INTEGRATED PLANNING AND SCHEDULING FOR PRECAST CONCRETE PRODUCTION

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Submitted by

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SUMMARY

Precast concrete technology has been widely used in many countries due to the advantages it has over traditional construction methods, such as increased construction speed and higher quality. Planning and scheduling play an important role in precast production management. This research focuses on make-to-order precast production with a comprehensive casting organization, with an aim of developing a special-purpose model for production planning and scheduling in precast plants.

Compared to manufacturing processes in other industries, prefabrication has its own distinctive features which should be taken into account in the model development for precast production planning and scheduling. Through field study, questionnaire survey, and follow-up interviews, current production practices in Singapore's precast plants are investigated and eight characteristics of precast construction are identified. Based on the literature review and precast production analysis, the objectives and performance measurement scheme for precast production planning and scheduling are established. The final production schedule should fully satisfy the precast component (PC) demands with a minimum total variable cost (total variable cost equals to total production-related cost minus total fixed cost).

To achieve the above objectives, an integrated planning and scheduling model for precast production (IPSMPP) is developed based on the concept of hierarchical production planning. The model captures the above distinctive features of precast production, and covers aggregate planning at tactical level (mid-term) and detailed scheduling at operational level (short-term). With different planning functions, several modules are developed at each level, including *Labour Sizing* and *Mould Planning* at the tactical level, and *Labour grouping*, *PC Allocation & Sequencing* and *Labour Transferring* at the operation level.

To solve the specific problems in every module, a Simulation-GA (Genetic Algorithm) based approach is established for IPSMPP, where the simulation produces production schedules with given values of decision variables and GA evaluates the schedule performance and adjusts values of the decision variables for new schedule development. In this approach, two discrete-event simulation engines, Simulation(A) and Simulation(D), are designed to satisfy different requirements of modelling detail in aggregate planning and detailed scheduling respectively. Different configurations of GA are proposed for every module based on the nature of decision variables involved. As simulation is for modeling and GA for optimization, they are integrated in this research to form a viable approach for precast production planning and scheduling.

In the IPSMPP model, new priority rules are designed to run simulations more effectively by capturing PC demands and mould requirements. Critical PC (CP) rule is established for PC dispatching in Simulation(A), whereas critical mould (CM) rule is created for labour transfer in Simulation(D). They both employ BLWMO — a special backward loading with mould as a single resource, to identify criticality of PCs or moulds. Instead of the traditional single forward simulation, a bidirectional simulation is introduced in both Simulation(A) and Simulation(D) for schedule development. Simulation(A) takes two scheduling passes and Simulation(D) adopts three scheduling passes to reduce excessive PC stock and overtime usage in the single forward simulation. Furthermore, algorithms for operation time calculation are created for both forward and backward simulations in Simulation(D) based on characteristics of various operations.

For validation purpose, a prototype system is developed based on the model and its inner workings. Two tests are conducted for the aggregate planning and detailed scheduling respectively. The validity of the model is demonstrated by comparison of the results from the prototype system, planning methods used in practice, and other conventional approaches. The prototype system can considerably reduce the total variable cost, thus leading to feasible schedules with best performance.

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LIST OF ABBREVIATIONS

Abbreviation	Term
APP	Aggregate production planning
B_PC	PC type that can be produced on both an exclusive mould type and a sharable mould type
BI_CM	IPSMPP employing bidirectional simulation based on CM labour transfer rule
BI_CP	IPSMPP employing bidirectional simulation based on CP rule
BLP	Bilevel programming
BLWMO	Backward loading with mould only
BLWMO_E	BLWMO that is conducted on an exclusive mould type
BLWMO_S	BLWMO that is conducted on a sharable mould type
BT	Break time
CB	Current loading bucket
CM	Critical mould rule
CP	Critical PC rule
CT	Current simulated time (simulation clock) during simulation
CV	Critical value
D_PC	Due date-related critical PCs
DRC	Dual-resource constrained
E_PC	PC type that can only be produced on an exclusive mould type
EDD	Earliest due date rule
F_ACT	Actual method used in practice
F_CM	Forward simulation based on CM labour transfer rule
F_CP	Forward simulation based on CP rule
F_EDD	Forward simulation based on EDD labour transfer rule
F_LQ	Forward simulation based on LQ labour transfer rule
F_TRD	Forward simulation based on traditional PC dispatching rules

FIA	Fixed-increment algorithm
FT(s)	Finish time(s)
GA	Genetic algorithm
HPP	Hierarchical production planning
IPSMPP	Integrated planning and scheduling model for precast production
JIT	Just-in-time
LMC	Lowest mould changeover rule
LSC	Lowest stock cost rule
M_PC	Mould-related critical PCs
Max_T	The maximum simulated time in Simulation(D)
MCA	Maximum contribution amount
Min_T	The minimum simulated time in Simulation(D)
MRP	Material requirements planning
MRPII	Manufacturing resource planning
MRP#	Machine requirements planning
MTO	Make-to-order
MTS	Make-to-stock
N_PC	Non-critical PCs
NEA	Next-event algorithm
NT	Normal time
OPT	Optimised production technology
OT	Overtime
PC(s)	Precast component(s)
PC_Gap@CB	PC Gap at CB
S_PC	PC type that can only be produced on a sharable mould type
SOT	Shortest operation time rule
SPR	Slack per remaining operation rule
SST	Shortest setup time rule
ST(s)	Start time(s)

Chapter 1

Introduction

1.1 Background

Precast concrete is defined as concrete that is cast elsewhere from its final position and used in structural or non-structural applications (PCI, 1999). Compared to traditional construction methods, precast concrete technology can improve buildability of buildings, enhance labour productivity and enable faster construction. Adoption of prefabrication can also lead to more consistent and higher quality, and safer and orderly working conditions (CIDB, 1997 and BCA, 1999).

The first use of precast concrete can be dated back to the nineteenth century (Sheppard and Phillips, 1989). In the 1940s, the precast industry experienced a rapid growth in Europe due to the major rebuilding task facing most of the European countries following the devastation of World War II, coupled with critical material shortages. During the last few decades, precast concrete has gained extensive recognition and application in developed countries with the developments in design, material, production and erection technologies. The percentage levels of precast usage in various countries are shown in Figure 1.1 (Ong, 1999).

In Singapore, the use of precast concrete components for buildings took off in the early 1980s when the Housing and Development Board (HDB), introduced large scale industrialization in its public housing programme (CIDB Construction Productivity Taskforce, 1992). However, it was only in recent years that the local construction industry has looked seriously into prefabrication to solve its problems of high dependency on unskilled foreign workers and the tightening of the local labour market, as well as to improve its competitive edge (Fong, 1997). Over the last decade, HDB has made remarkable achievements in the construction and upgrading of public housing through the extensive use of prefabrication technology. Figure 1.2 shows the precast concrete implementation programme by HDB in Singapore (Hock, 2001). It can be expected that precast technology will be more and more extensively applied in Singapore as well as in many other countries in future.

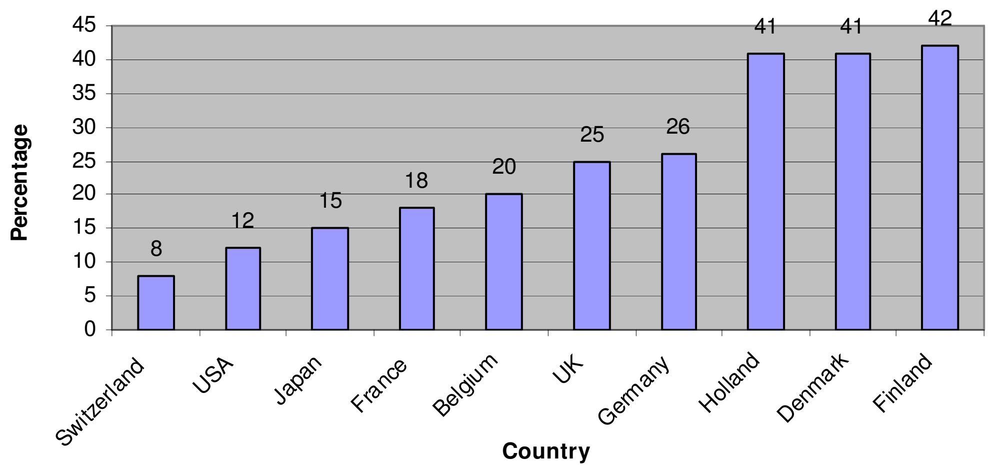


Figure 1.1: Precast Usage Levels in Various Countries

(Source: Ong, 1999)

