353	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	3745	
		BA_A1	AA31 - TA31	4878	AA31 - TA31	4676	
53	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
54	PA	BC_A1	No Solution		LA12 - LA12 - LA11 - GA11 - MA11	4824	No
		BC_A2			LA21 - LA21 - DA22 - DA22	3478	
		BA_A1			AA32 - TA31	4981	
55	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3615	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3586	
		BA_A1			AA31 - TA31	3949	
56	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
57	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5087	LA11 - LA11 - LA11 - GA11 - MA11	5068	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4237	
		BA_A1	AA31 - TA31	5243	AA31 - TA31	5225	
58	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
59	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5361	LA11 - LA11 - LA11 - GA11 - MA11	5342	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4340	
		BA_A1	AA31 - TA31	5517	AA31 - TA31	5499	
60	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5635	LA12 - LA12 - LA12 - GA11 - MA11	5032	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	LA21 - LA21 - DA22 - DA22	4219	
		BA_A1	AA31 - TA31	5791	AA31 - TA31	5310	
61	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4858	LA11 - LA11 - LA12 - GA11 - MA11	5613	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA22 - DA21	4379	
		BA_A1	AA31 - TA31	5055	AA31 - TA31	5770	
62	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
63	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5120	LA11 - LA11 - LA12 - GA11 - MA11	5792	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4490	
		BA_A1	AA31 - TA31	5329	AA31 - TA31	5948	
64	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5394	LA12 - LA12 - LA12 - GA11 - MA11	5274	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA21 - DA21	4593	
		BA_A1	AA31 - TA31	5603	AA31 - TA31	5584	
65	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5812	LA12 - LA12 - LA12 - GA11 - MA11	5515	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	LA21 - LA21 - DA22 - DA21	4356	
		BA_A1	AA31 - TA31	5968	AA31 - TA31	5672	

66	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5668	LA21 - LA21 - LA21 - GA11 - MA21	4540	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA11 - MA11 - DA22 - DA22	4429	
		BA_A1	AA31 - TA31	5877	AA31 - TA31	4854	
67	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
68	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4782	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4537	
		BA_A1			AA32 - TA31	5023	
69	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5023	Yes(1)
		BC_A2			MA21 - MA11 - DA22 - DA21	4670	
		BA_A1			AA32 - TA31	5161	

Table C.6 the Production Plans and Schedules for the 6th set of Orders

Order No.	Product	Comp.	System I Processing Route	System I Finishing time (time units)	System II Processing Route	System II Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 -MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
4	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
7	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
8	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
9	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
12	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
13	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
14	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 -MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	

15	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1803	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1268	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	1960	
16	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA11 - LA11 - LA11 - GA11 - MA11	2077	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	2234	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA12 - LA12 - LA12 - GA11 - MA11	1660	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1474	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	1863	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
19	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA11 - LA11 - LA11 - GA11 - MA11	2351	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1577	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2508	
20	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA12 - LA12 - LA12 - GA11 - MA11	1902	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1572	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1728	AA31 - TA31	2058	
21	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1772	LA12 - LA12 - LA12 - GA11 - MA11	2143	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2319	
22	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2027	LA11 - LA11 - LA12 - GA11 - MA11	2622	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1783	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2236	AA31 - TA31	2779	
23	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
24	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2301	LA11 - LA11 - LA12 - GA11 - MA11	2801	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1886	MA21 - MA21 - DA21 - DA21	1696	
		BA_A1	AA31 - TA31	2510	AA31 - TA31	2957	
26	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2496	LA12 - LA12 - LA12 - GA11 - MA11	2384	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1989	LA21 - LA21 - DA22 - DA22	1429	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	2593	
27	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
28	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2738	LA12 - LA12 - LA12 - GA11 - MA11	2661	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2092	MA21 - MA21 - DA22 - DA21	1716	
		BA_A1	AA32 - TA31	2904	AA31 - TA31	2864	
29	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	1582	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	1537	
		BA_A1			AA32 - TA31	1811	
30	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2983	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2237	
		BA_A1	AA31 - TA31	3246	AA31 - TA31	3139	
31	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA11 - LA11 - LA11 - GA11 - MA11	3257	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2340	
		BA_A1	AA31 - TA31	3520	AA31 - TA31	3413	

32	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA12 - LA12 - LA12 - GA11 - MA11	3042	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	LA21 - LA21 - DA22 - DA22	2219	
		BA_A1	AA31 - TA31	3794	AA31 - TA31	3225	
33	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2979	LA11 - LA11 - LA12 - GA11 - MA11	3528	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA22 - DA21	2379	
		BA_A1	AA31 - TA31	3136	AA31 - TA31	3684	
34	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
35	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
36	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3221	LA11 - LA11 - LA12 - GA11 - MA11	3706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2490	
		BA_A1	AA31 - TA31	3377	AA31 - TA31	3863	
37	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
38	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
39	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3462	LA12 - LA12 - LA12 - GA11 - MA11	3290	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2593	
		BA_A1	AA31 - TA31	3618	AA31 - TA31	3499	
40	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3814	LA12 - LA12 - LA12 - GA11 - MA11	3567	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	LA21 - LA21 - DA22 - DA21	2356	
		BA_A1	AA31 - TA31	3971	AA31 - TA31	3770	
41	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3781	LA21 - LA21 - LA21 - GA11 - MA21	2540	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA11 - MA11 - DA22 - DA22	2429	
		BA_A1	AA32 - TA31	3919	AA32 - TA31	2706	
42	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2782	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	2537	
		BA_A1			AA32 - TA31	2920	
43	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3103	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	2621	
		BA_A1			AA32 - TA31	3258	
44	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3351	Yes(1)
		BC_A2			MA21 - MA11 - DA22 - DA21	2646	
		BA_A1			AA32 - TA31	3532	
45	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4088	LA11 - LA11 - LA11 - GA11 - MA11	3888	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3313	
		BA_A1	AA31 - TA31	4245	AA31 - TA31	4045	
46	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4362	LA11 - LA11 - LA11 - GA11 - MA11	4162	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3416	
		BA_A1	AA31 - TA31	4519	AA31 - TA31	4319	
47	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
48	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4636	LA12 - LA12 - LA12 - GA11 - MA11	3948	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	MA21 - MA21 - DA21 - DA21	3519	
		BA_A1	AA31 - TA31	4793	AA31 - TA31	4131	

49	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4022	LA12 - LA12 - LA12 - GA11 - MA11	4196	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	LA21 - LA21 - DA22 - DA22	3358	
		BA_A1	AA31 - TA31	4330	AA31 - TA31	4405	
50	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
51	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4263	LA11 - LA11 - LA12 - GA11 - MA11	4433	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3622	
		BA_A1	AA31 - TA31	4420	AA31 - TA31	4590	
52	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4813	LA11 - LA11 - LA12 - GA11 - MA11	4612	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA22 - DA21	3660	
		BA_A1	AA31 - TA31	4969	AA31 - TA31	4769	
53	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4582	LA11 - LA11 - LA12 - GA11 - MA11	4791	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA21 - DA21	3771	
		BA_A1	AA31 - TA31	4878	AA31 - TA31	4948	
54	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
55	PA	BC_A1	No Solution		LA12 - LA12 - LA12 - GA11 - MA11	4472	No
		BC_A2			LA21 - LA21 - DA22 - DA22	3466	
		BA_A1			AA31 - TA31	4676	
56	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	LA21 - LA21 - LA21 - GA11 - MA21	3679	Yes(1)
		BC_B2	LB21 - MB21 - GB21	3229	MA11 - MA11 - DA22 - DA22	3574	
		BA_B1	AB31 - TB31	3496	AA32 - TA31	3817	
57	PA	BC_A1	No Solution		MB11 - LB11 - DB11 - DB11	3387	No
		BC_A2			LB21 - MB21 - GB21	3229	
		BA_A1			AB31 - TB31	3496	
58	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4009	Yes(1)
		BC_A2			MA11 - MA11 - LA12 - DA21	3637	
		BA_A1			AA32 - TA31	4164	
59	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4257	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3710	
		BA_A1			AA32 - TA31	4438	
60	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5087	LA11 - LA11 - LA11 - GA11 - MA11	4973	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4219	
		BA_A1	AA31 - TA31	5243	AA31 - TA31	5129	
61	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
62	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5361	LA11 - LA11 - LA11 - GA11 - MA11	5247	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	LA21 - MA21 - DA21 - DA21	4322	
		BA_A1	AA31 - TA31	5517	AA31 - TA31	5403	
63	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
64	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5635	LA12 - LA12 - LA12 - GA11 - MA11	5006	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4425	
		BA_A1	AA31 - TA31	5791	AA31 - TA31	5215	
65	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	

66	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4846	LA12 - LA12 - LA12 - GA11 - MA11	5196	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	LA21 - LA21 - DA22 - DA22	4290	
		BA_A1	AA31 - TA31	5055	AA31 - TA31	5489	
67	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5120	LA11 - LA11 - LA12 - GA11 - MA11	5518	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4528	
		BA_A1	AA31 - TA31	5329	AA31 - TA31	5674	
68	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5306	LA11 - LA11 - LA12 - GA11 - MA11	5697	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA22 - DA21	4566	
		BA_A1	AA31 - TA31	5603	AA31 - TA31	5853	
69	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
70	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5812	LA12 - LA12 - LA12 - GA11 - MA11	5438	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	MA21 - MA21 - DA21 - DA21	4677	
		BA_A1	AA31 - TA31	5968	AA31 - TA31	5760	
71	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5668	LA21 - LA21 - LA21 - GA11 - MA11	4514	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA11 - MA11 - DA22 - DA22	4405	
		BA_A1	AA31 - TA31	5877	AA31 - TA31	4854	
72	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4783	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4543	
		BA_A1			AA32 - TA31	4981	
73	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5067	Yes(1)
		BC_A2			MA11 - MA21 - DA22 - DA22	4682	
		BA_A1			AA32 - TA31	5249	
74	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5308	Yes(1)
		BC_A2			MA21 - MA11 - DA21 - DA22	4826	
		BA_A1			AA31 - TA31	5575	

Table C.7 the Production Plans and Schedules for the 7th set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
7	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
8	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
9	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
13	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
14	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 - MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	