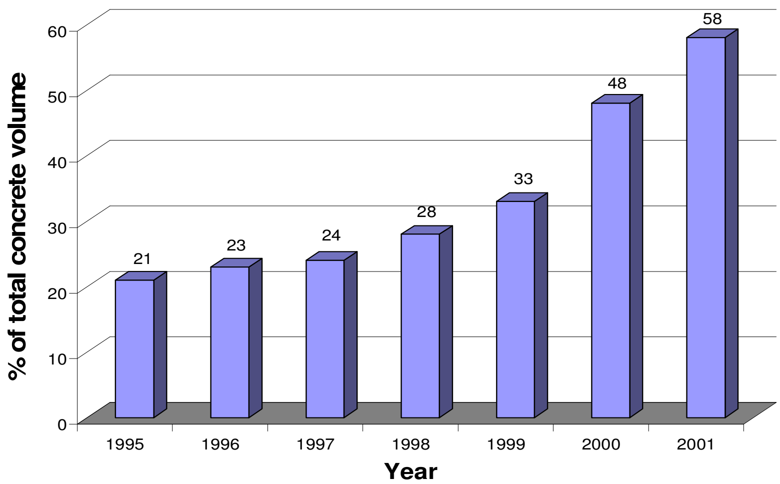


Figure 1.2: HDB Precast Implementation Programme

(Adapted from Hock, 2001)

1.2 Problem Statement

Production planning and scheduling play an important role in the precast concrete industry. However, according to the survey on current practices of precast companies in UK (Dawood and Neale, 1990), precasters primarily use a trial-and-error approach based on experiences. This approach has contributed to low working efficiency in planning process. Moreover, it cannot guarantee an optimal or good-enough solution. Therefore, a computerized model based on advanced technologies or algorithms should be developed for precast production planning and scheduling.

During the last few decades, three generic planning and control systems have been proposed, including material requirements planning (MRP)/manufacturing resource planning (MRPII), just-in-time (JIT), and optimised production technology (OPT). Despite their widespread applications in various manufacturing companies, each system has its limitations. These systems are generic in nature and may not be well suited for a specific domain, such as precast production. The precast industry can certainly benefit from the experiences in the manufacturing industry, but the precast industry is large enough and its needs distinct enough from manufacturing activities that it deserves its own body of research on production organization models and methods (Chan and Hu, 2002b).

In general, planning and scheduling cover two closely-related levels of activities: aggregate planning and detailed scheduling. At each level, research studies have been conducted, and various models and heuristics developed. In aggregate planning, machine requirements planning (MRP#) and aggregate production planning (APP) are two important research areas. Though tightly coupled, they are often studied as isolated problems. Besides, most researchers adopted mathematical programming to solve these problems. Despite its popularity in academia, the primary disadvantage of mathematical programming models is that they cannot solve a large and complex problem effectively (Leu and Hwang, 2001). On the other hand, detailed scheduling for precast production can be classified as a dual resource constrained (DRC) scheduling problem, since both mould and labour are used as critical resources. Though different operating decisions have been studied and various priority rules proposed in DRC research, it is worth the research effort to explore whether these decisions and rules are applicable to precast production scheduling and how they can be improved.

Precast production has its own characteristics and several specialized models have been established for planning and scheduling in precast plants. While the results given by these models in the tests seem promising, some limitations can be identified with these models. For example, all the planning models assume that the quantity of resources needed are given in advance. That is, resource planning is not taken into account in the models. Besides, sharable moulds are widely used for precast production and mould changeovers are usually a big concern in practice. But, they have not been modelled properly in these studies. Therefore, further research is needed to develop a more comprehensive and robust model for efficient and effective production planning and scheduling in precast plants.

1.3 Objective and Scope of Research

The main objective of this research is to develop a special-purpose model for production planning and scheduling in precast plants. Such model should take into specific account the distinctive features of precast production, and cover aggregate planning and detailed scheduling. The model should be able to generate optimal or satisfying production schedules and resource plans for implementation in practice. To achieve this objective, the following works should be conducted step by step in this research:

1. To identify the main distinctive features of precast production based on the current practices in precast plants;
2. To establish objectives for precast production planning and scheduling, and a scheme for measuring performance of alternative production schedules;
3. To design a conceptual model for precast production planning and scheduling, with particular considerations of the identified distinctive features and the established objectives;
4. To formulate inner workings or mechanisms of the conceptual model for precast planning and scheduling, i.e., devise scheduling methodologies, algorithms, and priority rules to materialize the conceptual model;

5. Based on the conceptual model and its inner workings, to develop a prototype system using a general programming language for model validation.

In order not to divert the focus, the scope of model development is further elaborated as follows. Firstly, the proposed special-purpose model should integrate intermediate tactical planning and short-run operational scheduling, while long-term strategic planning is not considered in the research.

Secondly, in the construction of precast projects, constructors can choose from two forms of precast supply: casting the components on site or purchasing them directly from precasters who produce precast components in precast plants. In most projects, the latter is adopted as additional space and facility are not available on site for precasting. The research concentrates on off-site precast production in precast plant.

At last, to provide the background for the model development, the current practices of precast plants in Singapore has been studied, and the distinctive features of precast production identified. The development and application of the model focuses on the following aspects which are derived from the survey on Singapore's precasters. These aspects will be further discussed in Chapter 3.

- Make-to-order production: Basically, production systems in precast plants can be classified into two categories: (1) make-to-order (MTO) where outline design is supplied by the client, customized moulds are required, and precast components (PCs) are produced according to order, and (2) make-to-stock (MTS) where standardized PCs are produced in batches and kept in stock for use of different orders. The model in this research is developed for MTO precast production;
- Casting process: In precast production, casting process is most critical, dominating the entire production progress. The research focuses on planning and scheduling for this process. Planning of other production activities (such as materials preparation, PC finishing and PC storage) can be derived from a "master plan" of casting process (Warszawski, 1990);
- Capacity planning: Resource planning in precast production may include two aspects, capacity planning (e.g., mould and labour) and material planning (e.g.,

concrete and rebar). Comparatively, capacity planning is more important than material planning. In practice, mould and labour are principal constraints for production schedule development, whereas material plan is established later based on the proposed production schedule. To reflect this feature and not to complicate the study, only capacity planning is included in this research.

- Stationary mould system: Mould systems employed in precast production includes two basic types: stationary moulds and movable moulds (Warszawski, 1990). Stationary system is extensively applied in MTO environment, as it requires low investment and has the flexibility to handle different components or production technologies simultaneously. This research is confined to precast production with a stationary mould system.
- Comprehensive labour organization: In general, labour in casting process are organized in two forms: specialization organization and comprehensive organization. In Singapore's context, most precasters use comprehensive organization due to its good adaptation to heterogeneous production and clear demarcation of responsibilities among different work teams. For this purpose and for ease of data collection, the research mainly studies precast production under a comprehensive organization.

1.4 Research Methodologies

To achieve the above mentioned objective, the main methodologies used in the research include literature review, field study, questionnaire survey, interview, model development and prototyping.

In order to understand the current state of research and identify the focus of this study, the existing systems and methodologies for production planning and scheduling are reviewed and summarized. The relevant modelling and optimization techniques are also studied to provide the background for model development.

Secondly, the distinctive features of precast production should be taken into specific account in the proposed model. For this purpose, field study is conducted in two selected precast companies and questionnaire survey and interviews are further performed to explore the current practices in precast plants. Related production data is also collected in the field study for model validation.

Thirdly, a conceptual model is proposed based on the literature review and the characteristics identified for precast production. It denotes the highest level of abstraction in terms of system structure and function for production planning and scheduling in precast plants. The model is further developed in more details for every module involved. Scheduling methodologies, priority rules and solution searching approach used in the modules are designed and established using advanced modelling and optimization techniques.

Finally, a prototype system is developed to implement the concepts and methodologies of the model. Model validation is carried out by testing the prototype system and comparing it with other approaches in two examples using actual data collected from precast plants.

1.5 Organization of Thesis

This thesis consists of eight chapters. Its organization is illustrated in Figure 1.3 and described as follows.

Chapter 1 introduces the background and need for research. The objective and scope of the study, and the methodologies used to achieve the objective are also presented.

In Chapter 2, the concept of three-level planning hierarchy is presented. Previous studies on production planning and scheduling are reviewed, including generic planning and control systems, methodologies for aggregate production planning and machine requirements planning, studies on dual-resource constrained scheduling, bilevel programming for hierarchical planning, as well as specialized models for precast production planning and scheduling. The limitations with these previous studies are explored. In addition, two advanced techniques, simulation for modeling and genetic algorithm (GA) for optimization, that are used in the model development, are discussed.