15	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA11 - LA11 - LA12 - GA11 - MA11	1800	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1161	LA21 - LA21 - DA22 - DA22	537	
		BA_A1	AA31 - TA31	1688	AA31 - TA31	1957	
16	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1993	LA11 - LA11 - LA11 - GA11 - MA11	1982	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1268	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2150	AA31 - TA31	2138	
17	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2267	LA12 - LA12 - LA12 - GA11 - MA11	1660	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2424	AA31 - TA31	1863	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
19	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2541	LA11 - LA11 - LA11 - GA11 - MA11	2256	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1474	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2698	AA31 - TA31	2412	
20	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2815	LA12 - LA12 - LA12 - GA11 - MA11	2041	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1577	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2972	AA31 - TA31	2224	
21	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
22	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1772	LA11 - LA11 - LA12 - GA11 - MA11	2527	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1582	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	2683	
23	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
24	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2027	LA11 - LA11 - LA12 - GA11 - MA11	2706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	2236	AA31 - TA31	2862	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2301	LA12 - LA12 - LA12 - GA11 - MA11	2289	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1783	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2510	AA31 - TA31	2498	
26	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2496	LA12 - LA12 - LA12 - GA11 - MA11	2566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1886	MA21 - MA21 - DA21 - DA21	1696	
		BA_A1	AA31 - TA31	2784	AA31 - TA31	2769	
27	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2738	LA21 - LA21 - LA21 - GA11 - MA11	1512	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	1989	MA11 - MA11 - DA22 - DA22	1429	
		BA_A1	AA32 - TA31	2904	AA32 - TA31	1679	
28	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
29	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	1782	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	1537	
		BA_A1			AA31 - TA31	2042	
30	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2102	Yes(1)
		BC_A2			MA21 - MA21 - DA22 - DA21	1716	
		BA_A1			AA32 - TA31	2257	
31	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2350	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	1731	
		BA_A1			AA32 - TA31	2531	

		BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	
32	PB	BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	No
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3089	LA11 - LA11 - LA11 - GA11 - MA11	2888	
33	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2312	No
		BA_A1	AA31 - TA31	3246	AA31 - TA31	3044	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3363	LA11 - LA11 - LA11 - GA11 - MA11	3162	
34	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2415	No
		BA_A1	AA31 - TA31	3520	AA31 - TA31	3318	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3637	LA12 - LA12 - LA12 - GA11 - MA11	2947	
35	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA21 - DA21	2518	No
		BA_A1	AA31 - TA31	3794	AA31 - TA31	3130	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2979	LA12 - LA12 - LA12 - GA11 - MA11	3195	
36	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2546	LA21 - LA21 - DA22 - DA22	2358	No
		BA_A1	AA31 - TA31	3136	AA31 - TA31	3404	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3221	LA11 - LA11 - LA12 - GA11 - MA11	3433	
37	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2621	No
		BA_A1	AA31 - TA31	3377	AA31 - TA31	3589	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3462	LA11 - LA11 - LA12 - GA11 - MA11	3611	
38	PA	BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA22 - DA21	2659	No
		BA_A1	AA31 - TA31	3618	AA31 - TA31	3768	
		BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	
39	PB	BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	No
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3814	LA11 - LA11 - LA12 - GA11 - MA11	3790	
40	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2753	MA21 - MA21 - DA21 - DA21	2770	No
		BA_A1	AA31 - TA31	3971	AA31 - TA31	3947	
		BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	
41	PB	BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	No
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3781	LA12 - LA12 - LA12 - GA11 - MA11	3472	
42	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2856	LA21 - LA21 - DA22 - DA22	2466	No
		BA_A1	AA32 - TA31	3919	AA31 - TA31	3675	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	2679	
43	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	2574	Yes(1)
		BA_A1			AA32 - TA31	2817	
		BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	
44	PB	BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	No
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3008	
45	PA	BC_A2	No Solution		MA11 - MA11 - LA12 - DA21	2636	Yes(1)
		BA_A1			AA31 - TA31	3216	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3256	
46	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	2709	Yes(1)
		BA_A1			AA32 - TA31	3437	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3403	
47	PA	BC_A2	No Solution		MA11 - MA11 - LA12 - DA22	2722	Yes(1)
		BA_A1			AA32 - TA31	3542	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4088	LA11 - LA11 - LA11 - GA11 - MA11	3972	
48	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3218	No
		BA_A1	AA31 - TA31	4245	AA31 - TA31	4129	

49	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4362	LA11 - LA11 - LA11 - GA11 - MA11	4246	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3321	
		BA_A1	AA31 - TA31	4519	AA31 - TA31	4403	
50	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4636	LA12 - LA12 - LA12 - GA11 - MA11	4005	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	MA21 - MA21 - DA21 - DA21	3424	
		BA_A1	AA31 - TA31	4793	AA31 - TA31	4214	
51	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4022	LA12 - LA12 - LA12 - GA11 - MA11	4196	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA21 - DA21	3571	
		BA_A1	AA31 - TA31	4330	AA31 - TA31	4488	
52	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4263	LA11 - LA11 - LA12 - GA11 - MA11	4517	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3674	
		BA_A1	AA31 - TA31	4420	AA31 - TA31	4674	
53	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4813	LA11 - LA11 - LA12 - GA11 - MA11	4696	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	LA21 - LA21 - DA22 - DA22	3497	
		BA_A1	AA31 - TA31	4969	AA31 - TA31	4852	
54	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
55	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4582	LA12 - LA12 - LA12 - GA11 - MA11	4437	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA22 - DA21	3713	
		BA_A1	AA31 - TA31	4878	AA31 - TA31	4759	
56	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
57	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3748	Yes(1)
		BC_A2			MA11 - MA11 - LA12 - DA22	3509	
		BA_A1			AA31 - TA31	4032	
58	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4066	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3617	
		BA_A1			AA31 - TA31	4300	
59	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4307	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	3738	
		BA_A1			AA32 - TA31	4445	
60	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
61	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4498	Yes(1)
		BC_A2			MA21 - MA11 - DA22 - DA21	3800	
		BA_A1			AA32 - TA31	4636	
62	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
63	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3382	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	3353	
		BA_A1			AA31 - TA31	3854	
64	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5087	LA11 - LA11 - LA11 - GA11 - MA11	4878	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4276	
		BA_A1	AA31 - TA31	5243	AA31 - TA31	5034	
65	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	

66	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5361	LA11 - LA11 - LA11 - GA11 - MA11	5152	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4379	
		BA_A1	AA31 - TA31	5517	AA31 - TA31	5308	
67	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
68	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
69	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5635	LA12 - LA12 - LA12 - GA11 - MA11	4911	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4517	
		BA_A1	AA31 - TA31	5791	AA31 - TA31	5120	
70	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
71	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4846	LA12 - LA12 - LA12 - GA11 - MA11	5101	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA21 - DA21	4666	
		BA_A1	AA31 - TA31	5055	AA31 - TA31	5394	
72	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5120	LA11 - LA11 - LA12 - GA11 - MA11	5423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4769	
		BA_A1	AA31 - TA31	5329	AA31 - TA31	5579	
73	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5306	LA11 - LA11 - LA12 - GA11 - MA11	5602	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	LA21 - LA21 - DA22 - DA22	4566	
		BA_A1	AA31 - TA31	5603	AA31 - TA31	5758	
74	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5812	LA11 - LA11 - LA12 - GA11 - MA11	5780	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	MA21 - MA21 - DA22 - DA21	4807	
		BA_A1	AA31 - TA31	5968	AA31 - TA31	5937	
75	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5668	LA12 - LA12 - LA12 - GA11 - MA11	5343	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA21 - MA21 - DA21 - DA21	4918	
		BA_A1	AA31 - TA31	5877	AA31 - TA31	5665	
76	PA	BC_A1	No Solution		LA12 - LA12 - LA11 - GA11 - MA11	5814	No
		BC_A2			LA21 - LA21 - DA22 - DA22	4674	
		BA_A1			AA32 - TA31	5970	
77	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4972	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4857	
		BA_A1			AA32 - TA31	5153	
78	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5213	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4941	
		BA_A1			AA32 - TA31	5351	
79	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5404	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4966	
		BA_A1			AA32 - TA31	5542	

Table C.8 the Production Plans and Schedules for the 8th set of Orders

Order No.	Product	Comp.	System I Processing Route	System I Finishing time (time units)	System II Processing Route	System II Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
4	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
7	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
8	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
9	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
11	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 - MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	
13	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
14	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA11 - LA11 - LA12 - GA11 - MA11	1800	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1161	LA21 - LA21 - DA22 - DA22	537	
		BA_A1	AA31 - TA31	1688	AA31 - TA31	1957	

15	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	1768	LA12 - LA12 - LA12 - GA11 - MA11	1660	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1268	MA21 - MA21 - DA21 - DA21	930	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	1863	
16	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
17	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
18	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2042	LA11 - LA11 - LA11 - GA11 - MA11	1982	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2199	AA31 - TA31	2138	
19	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2316	LA11 - LA11 - LA11 - GA11 - MA11	2256	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1474	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2473	AA31 - TA31	2412	
20	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2590	LA12 - LA12 - LA12 - GA11 - MA11	2041	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1577	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2747	AA31 - TA31	2224	
21	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1915	LA11 - LA11 - LA12 - GA11 - MA11	2527	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1582	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2071	AA31 - TA31	2683	
22	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2156	LA11 - LA11 - LA12 - GA11 - MA11	2706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	2313	AA31 - TA31	2862	
23	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2397	LA12 - LA12 - LA12 - GA11 - MA11	2289	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1783	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	2559	AA31 - TA31	2498	
24	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	2767	LA12 - LA12 - LA12 - GA11 - MA11	2566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1886	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2924	AA31 - TA31	2769	
25	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	2816	LA21 - LA21 - LA21 - GA11 - MA21	1540	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	1989	MA11 - MA11 - DA22 - DA22	1429	
		BA_A1	AA32 - TA31	2983	AA32 - TA31	1706	
26	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	1782	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	1537	
		BA_A1			AA32 - TA31	1920	
27	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2102	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	1621	
		BA_A1			AA32 - TA31	2257	
28	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2350	Yes(1)
		BC_A2			MA21 - MA11 - DA22 - DA21	1646	
		BA_A1			AA32 - TA31	2531	
29	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2506	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	1672	
		BA_A1			AA32 - TA31	2644	
30	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
31	PA	BC_A1	No Solution		LA21 - LA21 - LA11 - GA11 - MA11	2739	Yes(1)
		BC_A2			MA21 - MA21 - DA22 - DA21	1698	
		BA_A1			AA32 - TA31	2896	

32	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
33	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1229	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1496	
34	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
35	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3090	LA11 - LA11 - LA11 - GA11 - MA11	3002	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2312	
		BA_A1	AA31 - TA31	3247	AA31 - TA31	3159	
36	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3364	LA11 - LA11 - LA11 - GA11 - MA11	3276	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2415	
		BA_A1	AA31 - TA31	3521	AA31 - TA31	3433	
37	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3638	LA12 - LA12 - LA12 - GA11 - MA11	2947	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA21 - DA21	2518	
		BA_A1	AA31 - TA31	3795	AA31 - TA31	3244	
38	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2858	LA12 - LA12 - LA12 - GA11 - MA11	3188	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA21	2674	
		BA_A1	AA31 - TA31	3016	AA31 - TA31	3345	
39	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3124	LA11 - LA11 - LA12 - GA11 - MA11	3547	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2777	
		BA_A1	AA31 - TA31	3333	AA31 - TA31	3704	
40	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3398	LA11 - LA11 - LA12 - GA11 - MA11	3726	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA22 - DA21	2815	
		BA_A1	AA31 - TA31	3607	AA31 - TA31	3882	
41	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3815	LA12 - LA12 - LA12 - GA11 - MA11	3430	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	MA21 - MA21 - DA21 - DA21	2926	
		BA_A1	AA31 - TA31	3972	AA31 - TA31	3586	
42	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
43	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
44	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3672	LA21 - LA21 - LA21 - GA11 - MA21	2883	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA11 - MA11 - LA12 - LA12	2579	
		BA_A1	AA31 - TA31	3881	AA32 - TA31	3022	
45	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3125	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	2865	
		BA_A1			AA32 - TA31	3278	
46	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3366	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	2949	
		BA_A1			AA32 - TA31	3505	
47	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3608	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	2974	
		BA_A1			AA32 - TA31	3746	
48	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	2379	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	2350	
		BA_A1			AA31 - TA31	2584	

		BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	
49	PB	BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2473	No
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2580	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	2724	
50	PA	BC_A2	No Solution		MB11 - MB11 - DB11 - DB11	2461	Yes(2)
		BA_A1			AA31 - TA31	2948	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4089	LA11 - LA11 - LA11 - GA11 - MA11	3908	
51	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3335	No
		BA_A1	AA31 - TA31	4246	AA31 - TA31	4064	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4363	LA11 - LA11 - LA11 - GA11 - MA11	4182	
52	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3438	No
		BA_A1	AA31 - TA31	4520	AA31 - TA31	4338	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4637	LA12 - LA12 - LA12 - GA11 - MA11	3941	
53	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3443	MA21 - MA21 - DA21 - DA21	3576	No
		BA_A1	AA31 - TA31	4794	AA31 - TA31	4150	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3901	LA12 - LA12 - LA12 - GA11 - MA11	4131	
54	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA21 - DA21	3679	No
		BA_A1	AA31 - TA31	4058	AA31 - TA31	4424	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4142	LA11 - LA11 - LA12 - GA11 - MA11	4453	
55	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3818	No
		BA_A1	AA31 - TA31	4331	AA31 - TA31	4609	
		BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	
56	PB	BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3142	No
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4397	LA11 - LA11 - LA12 - GA11 - MA11	4632	
57	PA	BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3921	No
		BA_A1	AA31 - TA31	4605	AA31 - TA31	4788	
		BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	
58	PB	BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3171	No
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4814	LA11 - LA11 - LA12 - GA11 - MA11	4810	
59	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA22 - DA21	3959	No
		BA_A1	AA31 - TA31	4971	AA31 - TA31	4967	
		BC_B1	MB11 - LB11 - DB12 - DB11	3306	MB11 - LB11 - DB11 - DB11	3322	
60	PB	BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3200	No
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3446	
		BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3387	
61	PB	BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3229	No
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3496	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4702	LA12 - LA12 - LA12 - GA11 - MA11	4373	
62	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	4070	No
		BA_A1	AA31 - TA31	4879	AA31 - TA31	4695	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA11	3822	
63	PA	BC_A2	No Solution		MA11 - MA11 - LA12 - DA21	3453	Yes(1)
		BA_A1			AA32 - TA31	3960	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	4091	
64	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	4009	Yes(1)
		BA_A1			AA32 - TA31	4229	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	4332	
65	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	4093	Yes(1)
		BA_A1			AA32 - TA31	4471	

66	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4574	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4119	
		BA_A1			AA32 - TA31	4728	
67	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3382	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	3353	
		BA_A1			AA31 - TA31	3789	
68	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5088	LA11 - LA11 - LA11 - GA11 - MA11	4992	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4301	
		BA_A1	AA31 - TA31	5245	AA31 - TA31	5149	
69	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5362	LA11 - LA11 - LA11 - GA11 - MA11	5266	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4404	
		BA_A1	AA31 - TA31	5519	AA31 - TA31	5423	
70	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5636	LA12 - LA12 - LA12 - GA11 - MA11	4849	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4542	
		BA_A1	AA31 - TA31	5793	AA31 - TA31	5053	
71	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4944	LA12 - LA12 - LA12 - GA11 - MA11	5091	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA21 - DA21	4645	
		BA_A1	AA31 - TA31	5100	AA31 - TA31	5247	
72	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5185	LA11 - LA11 - LA12 - GA11 - MA11	5537	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4784	
		BA_A1	AA31 - TA31	5342	AA31 - TA31	5694	
73	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5426	LA11 - LA11 - LA12 - GA11 - MA11	5716	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA21 - DA21	4887	
		BA_A1	AA31 - TA31	5604	AA31 - TA31	5873	
74	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5813	LA12 - LA12 - LA12 - GA11 - MA11	5332	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	LA21 - LA21 - DA22 - DA22	4632	
		BA_A1	AA31 - TA31	5969	AA31 - TA31	5509	
75	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
76	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5745	LA12 - LA12 - LA11 - GA11 - MA11	5749	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA21 - MA21 - DA21 - DA22	4981	
		BA_A1	AA32 - TA31	5911	AA31 - TA31	5958	
77	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4919	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4356	
		BA_A1			AA32 - TA31	5086	
78	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5160	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4464	
		BA_A1			AA32 - TA31	5299	
79	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
80	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5402	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4740	
		BA_A1			AA32 - TA31	5542	
81	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4376	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	4335	
		BA_A1			AA31 - TA31	4874	
82	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	LB11 - LB11 - DB11 - DB11	4381	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4354	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4489	

83	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4445	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4463	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4571	
84	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5643	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4848	
		BA_A1			AA32 - TA31	5782	

Table C.9 the Production Plans and Schedules for the 9th set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
2	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
3	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
7	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
8	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
9	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
12	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
13	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 - MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	
14	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA11 - LA11 - LA12 - GA11 - MA11	1800	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1161	LA21 - LA21 - DA22 - DA22	537	
		BA_A1	AA31 - TA31	1688	AA31 - TA31	1957	

15	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
16	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	1768	LA12 - LA12 - LA12 - GA11 - MA11	1660	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1268	MA21 - MA21 - DA21 - DA21	930	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	1863	
17	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	657	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	740	
		BA_A1			AA32 - TA31	906	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
19	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2042	LA11 - LA11 - LA11 - GA11 - MA11	1982	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1237	
		BA_A1	AA31 - TA31	2199	AA31 - TA31	2138	
20	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2316	LA11 - LA11 - LA11 - GA11 - MA11	2256	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1474	MA21 - MA21 - DA21 - DA21	1340	
		BA_A1	AA31 - TA31	2473	AA31 - TA31	2412	
21	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2590	LA12 - LA12 - LA12 - GA11 - MA11	2041	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1577	LA21 - LA21 - DA22 - DA22	1219	
		BA_A1	AA31 - TA31	2747	AA31 - TA31	2224	
22	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
23	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1915	LA11 - LA11 - LA12 - GA11 - MA11	2527	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1582	MA21 - MA21 - DA22 - DA21	1379	
		BA_A1	AA31 - TA31	2071	AA31 - TA31	2683	
24	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2156	LA11 - LA11 - LA12 - GA11 - MA11	2706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1490	
		BA_A1	AA31 - TA31	2313	AA31 - TA31	2862	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2397	LA12 - LA12 - LA12 - GA11 - MA11	2289	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1783	MA21 - MA21 - DA21 - DA21	1593	
		BA_A1	AA31 - TA31	2559	AA31 - TA31	2498	
26	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
27	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	2767	LA12 - LA12 - LA12 - GA11 - MA11	2566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1886	LA21 - LA21 - DA22 - DA21	1356	
		BA_A1	AA31 - TA31	2924	AA31 - TA31	2769	
28	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	2816	LA21 - LA21 - LA21 - GA11 - MA21	1540	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	1989	MA11 - MA11 - DA22 - DA22	1429	
		BA_A1	AA32 - TA31	2983	AA32 - TA31	1706	
29	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	1754	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	1537	
		BA_A1			AA32 - TA31	1897	
30	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2102	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	1621	
		BA_A1			AA32 - TA31	2257	
31	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2350	Yes(1)
		BC_A2			MA21 - MA11 - DA22 - DA21	1646	
		BA_A1			AA32 - TA31	2531	

32	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2506	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	1672	
		BA_A1			AA32 - TA31	2644	
33	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	1379	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	1350	
		BA_A1			AA31 - TA31	1740	
34	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1387	No
		BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1473	
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1580	
35	PA	BC_A1	No Solution		LA21 - LA21 - LA11 - GA11 - MA11	2739	Yes(1)
		BC_A2			MA21 - MA21 - DA22 - DA21	1698	
		BA_A1			AA32 - TA31	2896	
36	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3090	LA11 - LA11 - LA11 - GA11 - MA11	3002	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2312	
		BA_A1	AA31 - TA31	3247	AA31 - TA31	3159	
37	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2222	MB11 - LB11 - DB11 - DB11	2222	No
		BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2142	
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2362	
38	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3364	LA11 - LA11 - LA11 - GA11 - MA11	3276	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2415	
		BA_A1	AA31 - TA31	3521	AA31 - TA31	3433	
39	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3638	LA12 - LA12 - LA12 - GA11 - MA11	2947	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA21 - DA21	2518	
		BA_A1	AA31 - TA31	3795	AA31 - TA31	3244	
40	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2286	MB11 - LB11 - DB12 - DB11	2243	No
		BC_B2	LB21 - MB21 - GB21	2171	LB21 - MB21 - GB21	2171	
		BA_B1	AB31 - TB31	2396	AB31 - TB31	2396	
41	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2858	LA12 - LA12 - LA12 - GA11 - MA11	3188	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA21	2674	
		BA_A1	AA31 - TA31	3016	AA31 - TA31	3345	
42	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3124	LA11 - LA11 - LA12 - GA11 - MA11	3547	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2777	
		BA_A1	AA31 - TA31	3333	AA31 - TA31	3704	
43	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3398	LA11 - LA11 - LA12 - GA11 - MA11	3726	No
		BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA22 - DA21	2815	
		BA_A1	AA31 - TA31	3607	AA31 - TA31	3882	
44	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3815	LA12 - LA12 - LA12 - GA11 - MA11	3430	No
		BC_A2	MA21 - MA21 - DA21 - DA21	2753	MA21 - MA21 - DA21 - DA21	2926	
		BA_A1	AA31 - TA31	3972	AA31 - TA31	3586	
45	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MB11 - LB11 - DB11 - DB11	2322	No
		BC_B2	LB21 - MB21 - GB21	2200	LB21 - MB21 - GB21	2200	
		BA_B1	AB31 - TB31	2446	AB31 - TB31	2446	
46	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3672	LA21 - LA21 - LA21 - GA11 - MA21	2883	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA11 - MA11 - LA12 - LA12	2579	
		BA_A1	AA31 - TA31	3881	AA32 - TA31	3022	
47	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB11 - DB11	2387	No
		BC_B2	LB21 - MB21 - GB21	2229	LB21 - MB21 - GB21	2229	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2496	
48	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3125	Yes(1)
		BC_A2			MA11 - MA11 - DA21 - DA21	3029	
		BA_A1			LA21 - LA21 - LA21 - GA11 - MA21	2506	

49	PA	BC_A1	No Solution		AA32 - TA31	3278	
		BC_A2			LA21 - LA21 - LA21 - GA11 - MA21	3366	
		BA_A1			MA11 - MA11 - DA22 - DA22	2865	Yes(1)
50	PA	BC_A1	No Solution		AA32 - TA31	3505	
		BC_A2			LA21 - LA21 - LA21 - GA11 - MA21	3608	
		BA_A1			MA11 - MA11 - DA22 - DA22	2973	Yes(1)
51	PA	BC_A1	No Solution		AA32 - TA31	3746	
		BC_A2			LB21 - LB21 - LB21 - GB21 - MB21	2382	
		BA_A1			MB21 - MB21 - LB21 - LB21	2353	Yes(2)
52	PA	BC_A1	No Solution		AA31 - TA31	2584	
		BC_A2			LB21 - LB21 - LB21 - GB21 - MB21	2669	
		BA_A1			MB11 - MB11 - DB11 - DB11	2461	Yes(2)
53	PA	BC_A1	No Solution		AA31 - TA31	2948	
		BC_A2			LB21 - LB21 - LB21 - GB21 - MB21	2901	
		BA_A1			LB11 - MB11 - DB11 - DB11	2568	Yes(2)
54	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4089	AA32 - TA31	3082	
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	LA11 - LA11 - LA11 - GA11 - MA11	3908	
		BA_A1	AA31 - TA31	4246	MA21 - MA21 - DA21 - DA21	3335	No
55	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	AA31 - TA31	4064	
		BC_B2	LB21 - MB21 - GB21	3142	MB11 - LB11 - DB11 - DB11	3222	
		BA_B1	AB31 - TB31	3362	LB21 - MB21 - GB21	3142	No
56	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4363	AB31 - TB31	3362	
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	LA11 - LA11 - LA11 - GA11 - MA11	4182	
		BA_A1	AA31 - TA31	4520	MA21 - MA21 - DA21 - DA21	3438	No
57	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4637	AA31 - TA31	4338	
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	LA12 - LA12 - LA12 - GA11 - MA11	3941	
		BA_A1	AA31 - TA31	4794	MA21 - MA21 - DA21 - DA21	3576	No
58	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3901	AA31 - TA31	4150	
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	LA12 - LA12 - LA12 - GA11 - MA11	4131	
		BA_A1	AA31 - TA31	4058	MA21 - MA21 - DA21 - DA21	3679	No
59	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	AA31 - TA31	4424	
		BC_B2	LB21 - MB21 - GB21	3171	MB11 - LB11 - DB12 - DB11	3243	
		BA_B1	AB31 - TB31	3396	LB21 - MB21 - GB21	3171	No
60	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4142	AB31 - TB31	3396	
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	LA11 - LA11 - LA12 - GA11 - MA11	4453	
		BA_A1	AA31 - TA31	4331	MA21 - MA21 - DA21 - DA21	3818	No
61	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4397	AA31 - TA31	4609	
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	LA11 - LA11 - LA12 - GA11 - MA11	4632	
		BA_A1	AA31 - TA31	4605	MA21 - MA21 - DA21 - DA21	3921	No
62	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4814	AA31 - TA31	4788	
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	LA11 - LA11 - LA12 - GA11 - MA11	4810	
		BA_A1	AA31 - TA31	4971	MA21 - MA21 - DA22 - DA21	3959	No
63	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	AA31 - TA31	4967	
		BC_B2	LB21 - MB21 - GB21	3200	MB11 - LB11 - DB11 - DB11	3322	
		BA_B1	AB31 - TB31	3446	LB21 - MB21 - GB21	3200	No
64	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	AB31 - TB31	3446	
		BC_B2	LB21 - MB21 - GB21	3229	MB11 - LB11 - DB11 - DB11	3387	
		BA_B1	AB31 - TB31	3496	LB21 - MB21 - GB21	3229	No
65	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4702	AB31 - TB31	3496	
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	LA12 - LA12 - LA12 - GA11 - MA11	4373	
		BA_A1	AA31 - TA31	4879	MA21 - MA21 - DA21 - DA21	4070	No

66	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	3822	Yes(1)
		BC_A2			MA11 - MA11 - DA21 - DA21	3206	
		BA_A1			AA32 - TA31	3960	
67	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4091	Yes(1)
		BC_A2			MA11 - MA11 - LA12 - DA21	3453	
		BA_A1			AA32 - TA31	4229	
68	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4332	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4009	
		BA_A1			AA32 - TA31	4471	
69	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4574	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4093	
		BA_A1			AA32 - TA31	4728	
70	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3382	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	3353	
		BA_A1			AA31 - TA31	3789	
71	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3669	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	3461	
		BA_A1			AA31 - TA31	3993	
72	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5088	LA11 - LA11 - LA11 - GA11 - MA11	4992	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4301	
		BA_A1	AA31 - TA31	5245	AA31 - TA31	5149	
73	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5362	LA11 - LA11 - LA11 - GA11 - MA11	5266	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4404	
		BA_A1	AA31 - TA31	5519	AA31 - TA31	5423	
74	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
75	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5636	LA12 - LA12 - LA12 - GA11 - MA11	4849	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4542	
		BA_A1	AA31 - TA31	5793	AA31 - TA31	5053	
76	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4944	LA12 - LA12 - LA12 - GA11 - MA11	5091	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA21 - DA21	4645	
		BA_A1	AA31 - TA31	5100	AA31 - TA31	5247	
77	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
78	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5185	LA11 - LA11 - LA12 - GA11 - MA11	5537	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4784	
		BA_A1	AA31 - TA31	5342	AA31 - TA31	5694	
79	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5426	LA11 - LA11 - LA12 - GA11 - MA11	5716	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA21 - DA21	4887	
		BA_A1	AA31 - TA31	5604	AA31 - TA31	5873	
80	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
81	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5813	LA12 - LA12 - LA12 - GA11 - MA11	5332	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	LA21 - LA21 - DA22 - DA22	4632	
		BA_A1	AA31 - TA31	5969	AA31 - TA31	5509	
82	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5745	LA12 - LA12 - LA11 - GA11 - MA11	5749	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA21 - MA21 - DA22 - DA21	4925	
		BA_A1	AA32 - TA31	5911	AA31 - TA31	5958	

83	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4919	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4356	
		BA_A1			AA32 - TA31	5086	
84	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5160	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4464	
		BA_A1			AA32 - TA31	5299	
85	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5402	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4740	
		BA_A1			AA32 - TA31	5542	
86	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
87	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5643	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4902	
		BA_A1			AA32 - TA31	5782	
88	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4382	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	4353	
		BA_A1			AA31 - TA31	4874	
89	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4669	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	4461	
		BA_A1			AA32 - TA31	4838	

Table C.10 the Production Plans and Schedules for the 10th set of Orders

Order No.	Product	Comp.	System I Processing Route	System I Finishing time (time units)	System II Processing Route	System II Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
5	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
7	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
8	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
9	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
13	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
14	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 - MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	

					LA11 - LA11 - LA12 - GA11 - MA11	1800	
15		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA21 - LA21 - DA22 - DA22	537	No
	PA	BC_A2	MA21 - MA21 - DA22 - DA22	1161	AA31 - TA31	1957	
		BA_A1	AA31 - TA31	1688	LA12 - LA12 - LA12 - GA11 - MA11	1660	
16		BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	1768	MA21 - MA21 - DA21 - DA21	930	No
	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1268	AA31 - TA31	1863	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA11	657	
17	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	740	Yes(1)
		BA_A1			AA32 - TA31	906	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	958	
18	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	848	Yes(1)
		BA_A1			AA32 - TA31	1097	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2042	LA11 - LA11 - LA11 - GA11 - MA11	1982	
19	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1237	No
		BA_A1	AA31 - TA31	2199	AA31 - TA31	2138	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2316	LA11 - LA11 - LA11 - GA11 - MA11	2256	
20	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1474	MA21 - MA21 - DA21 - DA21	1340	No
		BA_A1	AA31 - TA31	2473	AA31 - TA31	2412	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2590	LA12 - LA12 - LA12 - GA11 - MA11	2041	
21	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1577	LA21 - LA21 - DA22 - DA22	1219	No
		BA_A1	AA31 - TA31	2747	AA31 - TA31	2224	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1915	LA11 - LA11 - LA12 - GA11 - MA11	2527	
22	PA	BC_A2	MA21 - MA21 - DA22 - DA22	1582	MA21 - MA21 - DA22 - DA21	1379	No
		BA_A1	AA31 - TA31	2071	AA31 - TA31	2683	
		BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	
23	PB	BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	No
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2156	LA11 - LA11 - LA12 - GA11 - MA11	2706	
24	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1490	No
		BA_A1	AA31 - TA31	2313	AA31 - TA31	2862	
		BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	
25	PB	BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	No
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2397	LA12 - LA12 - LA12 - GA11 - MA11	2289	
26	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1783	MA21 - MA21 - DA21 - DA21	1593	No
		BA_A1	AA31 - TA31	2559	AA31 - TA31	2498	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	2767	LA12 - LA12 - LA12 - GA11 - MA11	2566	
27	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1886	LA21 - LA21 - DA22 - DA21	1356	No
		BA_A1	AA31 - TA31	2924	AA31 - TA31	2769	
		BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	2816	LA21 - LA21 - LA21 - GA11 - MA21	1540	
28	PA	BC_A2	MA21 - MA21 - DA21 - DA21	1989	MA11 - MA11 - DA22 - DA22	1429	Yes(1)
		BA_A1	AA32 - TA31	2983	AA32 - TA31	1678	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	1782	
29	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	1537	Yes(1)
		BA_A1			AA32 - TA31	1920	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	2102	
30	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	1621	Yes(1)
		BA_A1			AA32 - TA31	2257	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	2350	
31	PA	BC_A2	No Solution		MA21 - MA11 - DA22 - DA21	1646	Yes(1)
		BA_A1			AA32 - TA31	2531	