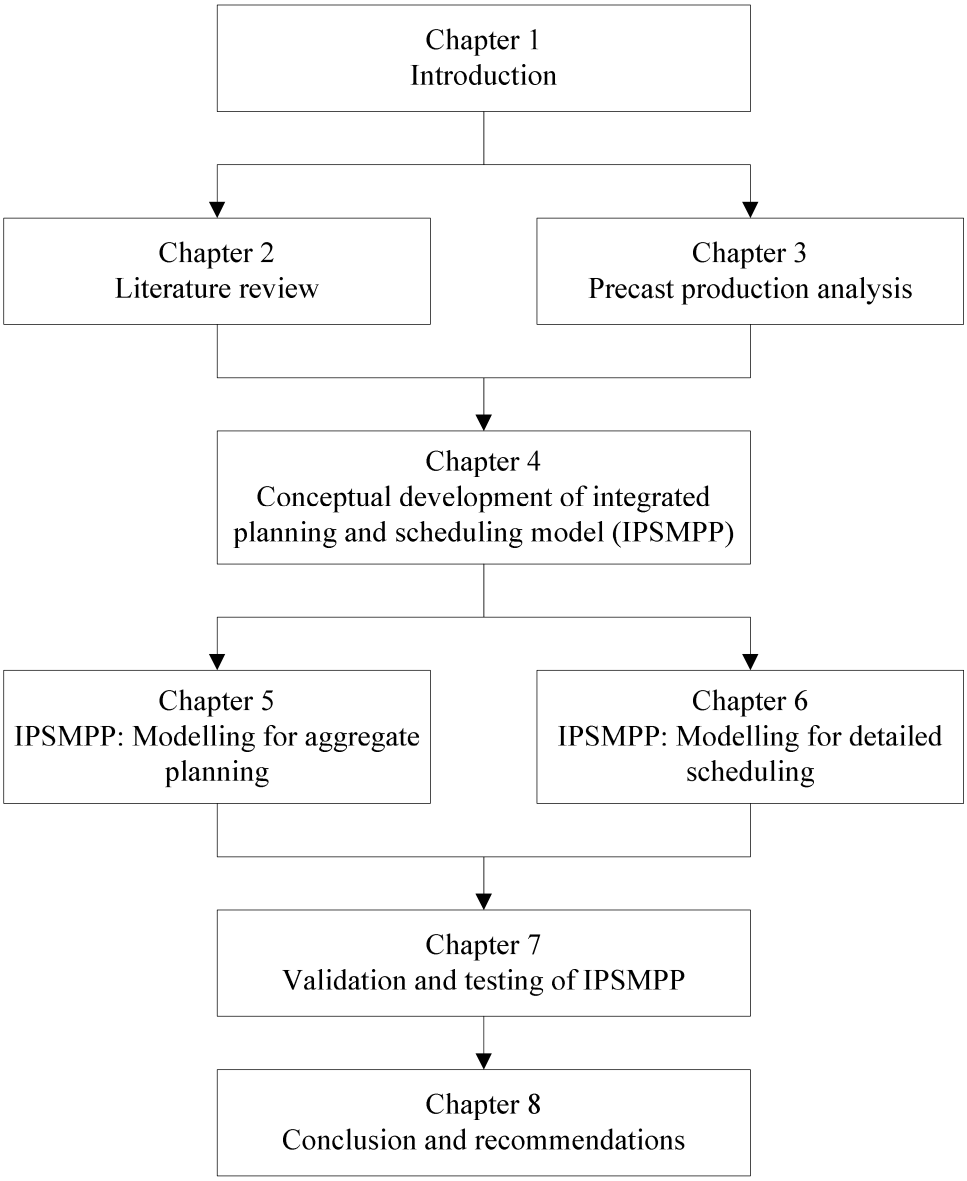


Figure 1.3: Organization of Thesis

Chapter 3 presents an investigation on precast production. At first, through field study, questionnaire survey, and follow-up interviews, relevant information of current production practices in Singapore's precast plants are collected and summarized. Then, the distinctive features of precast construction are identified. They form the basis for the model development. The planning and scheduling method used in practice is also addressed and the potential problems are investigated.

Chapters 4, 5, and 6 are the thrust of this research work. Based on the literature review in Chapter 2 and precast production analysis in Chapter 3, Chapter 4 establishes objectives and a performance measurement scheme for precast production planning and scheduling. A conceptual model, IPSMPP, is proposed for integrated production planning and scheduling in precast plants. The model covers both aggregate planning at the tactical level and detailed scheduling at the operational level. At the two levels, five modules (i.e., *Labour Sizing*, *Mould Planning*, *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring*) specially designed for different planning purposes. Simulation-GA based approach for every module and transferring feasibility from aggregate planning to detailed scheduling are explained.

As a further step in the model development, Chapters 5 and 6 concentrate on formulation of inner workings at the tactical level and the operational level respectively. In Chapter 5, the detailed structure of Simulation-GA based approach is presented for integrated *Mould Planning* and *Labour Sizing*. At the tactical level, a bidirectional simulation with fixed-increment time advance is adopted to generate alternative master production schedules. Scheduling methodologies in both forward simulation and backward simulation are explained in detail. In particular, a novel priority rule, CP rule, is established to take into consideration mould requirements and availability in the forward simulation so as to solve potential problem with the traditional rules. Finally, how GA works for aggregate planning is described.

Chapter 6 explains the Simulation-GA based approach for detailed scheduling, as well as decision variables, constraints, and priority rules involved in the modules of *Labour Grouping*, *PC Allocation & Sequencing* and *Labour Transferring*. In contrast to aggregate planning, detailed scheduling uses a bidirectional simulation with next-event time advance to model the production process at the operational level. The algorithms for operation time calculation are created for forward simulation and backward simulation based on characteristics of various casting operations. The bidirectional simulation at the operational level takes three scheduling passes, including two forward simulations and one backward simulation to get a detailed production schedule. Different priority rules and procedures are applied in every simulation pass for each module. Specifically, a new "where" labour transfer rule, CM rule, is designed to make a tradeoff between two traditional rules. Explanation is also given to implementation of GA in every module.

Based on the proposed model, a prototype system is developed using the general programming language, C#. In Chapter 7, the IPSMPP model is validated by testing the prototype system with two examples, one for aggregate planning and the other for detailed scheduling. In the tests, based on the established scheme for performance measurement, the prototype system is compared with other approaches using traditional priority rules and in forward scheduling direction. As explained in the chapter, the results show that the proposed model is an effective tool for precast production planning and scheduling.

Chapter 8 summarizes the research work carried out and primary contributions made, as well as the limitations existing in the current study. The recommendations for future research work in the area are also proposed.

Chapter 2

Literature Review

2.1 Production Planning and Scheduling

In precast companies and other manufacturing companies, the management needs to perform planning works for the production operations to ensure that they meet the need of the marketplace and support the overall business strategy.

2.1.1 Three-Level Planning Hierarchy

As proposed by Anthony (1965) and many researchers, all planning works can be classified into three broad categories or levels: strategic planning, tactical planning, and operational planning and scheduling. The three-level planning hierarchy is consistent with decision-making levels. In a firm or an organization, strategic planning represents the highest level of the decision-making hierarchy and is concerned with defining long-term objectives and designing infrastructure and overall capacity to support these objectives. Tactical planning is the middle level of decision-making activities for an intermediate range period. It focuses on reasonably obtaining and allocating resources to effectively utilize the firm's infrastructure and accomplish the production objectives. Operational scheduling is carried out at the lowest level of the hierarchy planning process. It makes decisions for a short planning period, and assures that individual tasks are performed efficiently with available resources to support the tactical plan. Some typical decisions made at strategic, tactical, and operational planning and scheduling levels are listed in Table 2.1 (adapted from Miller, 2001, and Heizer and Render, 2004).

Table 2.1: Typical Decisions Made at Strategic, Tactical, and Operational Planning and Scheduling Levels

(Adapted from Miller, 2001, and Heizer and Render, 2004)

Decision level	Typical decisions
Strategic	o Establishment, expanding or closing of plant and warehouse o Location, size, and capacity levels of plant and warehouse o Acquisition of production technology and long lead-time equipment o Transportation network o Order fulfillment approach (e.g., make-to-order vs. make-to-stock)
Tactical	o Assignment of products to plant o Workforce requirement (through hiring, firing, and overtime) o Increase of equipment (through purchasing or leasing) o Subcontract o Inventory buildup and deployment plan
Operational	o Scheduling and sequencing of daily production task at the item level o Labour scheduling o Equipment allocation o Inventory balancing and reconciliation

2.1.2 Aggregate Planning and Detailed Scheduling

In this research, the focus is placed on tactical planning and operational scheduling. In literature and practice, tactical planning and operational scheduling are usually referred to as "production planning and scheduling", with "production planning" being tactical in nature and "production scheduling" being operational in nature. Resource planning is directly related to production planning and scheduling. In the short term, the resource available provides a set of constraints to production scheduling, while in the longer run, implementation of production plans calls for adjustment for resources (Vollmann et al., 1997). Actually, resource planning and production planning and scheduling are on opposite sides of a coin, and they can be so intertwined as to become only a single ongoing function (Cox and Spencer, 1998). In this research, "production planning and scheduling" is defined in a broad sense. It is not just a process of establishing a master schedule for production volume that will occur in the next several time periods, or a detailed schedule on how individual operations will be executed within a short planning horizon, but it also involves acquisition and utilization of the workforce and other necessary resources to implement the production schedules.

As stated by Graves et al. (1993), production planning tends to employ aggregate data, seeks to describe large segments of the production environment, and typically considers planning horizons of one month to one year. By contrast, production scheduling tends to employ detailed data, seeks to describe smaller segments of the production environment and considers planning horizons of a few hours to several days or a few weeks. Therefore, to reveal these features, production (tactical) planning is also defined as "aggregate planning", whereas production (operational) scheduling is also called "detailed scheduling" in this research.

2.2 General Systems for Production Planning and Control

Three very different production planning and control systems have emerged for general manufacturing settings over the past three decades, namely, material requirements planning (MRP)/manufacturing resource planning (MRPII), just-in-time (JIT), and optimised production technology (OPT).

2.2.1 MRP/MRPII

MRP is a set of techniques which uses Bills of Material (BOMs), inventory data and the Master Production Schedule (MPS) to calculate requirements for items (Cox, Blackstone and Spencer, 1995). It takes requirements for finished products and works back through the BOMs and produce work orders and purchase orders for materials. One objective of MRP is to utilize each work center's capacity effectively. Such a system is so called a "push" system, which MPS pushes components into the factory, then into inventory, then back into manufacturing, and so on (Vollmann et al., 1997). During the 1970s and 1980s, several modifications and extensions were made to MRP by integrating additional features, such as Master Production Scheduling, Capacity Planning and Production Activity Control. MRP evolved into a complete planning and control system, Manufacturing Resources Planning (MRPII), which could be used not only to plan materials requirements but also labour and other resources requirements in a manufacturing company.

As MRP/MRPII is widely used in manufacturing, several limitations have been identified. For example, as noted by Kenworthy (1997), capacity requirement planning (CRP) in MRPII is an infinite capacity planning system. It plans each job on the required date even if insufficient capacity is available, which cannot assure a feasible plan with respect to capacity without the planer's intervention. Besides, in determining the offsets during the backward planning process, MPR uses a fixed and predetermined lead times, which, in reality, may be variable depending on dynamics of shop conditions (Watson et al., 1995).

2.2.2 JIT

JIT is both a philosophy and a set of techniques covering all aspects of a manufacture operation with the aim of producing only as required, with perfect quality and no waste (Jones and Roberts, 1990). The main underlying concepts include continuous improvement, total quality management, people involvement, waste removal, and so on. Traditional MRP-based systems drive the manufacturer towards full use of capacity of all resources, whereas JIT approach accepts the presence of idle workers as both inevitable and desirable in order to keep a balanced material flow. JIT is basically "pull" system and the emphasis is placed on customer demand. When a customer "pull" some product out of inventory, it pulls some replacement inventory from the factory, which pulls some parts from the shops, which pulls some materials from the store rooms, and so on (Vollmann et al., 1997). Most researchers agree that JIT requires a repetitive environment since one assumption made in JIT is that demand is stable (Cox and Spencer, 1998). It is not appropriate in job shops where products are made to order, variability is high, and demand is non-stationary (Silver et al., 1998).

2.2.3 OPT

OPT is finite scheduling technology that simplifies the scheduling problem by concentrating on developing and refining the schedule for the bottleneck resource only (Kenworthy, 1997). It claims that bottleneck resources need to be loaded to 100% of their capacity, whereas other operations apart from bottleneck should be run below full capacity in order to reduce inventory and operating cost while maintaining throughput. OPT simplifies the scheduling process and automatically ensures that the plans are feasible with respect to capacity. However, the main weaknesses of OPT are that it assumes bottlenecks are fixed and demand is statistically stable from one production period to the next. For this reason, OPT would perform best in a repetitive manufacture serving a stable market. Uncertainty over the number and stability of bottlenecks, the availability of resources or market demand causes OPT to become less effective (Jones and Roberts, 1990).

2.2.4 Discussion

Numerous successful implementations of these systems have been reported and considerable benefits achieved. At the same time, however, some limitations have been recognized for each system, as mentioned above, limiting their application scopes. Furthermore, these systems are generic in nature and may not totally fit into a specific domain such as precast production. The distinctive features of precast production, which will be discussed in Chapter 3, should be taken into account in development of a specialized planning and scheduling system.

2.3 Studies on Aggregate Planning

Aggregate planning is a process of determining both a tentative production plan and resources necessary to implement the plan. Two important research areas in aggregate planning are machine requirements planning (MRP#) and aggregate production planning (APP). They have received considerable attention from both practitioners and researchers during the past few decades and many models have been suggested for these planning problems (Behnezhad and Khoshnevis, 1996). In the thesis, MRP# is used to represent machine requirements planning, differentiating from MRP which is the abbreviation of material requirements planning.

2.3.1 MRP#

The machine requirements planning models determine the optimal number of machines (production equipment) along with the required information on their utilization schedule in each period of the planning horizon to meet the projected demand at minimum cost (Behnezhad and Khoshnevis, 1988). The early models for MRP# are descriptive in nature based on simplifying assumptions that planning horizon is infinite and production parameters are fixed. Miller and David (1977) made a comprehensive survey of past work on MRP# problem, and conducted simple arithmetic operations composed of some important factors, such as production output requirements, machine output rates, machine scrape factors and work time available. Since then, mathematical programming has been widely adopted as a modelling tool for MRP# problem.

Miller and David (1978) proposed a dynamic model for MRP# problem with finite planning horizon and changing production parameters. In the work of Behnezhad and Khoshnevis (1988), the effects of manufacturing progress function on MRP# were studied. Manufacturing progress function refers to the phenomenon that production productivity on machine is improved as more units of a product are produced. A mathematical programming model for MRP# accounting for such effect was developed. In their numerical example, comparisons were made between the models with and without inclusion of inventory buildup and shortage possibilities, demonstrating the significance of considering the manufacturing progress effects. Vander Veen and Jordan (1989) explored the interdependencies between machine investment and utilization decisions. A mathematical model was formulated with the aim of minimizing total investment and operating costs. It was used to solve MRP# problem with multiple-machine types and multiple-part types. Recently, Wand et al. (2000) proposed a fuzzy multiple attribute decision-making model for machine selection problem in flexible manufacturing cell. With the model, many important factors involved in machine selection can be considered.

2.3.2 APP

APP involves the simultaneous determination of company's production, inventory and employment levels over a finite time horizon, with the objective to minimize the total relevant costs while meeting non-constant, time varying demand (Nam and Logendran, 1992). Many models and techniques for APP have been reported in literature, from simple linear mathematical models and graphical techniques to sophisticated goal programming models and search and heuristic approaches. A comprehensive review of these studies was provided by Nam and Logendran (1992).

For example, Hanssmann and Hess (1960) proposed a linear programming method to solve the production and employment scheduling problem with linear cost functions. Lawrence and Burbridge (1976) identified multiple objectives involved in APP decisions, for example, maximization of sales revenue and minimization of production and distribution costs. They then formulated APP problems as a goal programming model with the consideration of these multiple objectives. Recently, Behnezhad and Khoshnevis (1996) presented a mathematical programming model that concurrently encompasses MRP# and APP problems. In the numerical example, the integrated model results in cost savings advantages over the individual MRP# and APP models. In the work of Aghezzaf E-H (2000), APP problem was solved in two stages with an approximation procedure. At first, workforce level was established and transferred into production capacity. Then the sub-problem, a lot-sizing problem, was solved with the capacity constraint to generate the final production plan. Porkka et al. (2003) recognized that early models for APP problems with set-up times does not work well since they either ignore production capacity consumed by set-up time or waste capacity by allocating unnecessary set-ups. They proposed two mix integer linear programming models to include set-up carry-over among consecutive planning periods. Comparison with a benchmark model without set-up carry-over showed that explicitly counting for set-up times and carry-overs in the proposed model cuts down the number of set-ups and frees a large amount of production capacity.

2.3.3 Discussion

Although a lot of research works have been conducted for MRP# and APP problems, they may have at least one of the two major weaknesses. At first, MRP# and APP have been treated as separate research topics in literature, while they are closely coupled in most production environments. The interdependence between MRP# and APP lies in the fact that a product generally requires both machinery and workforce for its production. When either the MRP# or the APP problem is investigated alone, a seemingly optimal plan is obtained under the assumption that the capacity of the other resource is unrestrictive (Behnezhad and Khoshnevis, 1996). The result of such uncoupled analyses could be inapplicable due to the possible imbalance between machines and operators, as well as suboptimal with respect to their total cost.

Secondly, among different models and methodologies proposed, mathematical programming is the most commonly used approach to solve MRP# and APP problems. Despite their popularity in academic works, the application of mathematical programming models in practice is limited. Many real-world systems are highly complex, so that valid mathematical models of them are themselves complex, precluding the possibility of any analytical solution (Law and Kelton 2000). In precast production planning, for example, it is very difficult to explicitly formulate sequence-dependent mould changeovers with a mathematical programming model. Even if it is simplified as sequence-independent changeovers with mixed-integer programming, as in usual lot-size models, problems still exist. State-of-the-art mixed integer programming codes are generally inadequate to solve production problems of any realistic size, given that they can handle only a small umber of integer variables (Nam, and Logendran, 1992).