		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	2506	
32	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	1672	Yes(1)
		BA_A1			AA32 - TA31	2644	
		BC_A1			LA21 - LA21 - LA11 - GA11 - MA11	2739	
33	PA	BC_A2	No Solution		MA21 - MA21 - DA22 - DA21	1698	Yes(1)
		BA_A1			AA32 - TA31	2896	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	1376	
34	PA	BC_A2	No Solution		MB11 - MB11 - DB11 - DB11	1335	Yes(2)
		BA_A1			AA31 - TA31	1712	
		BC_B1	MB11 - LB11 - DB12 - DB11	1306	LB11 - LB11 - DB11 - DB11	1381	
35	PB	BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1354	No
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1489	
		BC_B1	MB11 - LB11 - DB11 - DB11	1386	MB11 - LB11 - DB11 - DB11	1445	
36	PB	BC_B2	LB21 - MB21 - GB21	1229	LB21 - MB21 - GB21	1463	No
		BA_B1	AB31 - TB31	1496	AB31 - TB31	1571	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	1638	
37	PA	BC_A2	No Solution		LB11 - LB11 - DB11 - DB11	1560	Yes(2)
		BA_A1			AA31 - TA31	2042	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3090	LA11 - LA11 - LA11 - GA11 - MA11	3002	
38	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2237	MA21 - MA21 - DA21 - DA21	2312	No
		BA_A1	AA31 - TA31	3247	AA31 - TA31	3159	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3364	LA11 - LA11 - LA11 - GA11 - MA11	3276	
39	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2340	MA21 - MA21 - DA21 - DA21	2415	No
		BA_A1	AA31 - TA31	3521	AA31 - TA31	3433	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	3638	LA12 - LA12 - LA12 - GA11 - MA11	2947	
40	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2443	MA21 - MA21 - DA21 - DA21	2518	No
		BA_A1	AA31 - TA31	3795	AA31 - TA31	3244	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2858	LA12 - LA12 - LA12 - GA11 - MA11	3188	
41	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2546	MA21 - MA21 - DA21 - DA21	2674	No
		BA_A1	AA31 - TA31	3016	AA31 - TA31	3345	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3124	LA11 - LA11 - LA12 - GA11 - MA11	3547	
42	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2649	MA21 - MA21 - DA21 - DA21	2777	No
		BA_A1	AA31 - TA31	3333	AA31 - TA31	3704	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3398	LA11 - LA11 - LA12 - GA11 - MA11	3726	
43	PA	BC_A2	MA21 - MA21 - DA22 - DA22	2656	MA21 - MA21 - DA21 - DA21	2880	No
		BA_A1	AA31 - TA31	3607	AA31 - TA31	3882	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	3815	LA12 - LA12 - LA12 - GA11 - MA11	3430	
44	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2753	MA21 - MA21 - DA22 - DA21	2899	No
		BA_A1	AA31 - TA31	3972	AA31 - TA31	3586	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3672	LA21 - LA21 - LA21 - GA11 - MA21	2883	
45	PA	BC_A2	MA21 - MA21 - DA21 - DA21	2856	MA11 - MA11 - LA12 - LA12	2579	Yes(1)
		BA_A1	AA31 - TA31	3881	AA32 - TA31	3022	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3125	
46	PA	BC_A2	No Solution		MA11 - MA11 - DA21 - DA21	3002	Yes(1)
		BA_A1			AA32 - TA31	3278	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3366	
47	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	2950	Yes(1)
		BA_A1			AA32 - TA31	3505	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	2366	
48	PA	BC_A2	No Solution		MB11 - MB11 - DB11 - DB11	2232	Yes(2)
		BA_A1			AA31 - TA31	2584	

		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	3608	
49	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	3033	Yes(1)
		BA_A1			AA32 - TA31	3746	
		BC_B1	MB11 - LB11 - DB11 - DB11	2222	LB11 - LB11 - DB12 - DB12	2231	
50	PB	BC_B2	LB21 - MB21 - GB21	2142	LB21 - MB21 - GB21	2453	No
		BA_B1	AB31 - TB31	2362	AB31 - TB31	2592	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	2605	
51	PA	BC_A2	No Solution		MB11 - LB11 - DB11 - DB11	2350	Yes(2)
		BA_A1			AA31 - TA31	2948	
		BC_A1			MB11 - LB11 - DB12 - DB12	2368	
52	PA	BC_A2	No Solution		LB21 - MB21 - GB21	2582	No
		BA_A1			AB31 - TB31	2690	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	2834	
53	PA	BC_A2	No Solution		MB11 - LB11 - DB11 - DB11	2471	Yes(2)
		BA_A1			AA31 - TA31	3055	
		BC_B1	MB11 - LB11 - DB12 - DB11	2306	LB21 - LB21 - LB21 - GB21 - MB21	3065	
54	PB	BC_B2	LB21 - MB21 - GB21	2200	LB11 - LB11 - DB11 - DB11	2571	Yes(2)
		BA_B1	AB31 - TB31	2446	AA31 - TA31	3789	
		BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB11 - LB11 - DB12 - DB12	2589	
55	PB	BC_B2	LB21 - MB21 - GB21	2229	LB11 - LB11 - GB21	2646	Yes(1)
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2754	
		BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB12	2684	
56	PB	BC_B2	LB21 - MB21 - GB21	3142	LB11 - LB11 - GB21	2820	Yes(1)
		BA_B1	AB31 - TB31	3362	AB31 - TB31	2928	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4089	MB11 - LB11 - DB11 - DB11	3222	
57	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3237	LB21 - MB21 - GB21	3152	No
		BA_A1	AA31 - TA31	4246	AB31 - TB31	3362	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4363	LA11 - LA11 - LA11 - GA11 - MA11	3908	
58	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3335	No
		BA_A1	AA31 - TA31	4520	AA31 - TA31	4064	
		BC_B1	MB11 - LB11 - DB11 - DB11	3286	LA11 - LA11 - LA11 - GA11 - MA11	4182	
59	PB	BC_B2	LB21 - MB21 - GB21	3171	MA21 - MA21 - DA21 - DA21	3438	No
		BA_B1	AB31 - TB31	3396	AA31 - TA31	4338	
		BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4637	MB11 - LB11 - DB12 - DB11	3243	
60	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3443	LB21 - MB21 - GB21	3181	No
		BA_A1	AA31 - TA31	4794	AB31 - TB31	3396	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3901	LA12 - LA12 - LA12 - GA11 - MA11	3941	
61	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - MA21 - DA21 - DA21	3576	No
		BA_A1	AA31 - TA31	4058	AA31 - TA31	4150	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4142	LA12 - LA12 - LA12 - GA11 - MA11	4131	
62	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3679	No
		BA_A1	AA31 - TA31	4331	AA31 - TA31	4424	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4397	LA11 - LA11 - LA12 - GA11 - MA11	4453	
63	PA	BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA21 - DA21	3818	No
		BA_A1	AA31 - TA31	4605	AA31 - TA31	4609	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4814	LA11 - LA11 - LA12 - GA11 - MA11	4632	
64	PA	BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA21 - DA21	3921	No
		BA_A1	AA31 - TA31	4971	AA31 - TA31	4788	
		BC_B1	MB11 - LB11 - DB12 - DB11	2306	LA11 - LA11 - LA12 - GA11 - MA11	4810	
65	PB	BC_B2	LB21 - MB21 - GB21	2200	LA21 - LA21 - DA22 - DA22	3666	No
		BA_B1	AB31 - TB31	2446	AA31 - TA31	4967	

66	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4702	LA12 - LA12 - LA12 - GA11 - MA11	4373	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	4024	
		BA_A1	AA31 - TA31	4879	AA31 - TA31	4695	
67	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4002	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	3152	
		BA_A1			AA32 - TA31	4183	
68	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4243	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	3223	
		BA_A1			AA32 - TA31	4381	
69	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4436	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3415	
		BA_A1			AA32 - TA31	4574	
70	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4692	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	3523	
		BA_A1			AA32 - TA31	4831	
71	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB11 - DB11	3322	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3210	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3446	
72	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3379	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	3359	
		BA_A1			AA32 - TA31	3620	
73	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3675	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	3398	
		BA_A1			AA31 - TA31	3968	
74	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	LB11 - LB11 - DB11 - DB11	3444	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3762	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3870	
75	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3964	Yes(2)
		BC_A2			MB11 - LB11 - DB11 - DB11	3554	
		BA_A1			AA31 - TA31	4236	
76	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5088	LA11 - LA11 - LA11 - GA11 - MA11	4992	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4212	
		BA_A1	AA31 - TA31	5245	AA31 - TA31	5149	
77	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
78	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
79	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5362	LA11 - LA11 - LA11 - GA11 - MA11	5266	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4315	
		BA_A1	AA31 - TA31	5519	AA31 - TA31	5423	
80	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5636	LA12 - LA12 - LA12 - GA11 - MA11	4849	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4452	
		BA_A1	AA31 - TA31	5793	AA31 - TA31	5053	
81	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
82	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4944	LA12 - LA12 - LA12 - GA11 - MA11	5091	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA21 - DA21	4604	
		BA_A1	AA31 - TA31	5100	AA31 - TA31	5247	

		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5185	LA11 - LA11 - LA12 - GA11 - MA11	5537	
83	PA	BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4707	No
		BA_A1	AA31 - TA31	5342	AA31 - TA31	5694	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5426	LA11 - LA11 - LA12 - GA11 - MA11	5716	
84	PA	BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA22 - DA21	4745	No
		BA_A1	AA31 - TA31	5604	AA31 - TA31	5873	
		BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5813	LA12 - LA12 - LA12 - GA11 - MA11	5332	
85	PA	BC_A2	MA21 - MA21 - DA21 - DA21	4753	MA21 - MA21 - DA21 - DA21	4902	No
		BA_A1	AA31 - TA31	5969	AA31 - TA31	5509	
		BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5745	LA12 - LA12 - LA11 - GA11 - MA11	5749	
86	PA	BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA21 - MA21 - DA21 - DA21	5005	No
		BA_A1	AA32 - TA31	5911	AA31 - TA31	5958	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	4919	
87	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	4771	Yes(1)
		BA_A1			AA32 - TA31	5086	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	5160	
88	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	4796	Yes(1)
		BA_A1			AA32 - TA31	5299	
		BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	
89	PB	BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4229	No
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4496	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	5402	
90	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	4847	Yes(1)
		BA_A1			AA32 - TA31	5542	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	4382	
91	PA	BC_A2	No Solution		MB21 - MB21 - LB21 - LB21	4353	Yes(2)
		BA_A1			AA31 - TA31	4874	
		BC_A1			LB21 - LB21 - LB21 - GB21 - MB21	4669	
92	PA	BC_A2	No Solution		MB11 - MB11 - DB11 - DB11	4461	Yes(2)
		BA_A1			AA32 - TA31	4907	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA21	5643	
93	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA22	4955	Yes(1)
		BA_A1			AA32 - TA31	5782	
		BC_A1			LA21 - LA21 - LA21 - GA11 - MA11	5857	
94	PA	BC_A2	No Solution		MA11 - MA11 - DA22 - DA21	5038	Yes(1)
		BA_A1			AA32 - TA31	5995	