2.4 Studies on Detailed Scheduling

Detailed scheduling is concerned with how to utilize resources available to generate an efficient detailed production schedule. A considerable amount of research has been conducted on scheduling problems in job shops. This research can be categorized into two streams, one is for machine-limited system and the other for dual resource constrained (DRC) system (Treleven, 1989). A machine-limited system is the one in which all equipment is fully staffed, therefore machine is viewed as a single limiting resource for production. On the contrary, DRC system is the one in which all equipment in the shop is not fully staffed and, furthermore, workers are typically cross-trained so that they can process jobs on different machines (Kher, 2000). Therefore, capacity constraints on output of the system come from both machine and labour (Hottenstein and Bowman, 1998). In literature, most of the research on job shop has focused on the machine-limited systems. In such systems, dispatching rules are used to determine priority of jobs waiting for processing and have been studied as a critical control parameter in improving shop performance. In practice, however, many job shops are actually DRC systems, where both machine and worker represent potential capacity constraints. In such environments, dispatching rules alone are not adequate and extra operating policies are needed from the standpoint of efficient worker utilization and improved shop performance (Kher and Fry, 2001). Precast production is actually a DRC system, as explained in Chapter 3. Therefore, in this research, the literature review in the field of detailed scheduling concentrates on scheduling in DRC environments.

2.4.1 DRC Scheduling

In 1967, Rosser T. Nelson published the first study on DRC (Nelson, 1967). Since then, many researchers have put in effort in DRC research. Treleven (1989) made a comprehensive review on DRC literature, covering twenty-five articles. Later on, another literature review was provided by Hottenstein and Bowman (1998), examining sixteen simulation-based DRC studies in terms of different scheduling dimensions. More DRC research has been conduced recently. For example, Jensen (2000) brought together DRC and group technology research streams to evaluate the performance advantage result from labour and machine flexibility. In the study, three different shop configurations under four levels of staffing were used as control factors to resolve the apparent contradiction surrounding the usefulness of joint flexibility. Kher and Fry (2001) explored DRC problems in a job shop with incommensurable objectives. In such environment, customers are classified according to their criticality and high priority is assigned to orders from vital customers. Different operating policies in DRC systems were evaluated for offering a near-perfect performance for vital customers.

According to Hottenstein and Bowman (1998), there are basically five main dimensions covered in existing DRC studies, including labour flexibility, "when" labour transfer rules, "where" labour transfer rules, job dispatching rules, and labour transfer delay. Firstly, during the past two decades, development of labour flexibility has been increasingly used as a competitive priority in manufacturing industries. Workers are crossed-trained to have multiple skills so that they can be assigned to various tasks as the need arises. In DRC systems, labour flexibility can be modelled in variety of ways, including the machine-staffing level, the efficiency of labour that are transferred, the degree of centralized labour control, and the number of machines to which a labour can be transferred (Treleven, 1989). It is shown from both academic studies and manufacturing practice that labour flexibility does have a great impact on shop performance.

Secondly, labour transfer in DRC environments is concerned with two central questions: when to transfer labour, and to which work centre they should be transferred. Decisions about the two questions are referred to as the "when" and "where" labour transfer rules, respectively. Two basic "when" rules broadly used in literature are centralized rule and decentralized rule:

- Centralized rule: allows a worker to transfer after the completion of current job, even if the queue in the current work centre contains more jobs.
- Decentralized rule: allows a worker to transfer only when idle, i.e., after the worker completes all the jobs queuing before the current work centre.

Clearly, centralized rule is more flexible than decentralized rule in transferring worker to other worker centers (Kher and Fry, 2001). Compared to the question of when to transfer an eligible cross-trained worker, where the worker should be assigned has greater impact on shop performance, as noted by Hottenstein and Bowman (1998). Researchers have proposed some "where" rules, including the most commonly used LQ rule and EDD rule.

- LQ rule: labour are transferred based on the length of job queue in front of idle machines and the machine with the longest queue has the highest priority;
- EDD rule: labour are transferred based on the due date of jobs to be processed on idle machines, and the machine with the job with the earliest due date has the highest priority.

In DRC research, various dispatching rules have been proposed to dispatch jobs waiting for processing in front of every machine or work centre, as reviewed by Treleven (1989) and Hottenstein and Bowman (1998). Studies have been conducted to evaluate and compare the impact of different dispatching rules on shop performance. The results from these studies indicate that the dispatching rules which perform well in DRC systems are SOT (shortest operation time), EDD (earliest due date) and SPR (slack per remaining operation) (Treleven, 1989). When setup time is explicitly considered in job processing, SST (shortest setup time) rule may be used.

- SOT rule: jobs to be processed on a machine are dispatched according to their operation times, and the one with the shortest operation time is dispatched first.
- EDD rule: jobs are dispatched according to their due dates, and the one with the earliest due date is dispatched first.
- SPR rule: jobs are dispatched according to their slacks per remaining operation (SPR), and the one with the least slack per remaining operation is dispatched first. The slack of a job is defined the time length obtained by subtracting the sum of current time and job remaining time from the due date. And then SPR is calculated by dividing the slack time by the number of remaining operations of the job.
- SST rule: whenever a machine is freed, this rule selects for processing the job with the shortest setup time (Pinedo and Chao, 1999).

A time delay may be incurred in transferring labour from one work center to another. It is the time needed to orientate the transferred labour and have them get acquainted with the new machine. A few researchers acknowledged the labour transfer delay in their studies and examined its impacts on shop performance and relationships with other operating policies. Based on the results from these studies, Hottenstein and Bowman (1998) concluded that increasing transfer delay time increases mean flow time and flow-time variance, and thus a system that minimizes labour transfers would logically lead to superior system performance.

2.4.2 Discussion

While many studies have been made on generic DRC scheduling problems, some questions can be raised on detailed scheduling for precast production:

- Are the five scheduling decisions or operating policies in DRC studies applicable for precast production scheduling? If so, in what way should they be modelled?
- Among priority rules of every scheduling decision, such as "when" and "where" labour transfer rules, and job dispatching rules, which one should be used for precast production?
- Is it possible to improve the existing priority rules or develop new priority rules for precast production?

This research attempts to provide answers to these questions.

2.5 Bilevel Programming for Hierarchical Planning

Multilevel mathematical programming is widely accepted technique to solve decentralized planning problems with multiple decision makers in a hierarchical organization (Hejazi et al., 2002). A large class of multilevel programming only involves two levels and is called bilevel programming (BLP) (Zhang, 2003). As the philosophy of decentralized/hierarchical planning features greatly in the research, as discussed in the later chapters, the literature review also covers BLP.

2.5.1 Models and Algorithms

BLP problems are optimization problems at a two-level hierarchy, where the variables of the upper-level problem are the parameters of the lower-level problem. A decision maker at the upper level is known as the leader, and at the lower level, the follower. Each decision maker (leader or follower) tries to optimize his/her own objective function, but the decision of one affects the objective optimization of the other (Bard, 1998). More specifically, the leader takes the lead, and makes decision to optimize his/her objective. The follower, with full information of the leader's decision, reacts accordingly to optimize his/her objective (Gumus and Floudas, 2001). Note that the leader is limited to influencing, rather than fully controlling, the follower's decision.

The first formulation of BLP problems was done by Stackelberg (1934) in the context of market economy. In recent years, a rapid development and intensive investigation of these problems has been observed in both theoretical and applications oriented directions. Bard (1998), Dempe (2002) and Dempe (2003) presented comprehensive reviews over the historical development and research outcomes. The majority of research on BLP is concentrated on the linear version of the problem (Bard, 1998). One fundamental question in BLP studies is how to find an optimal solution for the decision problem. Many solution algorithms have been proposed for BLP problems. According to Dempe (2003), these algorithms can be divided into 3 classes as follows:

1. Algorithms to solve problems globally. Historically, researchers first concentrated on algorithms to get globally optimal solutions. Most of these algorithms were proposed for linear version of BLP problems, such as vertex enumeration method (Candler and Townsley, 1982) and Kuhn-Tucker method (Fortuny-Amat and McCarl, 1981).
2. Algorithms to compute locally optimal solutions. Since it is difficult to globally solve BLP problems which are non-convex in nature, many researchers focuses their investigations on deriving descent methods for computing locally optimal solutions (e.g. Dempe and Schmidt, 1996, and Dempe, 2000).
3. Heuristic algorithms. Due to minimal problem restrictions and global perspective of heuristic algorithms (e.g. genetic algorithm and tabu search method), researchers, in recent years, attempted to use these methods to solve complicated BLP problems, especially discrete BLP problems. Examples can be found in Wen and Huang (1996), and Yin (2000).

2.5.2 Applications

BLP has a wide scope of applications, such as transportation planning (LeBlanc and Boyce, 1986), price determination (Luh et al., 1987), pollution control (Amouzegar and Moshirvaziri, 1999), transmission network analysis (Hobbs et al., 2000). An overview of applications of BLP is given by Marcotte and Savard (2001).

Furthermore, some applications of BLP are concerned with production and resource planning. For example, Bard and Moore (1990) proposed a BLP model to account for variable demand in production planning. In this model, the manufacturer (leader) announces a production mix and advertising strategy for the planning horizon. Using this information, the customer (follower) then tries to structure a response that will satisfy his demand at minimum cost. In Nicholls (1995), operation of an aluminum smelter was simplified and represented with a nonlinear BLP model. A specialized solution algorithm was also developed based on vertex enumeration approach. Nevertheless, more work needs to be done with respect to allowing more variables and optimizing over multiple periods, as acknowledged by the author. Karlof and Wang (1996) focused on an altered form of standard flow-shop scheduling problem where the upper planner assigns the operators to the machines to minimize the total flowtime and the lower planner decides on the job's schedule to minimize makespan. The problem was modeled as a BLP problem and solved by a two-level branch and bound algorithm. In the computational experiments, however, the largest problem that could be solved with the proposed algorithm was only 10 machines and 10 jobs. A BLP framework was proposed by Ryu et al. (2004) to model a problem in enterprise-wide supply chain with the upper level corresponding to distribution network planning and the lower level to production planning problem. A numerical example was presented to illustrate the proposed framework. Cao and Chen (2006) addressed a capacitated plant selection problem in a decentralized manufacturing environment where the principal firm at the upper level selects the plants based on its overall business considerations, while the opened plants at the lower level operate independently to minimize their own production and operation costs. A two-level nonlinear programming model was developed to capture the interdependence relationship between the principal firm and the selected plants. It was then transformed into an equivalent single level model and solved by available optimization software.

2.5.3 Discussion

BLP has been extensively studied and applied in many fields, including some aspects in decentralized production planning. Nevertheless, the following two aspects would hinder the application of BLP techniques to planning and scheduling in precast plants.

Firstly, planning and scheduling for precast production is a complex problem. As discussed in Chapter 3, the problem involves a multi-period dual-resource constrained planning at both tactical level and operation level with consideration of sequence-dependent mould changeover times. It would be very difficult to accurately model such problem with BLP techniques. In fact, existing BLP models for production planning only concentrate on certain part of simplified production system, and the modeling details are usually kept at a high level. For example, only strategic and/or tactical planning with one type of resource is considered in most of the existing models. Even in Karlof and Wang (1996), where BLP model is established for operational level scheduling with both manpower and machine as resources, machine set-up time and cost are neglected.

Secondly, precast production planning and scheduling involves many binary and integer variables (such as labour size and PC assignment to mould), increasing the difficulty in problem solving. Even if it could be simplified as a nonlinear BLP problem, existing algorithms cannot guarantee a global optimal or satisfying solution. Bard (1991) has shown that even the simplest case among the BLP family, the linear BLP, is Nondeterministic Polynomial-time hard (NP-hard) to solve. The nonlinear BLP, as a strong NP-hard problem, is a more complex and challenging problem. Actually, most of the existing algorithms for nonlinear BLP can yield a local optimum only (Bard, 1998). In spite of various intriguing attempts that were made in solving the BLP problem, these algorithms are unfortunately either incapable of finding the global optimum or very computationally intensive and impractical for problems of a realistic size (Yang and Bell, 1998).

2.6 Specialized Models for Precast Production Planning and Scheduling

From a survey of production planning practices in UK precast industry (Dawood and Neale, 1990), it was concluded that planning works in practice are rather simple and based on subjective trial-and-error methods. Such practices have contributed to poor planning performance, leading to unsatisfied demand or excessive stock. This has attracted studies from a few researchers. Several planning and scheduling models have been developed specifically for precast concrete production.

2.6.1 Models for Precast Production Planning

Warszawski (1984) made a distinction between short (specific orders with each including a limited number of special elements) and long (a continuous demand for standard elements) production series. With the aim to supply orders on time at minimum associated cost, mathematical planning models were established for both types of series produced on one or several moulds. Despite its simplicity, the models only took account of mould as a single resource during the planning process. As stated by the author, there may be computational and practical difficulties in solving the models in real life with mathematical programming methods because of an excessively large number of variables and imprecisely estimated parameters. For this reason, an approximate planning procedure was further proposed to render satisfying solutions in real life. It was recommended that priority in production on a free mould should be given to elements with earliest delivery dates or with the least adjustment cost.

Dawood (1994) highlighted the issue that traditional production management is fragmented and developed an integrated production planning/stock forecasting model. The model uses forward scheduling to predict the effects of different management strategies on production and stock. Three set of heuristic rules, namely product selection rules, plant selection rules and allocation rules, were employed in the model. Product selection rules determine product dispatching sequence and three distinct rules were designed to represent different planning strategies. All the rules give priority to maintaining stock cover in order to satisfy demand without any delay. Other considerations include lowering inventory cost and preventing high-volume products from running out of stock. Then planning performances of the three rules were evaluated and compared in different cost categories. As noted by the author, the model was only suited for make-to-stock precast production.

In Dawood (1995b), a planning model was developed for production in precast factory and integrated with knowledge rules mimicking the human decision-making process. Similar to the model in Dawood (1994), this model uses the simulation technique coupled with three types of knowledge rules (product selection rules, plant selection rules and allocation rules). Besides, both models are limited to make-to-stock environment. The major difference lies in that backward planning, instead of forward planning, was applied in the model so as to minimize inventories. Based on knowledge elicited from production managers, three distinct product selection rules were also designed to satisfy, to a certain extent, several planning criteria, including minimizing stock holding cost, minimizing changeovers, and balancing the availability of products in stock.

2.6.2 Models for Precast Production Scheduling

A modified flow shop sequencing model (FSSM) was given by Chan and Hu (2001) for precast production scheduling under a specialization organization. The model is solved with genetic algorithm (GA) with an aim of minimizing makespan and tardiness penalty. Furthermore, based on the traditional FSSM, the model took additional account of precast operations in terms of working time session and preemption. Results from two simple tests showed that GA is able to produce a family of optimal and/or near optimal results efficiently. Therefore GA is superior to the heuristics (e.g., EDD), which in general generate only a single feasible schedule. However, some limitations can be identified with the model. Firstly, the scheduling objectives for traditional flow shop problems (i.e., makespan and tardiness penalty) may not be appropriate for precast production. Secondly, the model works under an assumption that mould does not constitute a constraint to production, which is usually not true in practice. Thirdly, in precast production, different types of precast components may be produced with a sharable mould, causing extra time for mould changeover. The ordinary practice is not considered in the model.

Leu and Hwang (2001) proposed a similar model for resource constrained repetitive precast production. GA was also adopted to search for an optimal production schedule with a minimum makespan. In contrast with the work of Chan and Hu (2001), the model took into consideration several limited resources involved in production process, including labour, mould, cranes and steaming curing facilities. In an experimental test, the strength of GA in solving such problem was demonstrated and the impact of resource sharing on makespan was evaluated. In spite of the good result, the model suffered from the same limitations as FSSM proposed by Chan and Hu (2001), except that it used mould as a constraint.

Chan and Hu (2002b) applied constraint programming approach to solve scheduling problem of a comprehensive precast production process. The problem was first formulated with a mathematical model for constrained precast scheduling. Then constraint programming approach was proposed to solve the model because it is capable of handling complex combinational problems by directly employing constraints to locate optimal solutions. This was finally justified in an example problem, where constraint programming performed better than the other three heuristics in terms of the overall performance. While constraint programming approach seemed attractive, the proposed model apparently oversimplified the practical scheduling problem in the several aspects. For example, mould was considered the only critical resource and labour cost was assumed fixed, which is inconsistent with production practice. In addition, mould changeover was not correctly captured by the model in that it assumed zero changeover time and sequence-independent changeover cost.

2.6.3 Discussion

It is should be noted that, in addition to the above-mentioned specific limitations, all these models focused on either constrained production planning or shop-floor scheduling, and none of them integrates the two closely coupled problems together. Furthermore, these models work under the assumption that the required resources (e.g., mould and labour) have been given. Therefore, a more comprehensive model is needed which covers production planning and scheduling with resource planning incorporated.

2.7 Simulation and Genetic Algorithm

Simulation and genetic algorithm (GA) are popular techniques for modelling and optimization respectively. They are used jointly in this research for precast production planning and scheduling. Therefore, the literature review is also conducted on these two topics.