Table C.11 the Production Plans and Schedules for the 11th set of Orders

Order No.	Product	Comp.	System I		System II		
			Processing Route	Finishing time (time units)	Processing Route	Finishing time (time units)	Resource Regrouped?
0	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	395	LA11 - LA11 - LA11 - GA11 - MA11	395	No
		BC_A2	MA21 - MA21 - DA21 - DA21	237	MA21 - MA21 - DA21 - DA21	237	
		BA_A1	AA31 - TA31	588	AA31 - TA31	588	
1	PB	BC_B1	MB11 - LB11 - DB11 - DB11	222	MB11 - LB11 - DB11 - DB11	222	No
		BC_B2	LB21 - MB21 - GB21	142	LB21 - MB21 - GB21	142	
		BA_B1	AB31 - TB31	362	AB31 - TB31	362	
2	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	623	LA11 - LA11 - LA11 - GA11 - MA11	623	No
		BC_A2	MA21 - MA21 - DA21 - DA21	340	MA21 - MA21 - DA21 - DA21	340	
		BA_A1	AA31 - TA31	780	AA31 - TA31	780	
3	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	897	LA11 - LA11 - LA11 - GA11 - MA11	897	No
		BC_A2	MA21 - MA21 - DA21 - DA21	443	LA21 - LA21 - DA22 - DA22	219	
		BA_A1	AA31 - TA31	1054	AA31 - TA31	1054	
4	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1171	LA12 - LA12 - LA12 - GA11 - MA11	423	No
		BC_A2	MA21 - MA21 - DA21 - DA21	546	MA21 - MA21 - DA22 - DA21	379	
		BA_A1	AA31 - TA31	1328	AA31 - TA31	658	
5	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1445	LA12 - LA12 - LA12 - GA11 - MA11	566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	649	MA21 - MA21 - DA21 - DA21	490	
		BA_A1	AA31 - TA31	1602	AA31 - TA31	866	
6	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	1719	LA11 - LA11 - LA11 - GA11 - MA11	1171	No
		BC_A2	MA21 - MA21 - DA22 - DA22	656	MA21 - MA21 - DA21 - DA21	593	
		BA_A1	AA31 - TA31	1876	AA31 - TA31	1328	
7	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	423	LA12 - LA12 - LA12 - GA11 - MA11	807	No
		BC_A2	MA21 - MA21 - DA21 - DA21	753	LA21 - LA21 - DA22 - DA21	356	
		BA_A1	AA31 - TA31	909	AA31 - TA31	964	
8	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	566	LA12 - LA12 - LA12 - GA11 - MA11	1048	No
		BC_A2	MA21 - MA21 - DA21 - DA21	856	MA21 - MA21 - DA21 - DA21	696	
		BA_A1	AA31 - TA31	1140	AA31 - TA31	1205	
9	PB	BC_B1	MB11 - LB11 - DB11 - DB11	286	MB11 - LB11 - DB12 - DB11	243	No
		BC_B2	LB21 - MB21 - GB21	171	LB21 - MB21 - GB21	171	
		BA_B1	AB31 - TB31	396	AB31 - TB31	396	
10	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	807	LA11 - LA11 - LA12 - GA11 - MA11	1442	No
		BC_A2	MA21 - MA21 - DA21 - DA21	959	LA21 - LA21 - DA22 - DA22	429	
		BA_A1	AA31 - TA31	1225	AA31 - TA31	1599	
11	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1048	LA11 - LA11 - LA12 - GA11 - MA11	1621	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1062	MA21 - MA21 - DA22 - DA21	716	
		BA_A1	AA31 - TA31	1414	AA31 - TA31	1778	
12	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1290	LA12 - LA12 - LA12 - GA11 - MA11	1290	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1165	MA21 - MA21 - DA21 - DA21	827	
		BA_A1	AA31 - TA31	1499	AA31 - TA31	1446	
13	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1531	LA11 - LA11 - LA12 - GA11 - MA11	1800	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1161	LA21 - LA21 - DA22 - DA22	537	
		BA_A1	AA31 - TA31	1688	AA31 - TA31	1957	
14	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	1768	LA12 - LA12 - LA12 - GA11 - MA11	1660	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1268	MA21 - MA21 - DA21 - DA21	930	
		BA_A1	AA31 - TA31	1962	AA31 - TA31	1863	

15	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA11	657	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	740	
		BA_A1			AA32 - TA31	906	
16	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	958	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	848	
		BA_A1			AA32 - TA31	1097	
17	PB	BC_B1	MB11 - LB11 - DB12 - DB11	306	MB11 - LB11 - DB11 - DB11	322	No
		BC_B2	LB21 - MB21 - GB21	200	LB21 - MB21 - GB21	200	
		BA_B1	AB31 - TB31	446	AB31 - TB31	446	
18	PB	BC_B1	MB11 - LB11 - DB11 - DB11	386	MB11 - LB11 - DB11 - DB11	387	No
		BC_B2	LB21 - MB21 - GB21	229	LB21 - MB21 - GB21	229	
		BA_B1	AB31 - TB31	496	AB31 - TB31	496	
19	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	1162	Yes(1)
		BC_A2			MA21 - MA21 - DA22 - DA21	968	
		BA_A1			AA32 - TA31	1361	
20	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1222	MB11 - LB11 - DB11 - DB11	1222	No
		BC_B2	LB21 - MB21 - GB21	1142	LB21 - MB21 - GB21	1142	
		BA_B1	AB31 - TB31	1362	AB31 - TB31	1362	
21	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2042	LA11 - LA11 - LA11 - GA11 - MA11	1982	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1371	MA21 - MA21 - DA21 - DA21	1372	
		BA_A1	AA31 - TA31	2199	AA31 - TA31	2138	
22	PB	BC_B1	MB11 - LB11 - DB11 - DB11	1286	MB11 - LB11 - DB12 - DB11	1243	No
		BC_B2	LB21 - MB21 - GB21	1171	LB21 - MB21 - GB21	1171	
		BA_B1	AB31 - TB31	1396	AB31 - TB31	1396	
23	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2316	LA11 - LA11 - LA11 - GA11 - MA11	2256	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1474	LA21 - LA21 - DA22 - DA22	1255	
		BA_A1	AA31 - TA31	2473	AA31 - TA31	2412	
24	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	2590	LA12 - LA12 - LA12 - GA11 - MA11	2041	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1577	MA21 - MA21 - DA21 - DA21	1475	
		BA_A1	AA31 - TA31	2747	AA31 - TA31	2224	
25	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	1915	LA11 - LA11 - LA12 - GA11 - MA11	2527	No
		BC_A2	MA21 - MA21 - DA22 - DA22	1582	MA21 - MA21 - DA22 - DA21	1513	
		BA_A1	AA31 - TA31	2071	AA31 - TA31	2683	
26	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2156	LA11 - LA11 - LA12 - GA11 - MA11	2706	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1680	MA21 - MA21 - DA21 - DA21	1625	
		BA_A1	AA31 - TA31	2313	AA31 - TA31	2862	
27	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	2397	LA12 - LA12 - LA12 - GA11 - MA11	2289	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1783	LA21 - LA21 - DA22 - DA22	1363	
		BA_A1	AA31 - TA31	2559	AA31 - TA31	2498	
28	PB	BC_B1	MB11 - LB11 - DB12 - DB11	1306	MB11 - LB11 - DB11 - DB11	1322	No
		BC_B2	LB21 - MB21 - GB21	1200	LB21 - MB21 - GB21	1200	
		BA_B1	AB31 - TB31	1446	AB31 - TB31	1446	
29	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	2767	LA12 - LA12 - LA12 - GA11 - MA11	2566	No
		BC_A2	MA21 - MA21 - DA21 - DA21	1886	MA21 - MA21 - DA21 - DA21	1728	
		BA_A1	AA31 - TA31	2924	AA31 - TA31	2769	
30	PA	BC_A1	LA12 - LA12 - LA11 - GA11 - MA11	2816	LA21 - LA21 - LA21 - GA11 - MA11	1549	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	1989	MA11 - MA11 - DA22 - DA21	1490	
		BA_A1	AA32 - TA31	2983	AA32 - TA31	1687	
31	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	1861	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	1564	
		BA_A1			AA32 - TA31	1999	

32	PA	BC_A1 BC_A2 BA_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - DA22 - DA22 AA32 - TA31	2102 1672 2257	Yes(1)
33	PA	BC_A1 BC_A2 BA_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21 MA11 - MA11 - DA22 - DA21 AA32 - TA31	2350 1755 2531	Yes(1)
34	PA	BC_A1 BC_A2 BA_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21 MA21 - MA11 - DA22 - DA21 AA32 - TA31	2627 1781 2802	Yes(1)
35	PA	BC_A1 BC_A2 BA_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21 MB21 - MB21 - LB21 - LB21 AA31 - TA31	1379 1350 1721	Yes(2)
36	PA	BC_A1 BC_A2 BA_A1	No Solution		LA21 - LA11 - LA21 - GA11 - MA11 MA21 - MA11 - DA22 - DA21 AA32 - TA31	2842 1811 2981	Yes(1)
37	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	1386 1229 1496	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	1387 1473 1580	No
38	PA	BC_A1 BC_A2 BA_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21 MB11 - MB11 - DB11 - DB11 AA31 - TA31	1724 1461 2042	Yes(2)
39	PA	BC_A1 BC_A2 BA_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21 LB11 - MB11 - DB11 - DB11 AA31 - TA31	1926 1568 2310	Yes(2)
40	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3090 2237 3247	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	2969 2312 3126	No
41	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	2222 2142 2362	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	2222 2142 2362	No
42	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3364 2340 3521	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3243 2415 3400	No
43	PA	BC_A1 BC_A2 BA_A1	LA11 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3638 2443 3795	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3003 2518 3212	No
44	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	2858 2546 3016	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3188 2621 3486	No
45	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3124 2649 3333	LA11 - LA11 - LA12 - GA11 - MA11 MA21 - MA21 - DA22 - DA21 AA31 - TA31	3514 2659 3671	No
46	PA	BC_A1 BC_A2 BA_A1	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA22 - DA22 AA31 - TA31	3398 2656 3607	LA11 - LA11 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3693 2837 3850	No
47	PA	BC_A1 BC_A2 BA_A1	LA12 - LA11 - LA11 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3815 2753 3972	LA12 - LA12 - LA12 - GA11 - MA11 MA21 - MA21 - DA21 - DA21 AA31 - TA31	3430 2940 3756	No
48	PB	BC_B1 BC_B2 BA_B1	MB11 - LB11 - DB11 - DB11 LB21 - MB21 - GB21 AB31 - TB31	2286 2171 2396	MB11 - LB11 - DB12 - DB11 LB21 - MB21 - GB21 AB31 - TB31	2243 2171 2396	No

49	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	2907	Yes(1)
		BC_A2			MA11 - MA11 - LA12 - DA21	2636	
		BA_A1			AA32 - TA31	3045	
50	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3149	Yes(1)
		BC_A2			MA11 - MA11 - LA12 - DA21	2674	
		BA_A1			AA32 - TA31	3287	
51	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3390	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	2690	
		BA_A1			AA32 - TA31	3528	
52	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3632	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	2711	
		BA_A1			AA32 - TA31	3790	
53	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	2376	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	2335	
		BA_A1			AA31 - TA31	2584	
54	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	2578	Yes(2)
		BC_A2			LB11 - MB11 - DB11 - DB11	2441	
		BA_A1			AA31 - TA31	3079	
55	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	2809	Yes(2)
		BC_A2			LB11 - MB11 - DB12 - DB11	2471	
		BA_A1			AA31 - TA31	3159	
56	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3040	Yes(2)
		BC_A2			LB11 - MB11 - DB11 - DB11	2569	
		BA_A1			AA31 - TA31	3320	
57	PA	BC_A1	No Solution		LB11 - LB11 - LB11 - GB21 - MB11	2777	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	2667	
		BA_A1			AA31 - TA31	3571	
58	PB	BC_B1	MB11 - LB11 - DB12 - DB11	2306	MA21 - LA21 - DA21 - DA22	3603	No
		BC_B2	LB21 - MB21 - GB21	2200	LA12 - MA11 - GA11	2600	
		BA_B1	AB31 - TB31	2446	AA31 - TA31	3906	
59	PB	BC_B1	MB11 - LB11 - DB11 - DB11	2386	MB21 - LB11 - DB11 - DB12	2755	Yes(1)
		BC_B2	LB21 - MB21 - GB21	2229	LB11 - LB11 - GB21	2846	
		BA_B1	AB31 - TB31	2496	AB31 - TB31	2953	
60	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4089	LA11 - LA11 - LA11 - GA11 - MA11	3875	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3237	MA21 - MA21 - DA21 - DA21	3674	
		BA_A1	AA31 - TA31	4246	AA31 - TA31	4052	
61	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4363	LA11 - LA11 - LA11 - GA11 - MA11	4149	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3340	MA21 - MA21 - DA21 - DA21	3777	
		BA_A1	AA31 - TA31	4520	AA31 - TA31	4305	
62	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	4637	LA12 - LA12 - LA12 - GA11 - MA11	3908	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3443	MA21 - MA21 - DA22 - DA22	3676	
		BA_A1	AA31 - TA31	4794	AA31 - TA31	4137	
63	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3222	MB11 - LB11 - DB11 - DB11	3222	No
		BC_B2	LB21 - MB21 - GB21	3142	LB21 - MB21 - GB21	3147	
		BA_B1	AB31 - TB31	3362	AB31 - TB31	3362	
64	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	3901	LA12 - LA12 - LA12 - GA11 - MA11	4099	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3546	MA21 - LA21 - DA22 - DA22	3784	
		BA_A1	AA31 - TA31	4058	AA31 - TA31	4391	
65	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4142	LA11 - LA11 - LA12 - GA11 - MA11	4420	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3649	MA21 - MA21 - DA21 - DA21	3880	
		BA_A1	AA31 - TA31	4331	AA31 - TA31	4576	

66	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4397	LA11 - LA11 - LA12 - GA11 - MA11	4599	No
		BC_A2	MA21 - MA21 - DA22 - DA22	3656	MA21 - MA21 - DA22 - DA22	3892	
		BA_A1	AA31 - TA31	4605	AA31 - TA31	4755	
67	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	4814	LA11 - LA11 - LA12 - GA11 - MA11	4778	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3753	MA21 - MA21 - DA21 - DA21	3983	
		BA_A1	AA31 - TA31	4971	AA31 - TA31	4934	
68	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3286	MB11 - LB11 - DB12 - DB11	3243	No
		BC_B2	LB21 - MB21 - GB21	3171	LB21 - MB21 - GB21	3176	
		BA_B1	AB31 - TB31	3396	AB31 - TB31	3396	
69	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4702	LA12 - LA12 - LA12 - GA11 - MA11	4340	No
		BC_A2	MA21 - MA21 - DA21 - DA21	3856	MA21 - MA21 - DA21 - DA21	4086	
		BA_A1	AA31 - TA31	4879	AA31 - TA31	4662	
70	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3376	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB11	3335	
		BA_A1			AA32 - TA31	3605	
71	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	3989	Yes(1)
		BC_A2			MA11 - MA11 - DA21 - DA22	4181	
		BA_A1			AA32 - TA31	4339	
72	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4230	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4001	
		BA_A1			AA32 - TA31	4425	
73	PA	BC_A1	No Solution		LA12 - LA12 - LA11 - GA11 - MA11	4811	No
		BC_A2			MA21 - MA21 - DA22 - DA22	4193	
		BA_A1			AA32 - TA31	4967	
74	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4481	Yes(1)
		BC_A2			MA11 - MA11 - DA21 - DA22	4213	
		BA_A1			AA32 - TA31	4619	
75	PB	BC_B1	MB11 - LB11 - DB12 - DB11	3306	LB11 - LB11 - DB11 - DB11	3381	No
		BC_B2	LB21 - MB21 - GB21	3200	LB21 - MB21 - GB21	3354	
		BA_B1	AB31 - TB31	3446	AB31 - TB31	3489	
76	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3605	Yes(2)
		BC_A2			MB11 - LB11 - DB11 - DB11	3491	
		BA_A1			AA32 - TA31	3883	
77	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	4713	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA21	4221	
		BA_A1			AA32 - TA31	4852	
78	PB	BC_B1	MB11 - LB11 - DB11 - DB11	3386	MB11 - LB11 - DB12 - DB12	3501	No
		BC_B2	LB21 - MB21 - GB21	3229	LB21 - MB21 - GB21	3692	
		BA_B1	AB31 - TB31	3496	AB31 - TB31	3800	
79	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	3894	Yes(2)
		BC_A2			LB11 - LB11 - DB11 - DB11	3686	
		BA_A1			AA32 - TA31	4085	
80	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5088	LA11 - LA11 - LA11 - GA11 - MA11	5055	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4237	MA21 - MA21 - DA21 - DA21	4324	
		BA_A1	AA31 - TA31	5245	AA31 - TA31	5211	
81	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4222	MB11 - LB11 - DB11 - DB11	4222	No
		BC_B2	LB21 - MB21 - GB21	4142	LB21 - MB21 - GB21	4142	
		BA_B1	AB31 - TB31	4362	AB31 - TB31	4362	
82	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5362	LA11 - LA11 - LA11 - GA11 - MA11	5329	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4340	MA21 - MA21 - DA21 - DA21	4440	
		BA_A1	AA31 - TA31	5519	AA31 - TA31	5485	

83	PA	BC_A1	LA11 - LA11 - LA11 - GA11 - MA11	5636	LA12 - LA12 - LA12 - GA11 - MA11	5019	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4443	MA21 - MA21 - DA21 - DA21	4543	
		BA_A1	AA31 - TA31	5793	AA31 - TA31	5297	
84	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	4944	LA11 - LA11 - LA12 - GA11 - MA11	5600	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4546	MA21 - MA21 - DA21 - DA21	4648	
		BA_A1	AA31 - TA31	5100	AA31 - TA31	5756	
85	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5185	LA11 - LA11 - LA12 - GA11 - MA11	5778	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4649	MA21 - MA21 - DA21 - DA21	4752	
		BA_A1	AA31 - TA31	5342	AA31 - TA31	5935	
86	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5426	LA12 - LA12 - LA12 - GA11 - MA11	5260	No
		BC_A2	MA21 - MA21 - DA22 - DA22	4656	MA21 - MA21 - DA21 - DA21	4881	
		BA_A1	AA31 - TA31	5604	AA31 - TA31	5571	
87	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4286	MB11 - LB11 - DB12 - DB11	4243	No
		BC_B2	LB21 - MB21 - GB21	4171	LB21 - MB21 - GB21	4171	
		BA_B1	AB31 - TB31	4396	AB31 - TB31	4396	
88	PB	BC_B1	MB11 - LB11 - DB12 - DB11	4306	MB11 - LB11 - DB11 - DB11	4322	No
		BC_B2	LB21 - MB21 - GB21	4200	LB21 - MB21 - GB21	4200	
		BA_B1	AB31 - TB31	4446	AB31 - TB31	4446	
89	PA	BC_A1	LA12 - LA11 - LA11 - GA11 - MA11	5813	LA12 - LA12 - LA12 - GA11 - MA11	5502	No
		BC_A2	MA21 - MA21 - DA21 - DA21	4753	MA21 - MA21 - DA21 - DA21	4984	
		BA_A1	AA31 - TA31	5969	AA31 - TA31	5658	
90	PA	BC_A1	LA12 - LA12 - LA12 - GA11 - MA11	5745	LA21 - LA21 - LA21 - GA11 - MA21	4955	Yes(1)
		BC_A2	MA21 - MA21 - DA21 - DA21	4856	MA11 - MA11 - DA22 - DA22	4358	
		BA_A1	AA32 - TA31	5911	AA32 - TA31	5093	
91	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5196	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4466	
		BA_A1			AA32 - TA31	5335	
92	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5438	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4594	
		BA_A1			AA32 - TA31	5604	
93	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4379	Yes(2)
		BC_A2			MB21 - MB21 - LB21 - LB21	4350	
		BA_A1			AA31 - TA31	4885	
94	PB	BC_B1	MB11 - LB11 - DB11 - DB11	4386	MB11 - LB11 - DB11 - DB11	4387	No
		BC_B2	LB21 - MB21 - GB21	4229	LB21 - MB21 - GB21	4473	
		BA_B1	AB31 - TB31	4496	AB31 - TB31	4580	
95	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4724	Yes(2)
		BC_A2			LB11 - LB11 - DB11 - DB11	4521	
		BA_A1			AA31 - TA31	5020	
96	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	4926	Yes(2)
		BC_A2			MB11 - MB11 - DB11 - DB12	4458	
		BA_A1			AA31 - TA31	5126	
97	PA	BC_A1	No Solution		LA21 - LA21 - LA21 - GA11 - MA21	5679	Yes(1)
		BC_A2			MA11 - MA11 - DA22 - DA22	4702	
		BA_A1			AA32 - TA31	5817	
98	PA	BC_A1	No Solution		LB21 - LB21 - LB21 - GB21 - MB21	5157	Yes(2)
		BC_A2			LB11 - LB11 - DB11 - DB11	4645	
		BA_A1			AA31 - TA31	5383	
99	PA	BC_A1	No Solution		LB11 - LB11 - LB11 - GB21 - MB11	4973	Yes(2)
		BC_A2			MB11 - MB11 - DB12 - DB12	4572	
		BA_A1			AA32 - TA31	5160	

BIBLIOGRAPHY

Anosike, A. I. (2005). "Agent-Based Modelling, Simulation and Control of Dynamically Integrated Manufacturing Systems." University of Exeter, PhD Thesis.

Babiceanu, R. F. and F. F. Chen (2007). "Manufacturing scheduling in decentralised holonic systems using artificial intelligence techniques." International Journal of Manufacturing Technology and Management **11**(3-4): 389-410.

Babiceanu, R. F., F. F. Chen and R. H. Sturges (2004). Framework for the control of automated material-handling systems using the holonic manufacturing approach, Taylor and Francis Ltd.

Baker, A. D. (1998). "A survey of factory control algorithms that can be implemented in a multi-agent heterarchy: dispatching, scheduling, and pull." Journal of Manufacturing Systems **17**(4): 297-320.

Balakrishnan, J. and C. Cheng (1998). "Dynamic layout algorithms: a state-of-the-art survey." Omega **26**(4): 507-521.

Balakrishnan, J., F. Jacobs and M. Venkataramanan (1992). "Solutions for the constrained dynamic facility layout problem." European Journal of Operational Research **57**(2): 280-286.

Benjaafar, S., S. Heragu and S. Irani (2002). "Next generation factory layouts: research challenges and recent progress." Interfaces **32**(6): 58-76.

Bond, A. and L. Gasser (1988). "Distributed artificial intelligence." San Mateo: Morgan Kaufmann.

Burbidge, J. (1991). "Production flow analysis for planning group technology." Journal of Operations Management **10**(1): 5-27.

Butler, J. and H. Ohtsubo (1992). "ADDYMS: architecture for distributed dynamic manufacturing scheduling." Artificial Intelligence Applications in Manufacturing: 199-213.

Buzacott, J. A. and D. D. Yao (1986). "Flexible manufacturing systems: a review of analytical models." Management Science **32**(7): 890-905.

Caridi, M. and S. Cavalieri (2004). "Multi-agent systems in production planning and control: an overview." Production Planning & Control **15**(2): 106-118.

Cha, Y., M. Shin, K. Ryu and M. Jung (2007). "Goal-balancing process for goal formation in the fractal manufacturing system." International Journal of Production Research **45**(20): 4771-4791.