2.7.1 Simulation

2.7.1.1 Overview of Simulation

By definition, simulation is a process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system, or of evaluating various strategies for the operation of the system (Shannon, 1983). Simulation is one of the most important operations-research techniques (Lane et al., 1993). The main strengths of simulation lie in that it is capable of:

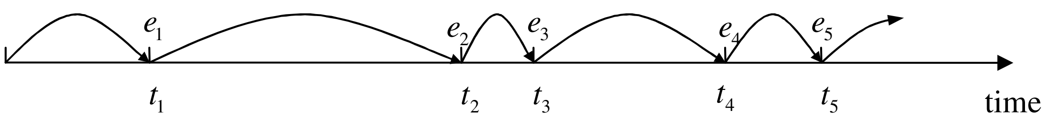
- Investigating real-world systems that are too complex to be accurately described by a mathematical model and evaluated analytically;
- Answering "what-if" type questions i.e., studying what would happen if the system is run under the given conditions;
- Comparing alternative operating policies for a single system to see which one achieves the best performance;
- Studying a system on different scales as required. For example, it allows to examine the detailed process of a system in expanded time, or alternatively to examine a system with a long time frame in compressed time.

2.7.1.2 Discrete-Event Simulation

A distinct type of simulation, discrete-event simulation, is most commonly used in process modelling and scheduling in construction and manufacturing. Discrete-event simulation concerns the modelling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. These points in time are the ones at which events occurs, where an event is defined as an instantaneous occurrence that may change the state of the system (Law and Kelton, 2000). Obviously, discrete-event simulation model is dynamic in nature.

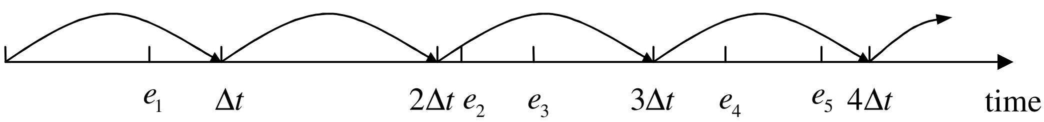
Discrete-event simulation has experienced widespread use because of its ability to represent, to any level of detail, the complexities, uncertainties, and dynamics of real-world systems (Watson et al., 1995). For example, many discrete-event simulation-based models have been proposed for construction project scheduling, such as PROMAX (Dabbas and Halpin, 1982), CIPROS (Tommelein et al., 1994), HSM (Sawhney and AbouRizk, 1995), PICASSO (Senior and Halpin, 1998), and STROBOSCOPE CPM add-on (Ioannou and Martinez, 1998).

There are two main approaches suggested for advancing the simulation clock (the current value of simulated time) in discrete-event simulation: next-event algorithm (NEA) and fixed-increment algorithm (FIA). Figure 2.1 and Figure 2.2 (adapted from Law and Kelton, 2000) give the illustrations of NEA and FIA respectively.



Notation: t_i = simulation clock e_i = time of occurrence of the ith event

Figure 2.1: Illustration of Next-Event Algorithm
(Adapted from Law and Kelton, 2000)



Notation: $n\Delta t$ = simulation clock e_i = time of occurrence of the ith event

Figure 2.2: Illustration of Fixed-Increment Algorithm
(Adapted from Law and Kelton, 2000)

With NEA, the simulation clock is advanced from one event time to another according to the sequence of occurrences of every event. On the other hand, with FIA, the simulation clock is advanced in increments of exactly Δt time units, and any events that have occurred during a certain time interval of Δt are considered to occur at the end of the interval. NEA is adopted by most of discrete-event simulation models and software since it can accurately process events, whereas FIA is primarily used for systems where all events can be reasonably assumed to occur at one of the time $n \cdot \Delta t$ ($n = 0, 1, 2, \ldots$) for an appropriately chosen Δt (Law and Kelton, 2000).

The procedure of NEA in discrete-event simulation for scheduling is given in Table 2.2 (adapted from Senior, 1995).

Table 2.2: Procedure of NEA in Discrete-Event Simulation

(Adapted from Senior, 1995)

[1] Start. Initialize the simulation clock: CT = 0;
[2] Check if any task can be started. If yes, continue; if no, go to step[7];
[3] Move resource units needed to the task;
[4] Calculate End Event Time: EET = CT + Task Duration;
[5] Record EET in Event List (a list containing all the times when every event occurs);
[6] Return to step[2];
[7] Check if Event List is empty. If yes, go to step[11]; if no, continue;
[8] Reset the simulation clock: CT = next earliest EET in Event List;
[9] Terminate tasks associated with chosen EET;
[10] Release resource units retained by the task to successors;
[11] Check if end condition is satisfied. If yes, stop the simulation; if no, go to step[2].

2.7.1.3 Backward Simulation

Traditionally, simulation has been widely used as predictive tool to conduct "what-if" analysis. In this case, with a given initial state or set of conditions, simulation is carried out to find out the final state of the system. This type of simulation is usually referred to as forward simulation since the simulation clock is advanced forward in time. In contrast, it is often necessary to determine the conditions to achieve a specific target or find out the initial state that can lead to a desired final state. This can be named condition-seeking problem (Inoue et al., 1985). Forward simulation may be used for handling this problem, but it would take considerable time and effort to test all possible conditions, especially for a complex system. To solve the condition-seeking problem efficiently, backward simulation approach was introduced by some researchers (Mejtsky, 1985, Inoue et al., 1985, Watson et al., 1993). The concept of backward simulation focuses on starting from a desired state and moving backwards in time to determine the sequence of events leading to the desired state (Jain and Chan, 1997).

In production management, several studies were performed to apply backward simulation in scheduling (Ying and Clark, 1994, Watson, Medeiros and Sadowski, 1995, Jain and Chan, 1997, and Watson, 1997). In their works, backward simulation starts from due dates, proceeds in reverse chronological order, and determines the sequence of operations and order release times. In conventional forward simulation-based scheduling, jobs are executed as early as possible within the resource constraints to minimize any order tardiness. Although the forward schedule may be feasible without any delay, it may result in excessive inventory. On the contrary, in the backward scheduling, the commitment of resources and materials is delayed until it becomes essential to do so, based on the lead times of jobs. As a result, jobs are neither started too early nor completed late (Hastings and Yeh, 1990). This means that the levels of work-in-process (WIP) and finished-good inventory are minimized.

Backward simulation can be viewed as a reverse version of a regular forward simulation. Both simulation approaches employ the same time advance and Event List processing mechanisms. Watson et al. (1993), in comparison with forward simulation, summarized the characteristics of backward simulation in scheduling, including:

- Reversed job route through the facility;
- Bill of material processed top-down;
- Special dispatching rules required;
- Possible output of unachievable backward schedule in the case that an order release is scheduled prior to the current time.

2.7.2 Genetic Algorithm (GA)

2.7.2.1 Overview of GA

Genetic Algorithm (GA), invented by J.H., Holland, emulates biological evolution in the computer and tries to build programs that can adapt by themselves to perform a given function (Goldberg, 1989). Briefly, GA is a robust adaptive optimization technique based on a biological paradigm (Beaty, 1992). One of the main advantages of GA is that it can search for solutions to an optimization problem without having to know much about the specific inner workings or structural properties of the problem. GA can handle any kind of objective functions and any kind of constraints (i.e., linear and non-linear) defined on discrete, continuous, or mixed search spaces (Gen and Cheng, 1997). In addition, most classical optimization methods employ a point-to-point search approach through iterations. As stated by Gen and Cheng (1997), this point-to-point approach takes the danger of falling in local optima. On the other hand, GA performs a multiple directional search by maintaining a population of potential solutions on each iteration. The population-to-population approach attempts to make the search escape from local optima. Furthermore, compared to the heuristic approach that usually generates only a single feasible solution, GA may recommend a family of optimal and/or near optimal solutions, which are more useful for decision making when other considerations are required (Chan and Hu, 2001, and Leu and Hwang, 2001).

Therefore, as a generic optimization tool, GA has received considerable attention and has been successfully applied in a wide range of different domains to solve complex problems that are difficult to solve by conventional optimization techniques. Some applications of GA include shop scheduling and sequencing (e.g., Bean, 1994, and Chen et al., 1995), facility layout (e.g., Tate and Smith, 1995), transportation (e.g., Vignaux and Michalewicz, 1991), project scheduling (e.g., Chan et al., 1996), and so on. In addition, Chan and Hu (2001) and Leu and Hwang (2001) also applied GA in production scheduling in precast plants, as discussed in the previous section.

2.7.2.2 Procedure of GA

Some concepts used in GA are given below:

- Chromosome: representation of an individual solution to the problem to be solved at hand. A chromosome is constructed by a string of symbols;
- Gene: one of the elements constituting a chromosome. Each gene represents part of a solution to the problem;
- Generation: one of successive iterations through which chromosomes evolve into the final solution(s) to the problem;
- Population: a set of chromosomes in each generation, consisting of parent and offspring chromosomes;

- Parent: chromosomes randomly generated in the 1st generation, or chromosomes in later generations which survive from the preceding generation;
- Offspring: new chromosomes in a generation which is created from parent chromosomes in the generation using crossover or mutation;
- Crossover: An operator used to create offspring by merging to two parent chromosomes;
- Mutation: An operator used to create offspring by modifying one parent chromosome;
- Fitness: a value associated with an individual chromosome, based on which some chromosomes in a generation are selected to form the population (parents only) in the succeeding generation. It is usually measured by value of the objective function corresponding to the chromosome.