Conway, D. and M. Venkataramanan (1994). "Genetic search and the dynamic facility layout problem." Computers & Operations Research **21**(8): 955-960.

Deshpande, S. and J. Cagan (2004). "An agent based optimization approach to manufacturing process planning." Journal of Mechanical Design **126**: 46.

Dilts, N. (1991). "The evolution of control architectures for automated manufacturing systems." Journal of Manufacturing Systems **10**(1): 79-93.

Duffie, N. A., R. Chitturi and J. I. Mou (1988). "Fault-tolerant heterarchical control of heterogeneous manufacturing system entities." Journal of Manufacturing Systems **7**(4): 315-328.

Duffie, N. A. and R. S. Piper (1987). "Non-hierarchical control of a flexible manufacturing cell." Robotics and computer-integrated manufacturing **3**(2): 175-179.

Finin, T., R. Fritzson, D. McKay and R. McEntire (1994). KQML as an agent communication language. In the Proceedings of the third International Conference on Information and Knowledge Management, ACM Press.

Fox, M., M. Barbuceanu and R. Teigen (2000). "Agent-oriented supply-chain management." International Journal of Flexible Manufacturing Systems **12**(2): 165-188.

Galan, R., J. Racero, I. Eguia and D. Canca (2007). "A methodology for facilitating reconfiguration in manufacturing: The move towards reconfigurable manufacturing systems." International Journal of Advanced Manufacturing Technology **33**(3-4): 345-353.

Giret, A. and V. Botti (2004). "Holons and agents." Journal of Intelligent Manufacturing **15**(5): 645-659.

Gou, L., P. Luh and Y. Kyoya (1998). "Holonic manufacturing scheduling: architecture, cooperation mechanism, and implementation." Computers in Industry **37**(3): 213-231.

Gu, P., S. Balasubramanian and D. Norrie (1997). "Bidding-based process planning and scheduling in a multi-agent system." Computers & Industrial Engineering **32**(2): 477-496.

Gu, P., S. Balasubramanian and D. H. Norrie (1995). Bidding-based autonomous process planning and scheduling. SPIE.

Ham, I., K. Hitomi and T. Yoshida (1985). Group technology: applications to production management. Kluwer-Nijhoff.

Hitomi, K. (1996). Manufacturing systems engineering : a unified approach to manufacturing technology, production management, and industrial economics. 2nd Edition, London, Taylor & Francis.

Hou, T. H. and H. P. Wang (1991). "Integration of a CAPP system and an FMS." Computers & Industrial Engineering **20**(2): 231-242.

Huang, S. H., H. C. Zhang and M. L. Smith (1995). "A progressive approach for the integration of process planning and scheduling." IIE transactions **27**(4): 456-464.

Iwata, K. and Y. Fukuda (1989). A new proposal of dynamic process planning in machine shop. Proceedings of CIRP International Workshop on CAPP, Hannover, Germany.

Jackson, R. and A. Jones (1987). "An architecture for decision making in the factory of the future." Interfaces **17**(6): 15-28.

Jones, A. and C. McLean (1986). "A proposed hierarchical control model for automated manufacturing systems." Journal of Manufacturing Systems **5**(1): 15-25.

Kaku, B. and J. Mazzola (1997). "A tabu-search heuristic for the dynamic plant layout problem." INFORMS Journal on Computing **9**(4): 374.

Kempenaers, J., J. PinteJan and J. P. Kruth (1996). "A collaborative process planning and scheduling system." Advances in Engineering Software **25**(1): 3-8.

Khoshnevis, B. and Q. M. Chen (1991). "Integration of process planning and scheduling functions." Journal of Intelligent Manufacturing **2**(3): 165-175.

Kiritsis, D. and M. Porchet (1996). "A generic Petri net model for dynamic process planning and sequence optimization." Advances in Engineering Software **25**(1): 61-71.

Kochhar, J. and S. Heragu (1999). "Facility layout design in a changing environment." International Journal of Production Research **37**(11): 2429-2446.

Koren, Y., U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy and H. Van Brussel (1999). "Reconfigurable manufacturing systems." CIRP Annals-College International de Recherches pour la Production **48**(2): 527-540.

Kouvelis, P., A. Kurawarwala and G. Gutierrez (1992). "Algorithms for robust single and multiple period layout planning for manufacturing systems." European Journal of Operational Research **63**(2): 287-303.

Larsen, N. and L. Alting (1990). Simultaneous engineering within process and production planning. Proceedings of Pacific Conference on Manufacturing, Australia.

Leitao, P., A. W. Colombo and F. J. Restivo (2005). "ADACOR: A collaborative production automation and control architecture." IEEE Intelligent Systems **20**(1): 58-66.

Leitao, P. and F. Restivo (2006). "ADACOR: A holonic architecture for agile and adaptive manufacturing control." Computers in Industry **57**(2): 121-130.

Leitao, P. and F. Restivo (2008). "A holonic approach to dynamic manufacturing scheduling." Robotics and Computer-Integrated Manufacturing **24**(5): 625-634.

Lin, G. and J. Solberg (1992). "Integrated shop floor control using autonomous agents." IIE transactions **24**(3): 57-71.

Lin, G. Y. and J. J. Solberg (1992). "Integrated shop floor control using autonomous agents." IIE transactions **24**(3): 57-71.

Macchiaroli, R. and S. Riemma (2002). "A negotiation scheme for autonomous agents in job shop scheduling." International Journal of Computer Integrated Manufacturing **15**: 222-232.

Maione, B. and D. Naso (2001). "Evolutionary adaptation of dispatching agents in heterarchical manufacturing systems." International Journal of Production Research **39**(7): 1481-1503.

Maione, G. and D. Naso (2003). "A genetic approach for adaptive multiagent control in heterarchical manufacturing systems." Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on **33**(5): 573-588.

Meng, G. and S. Heragu (2004). "Batch size modeling in a multi-item, discrete manufacturing system via an open queuing network." IIE transactions **36**(8): 743-753.

Meng, G., S. Heragu and H. Zijm (2004). "Reconfigurable layout problem." International Journal of Production Research **42**(22): 4709-4729.

Okino, N. (1989). "Bionic Manufacturing Systems - Modelon-based Approach." In the Proceedings of the CAM-I 18th Annual International Conference, New Orleans, Louisiana, (Computer-aided Manufacturing - International Inc.)(485-492).

Okino, N. (1992). A prototyping of bionic manufacturing system.

Ou-Yang, C. and J. Lin (1998). "The development of a hybrid hierarchical/heterarchical shop floor control system applying bidding method in job dispatching." Robotics and Computer-Integrated Manufacturing **14**(3): 199-217.

Rosenblatt, M. (1986). "The dynamics of plant layout." Management Science **32**(1): 76-86.

Rosenblatt, M. and D. Kropp (1992). "The single period stochastic plant layout problem." IIE transactions **24**(2): 169-176.

Rosenblatt, M. and H. Lee (1987). "A robustness approach to facilities design." International Journal of Production Research **25**(4): 479-486.

Ryu, K. and M. Jung (2003). "Agent-based fractal architecture and modelling for developing distributed manufacturing systems." International Journal of Production Research **41**(17): 4233-4255.

Ryu, K. and M. Jung (2004). "Goal-orientation mechanism in a fractal manufacturing system." International Journal of Production Research **42**(11): 2207-2225.

Ryu, K., Y. Son and M. Jung (2003). "Modeling and specifications of dynamic agents in fractal manufacturing systems." Computers in Industry **52**(2): 161-182.

Ryu, K., E. Yücesan and M. Jung (2006). "Dynamic restructuring process for self-reconfiguration in the fractal manufacturing system." International Journal of Production Research **44**(15): 3105-3129.

Shin, M., Y. Cha, K. Ryu and M. Jung (2006). "Conflict detection and resolution for goal formation in the fractal manufacturing system." International Journal of Production Research **44**(3): 447-465.

Shin, M., J. Mun and M. Jung (2009[b]). "Self-evolution framework of manufacturing systems based on fractal organization." Computers & Industrial Engineering **56**(3): 1029-1039.

Shin, M., J. Muna, K. Leeb and M. Junga (2009[a]). "r-FrMS: a relation-driven fractal organisation for distributed manufacturing systems." International Journal of Production Research **47**(7): 1791-1814.

Smith, R. (1980). "The contract net protocol." IEEE Transactions on Computers **29**(12): 1104-1113.

Sousa, P. and C. Ramos (1999). "A distributed architecture and negotiation protocol for scheduling in manufacturing systems." Computers in Industry **38**(2): 103-113.

Ssemakula, M. E. and W. J. Cloyd (1994). "Functional specification of a dynamic process planning system." Computers & Industrial Engineering **27**(1-4): 99-102.

St John, C. H., A. R. Cannon and R. W. Pouder (2001). "Change drivers in the new millennium: implications for manufacturing strategy research." Journal of Operations Management **19**(2): 143-160.

Stecke, K. E. (1983). "Formulation and solution of nonlinear integer production planning problems for flexible manufacturing systems." Management Science **29**(3): 273-288.

Suresh, N. and J. Kay (1998). Group technology and cellular manufacturing: a state-of-the-art synthesis of research and practice. Kluwer Academic Pub.

Tan, W. and B. Khoshnevis (2000). "Integration of process planning and scheduling-a review." Journal of Intelligent Manufacturing **11**(1): 51-63.

Tonshoff, H., U. Beckendorff and N. Andres (1989). FLEXPLAN: A concept for intelligent process planning and scheduling. Proceedings of the CIRP International Workshop, Hanover, Germany.

Urban, T. (1993). "A heuristic for the dynamic facility layout problem." IIE transactions **25**(4): 57-63.

Usher, J. M. and K. J. Fernandes (1996). "A two-phased approach to dynamic process planning." Computers & Industrial Engineering **31**(1-2): 173-176.

Van Brussel, H., J. Wyns, P. Valckenaers, L. Bongaerts and P. Peeters (1998). "Reference architecture for holonic manufacturing systems: PROSA." Computers in Industry **37**(3): 255-274.

Warnecke, H. (1993). The fractal company. Springer.

Wong, T., C. Leung, K. Mak and R. Fung (2006). "Dynamic shopfloor scheduling in multi-agent manufacturing systems." Expert Systems with Applications **31**(3): 486-494.

Xiaobo, Z., W. Jiancai and L. Zhenbi (2000a). "A stochastic model of a reconfigurable manufacturing system Part 1: A framework." International Journal of Production Research **38**(10): 2273-2285.

Xiaobo, Z., J. Wang and Z. Luo (2000b). "A stochastic model of a reconfigurable manufacturing system Part 2: Optimal configurations." International Journal of Production Research **38**(12): 2829-2842.

Xiaobo, Z., J. Wang and Z. Luo (2001). "A stochastic model of a reconfigurable manufacturing system Part 3: Optimal selection policy." International Journal of Production Research **39**(4): 747-758.

Zhang, H. C. (1993). "IMMP: a prototype to integrate process planning and job shop scheduling functions." CIRP annals **42**(1): 513-518.

Zhang, Z. and H. Sharifi (2000). "A methodology for achieving agility in manufacturing organisations." International Journal of Operations & Production Management **20**(4): 496-513.