Figure 2.3 describes the general procedure of GA (adapted from Gen and Cheng, 1997). GA works iteratively through successive generations with a constant population size. At first, an initial set of parent chromosomes are generated, usually at random, to form the population in the 1st generation. The chromosomes in the population are then evaluated using fitness. In each generation, offspring chromosomes are generated using either crossover operator or mutation operator, and also evaluated using fitness. A new generation is formed by selecting some of the parents and offspring and rejecting others at the current generation according to the fitness values such that fitter chromosomes have higher probabilities of being selected. After some generations, GA converges to the best chromosome(s), which is hopefully the optimal or suboptimal solution(s) to the problem.

In addition, the performance of GA is also determined by several parameters, including population size, the number of generations, crossover rate (the ratio of the expected number of chromosomes undergoing crossover to the population size), and mutation rate (the rate at which new genes are introduced into the population through mutation). These parameters have no fixed values that can be widely applicable to various optimization problems. For a particular problem, the values of these parameters have to be tuned to get a good performance of GA.

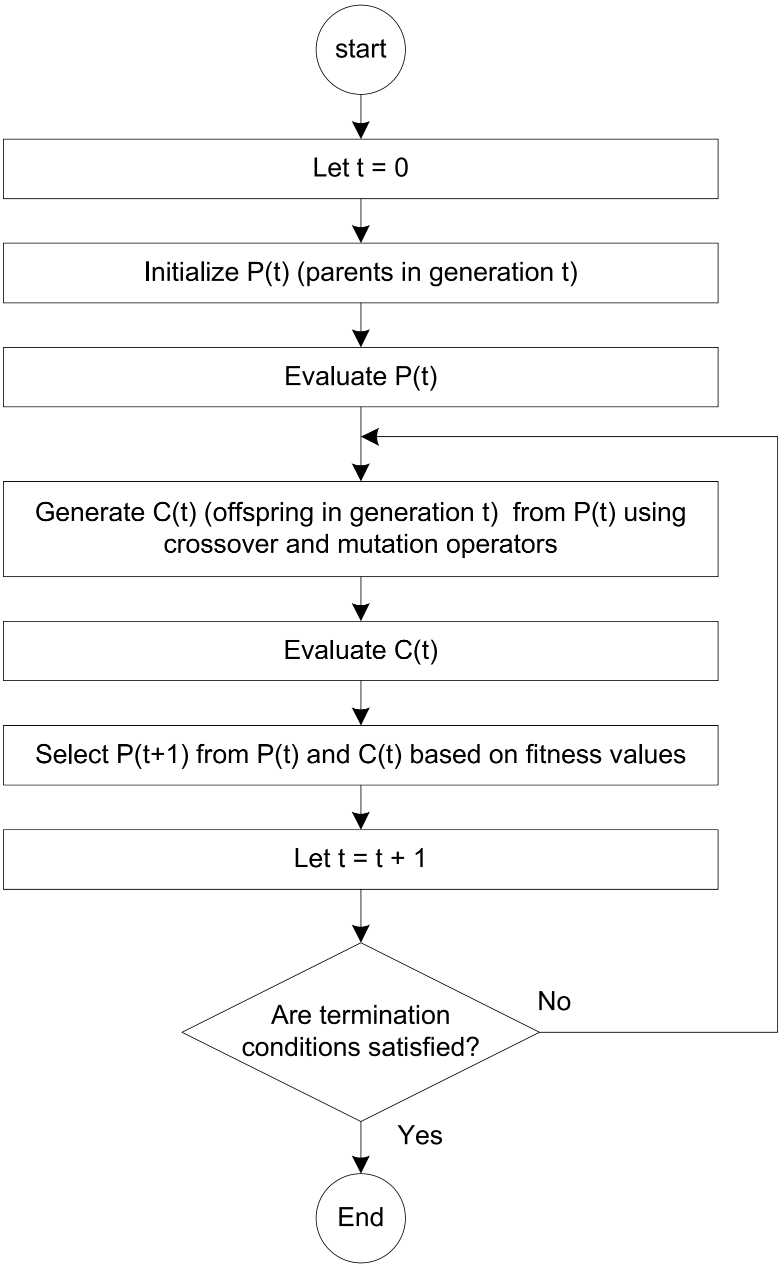


Figure 2.3: Procedure of Genetic Algorithm

(Adapted from Gen and Cheng, 1997)

Chapter 3

Precast Production Analysis

3.1 Investigation on Precast Production

The main objective of this research is to establish an integrated planning and scheduling model for make-to-order precast production. For this purpose, an investigation on current practices in prefabrication plants was conducted.

3.1.1 Investigation Objectives

As an initial stage of this research, the objectives of this investigation are:

1. To study current practices of precast production as well as planning and scheduling techniques used in practice;
2. To identify the need for a specialized planning and scheduling model to improve the production efficiency in the industry;
3. To explore distinctive features of production process in prefabrication plants and to form a basis for establishing the above model;
4. To collect data from precast plants for validating the model.

3.1.2 Methodologies of Investigation

Field study, questionnaire survey and interview are selected as methodologies of investigation on precast production.

3.1.2.1 Field Study

Field study is concerned with processes and patterns, uses direct and participant observation and interview techniques, and enables hypothesis to be tested based on data gathered (Miller, 2002). In the investigation, a two-week pilot field study was first conducted in two selected prefabrication companies in Singapore: Fermold Pte Ltd and Excel Precast Pte Ltd. The field study aims to get a first-hand understanding knowledge of precast production practice and other relevant issues, and thus to serve as the basis for subsequent questionnaire survey on precast production in a more comprehensive scope. The areas covered in the field study include precast production process, planning and scheduling, resource arrangement, material preparation, shop drawing development, precast stock management, and precast delivery system. In addition to site observation, inquiry was made with production manager, planning engineer and site engineer to clarify any problems encountered. During the field study, first-hand production data was also collected as inputs of the tests for final model validation, which will be discussed in Chapter 7.

3.1.2.2 Questionnaire Survey and Interview

As the second step of the investigation, a questionnaire survey was conducted to elicit information on common production practices of precast plants in Singapore. Mail questionnaire has been extensively adopted for information collection because of its ease of use and high coverage of sampling. From the websites of Housing & Development Board (HDB, http://www.hdb.gov.sg) and Building & Construction Authority (BCA, http://www.bca.gov.sg/), 22 precasters that operate in Singapore were selected as the targets of the questionnaire survey.

However, questionnaire survey is not without its limitations. The common problem with questionnaire is that it provides little motivation for respondents, resulting in low response rate. Also, ambiguities or misinterpretations may occur when respondents read the questions or questioner reads the answers (Palys, 1997). For this reason, follow-up contacts were made with all the targeted precasters after the questionnaires were mailed out to increase the response rate. Furthermore, interviewing allows a researcher to gain access to the observations of others and learn about their perceptions and interpretations of a given phenomenon (Sherry, 2001). Therefore, phone interviews were conducted with most of the respondents to clarify possible ambiguities or misunderstandings, as well as to get insight into underlying reasons for the answers provided in the returned questionnaires.

3.1.3 Questionnaire Design and Survey Results

The questionnaire is designed on the basis of the field study and literature review. Through the field study, it is learned that most precast plants in Singapore operate under a make-to-order (MTO) environment, and mould and labour are most critical resources in precast production. Therefore, the questionnaire focuses on current practices in a MTO precast production and covers four main parts, as follows:

1. Part I aims to clarify the basic issues of precast production practices, e.g., production system adopted, critical resource(s) for production, curing method used, etc.;
2. Part II focuses on mould arrangement in precast plants, with respects to type of mould system, mould planning method, percentage of sharable moulds, and significance of mould changeover;
3. Part III is concerned with labour utilization, covering questions on labour planning, labour allocation into PC groups, working shift(s), OT usage, and casting organization;
4. Part IV is about planning and scheduling in practice. The emphasis is placed on planning and scheduling objectives, actual planning method, and computer software used in planning.

The questions in the questionnaire are semi-structured including both selection questions and open-ended questions. For selection questions, besides the options provided in the questionnaire, the respondents can choose to provide other answers. A full copy of the questionnaire is given in Appendix A.

Of the total 22 targeted precasters, 15 responded to the questionnaire survey with a response rate of 68%. Respondents are professionals working in precast production, such as general manager, production manager and plant engineer. Also, 13 respondents agreed to be interviewed via telephone. Table 3.1 lists the targeted precasters, the respondents and their designations, and the respondents interviewed.

Part of the preliminary results from the questionnaire survey and interview are summarized in Table 3.2. These results are used as supporting materials to infer distinctive features of precast production, establish objectives and performance measurement for precast production planning, and develop an integrated planning and scheduling model in the following sections.

Table 3.1: Targeted Precasters and Respondents in Questionnaire Survey and Interview

S/N	Targeted precasters	Survey respondents	Designation	Phone interview
1	CAA Technologies Pte Ltd	✓	General manager	✓
2	Chip Eng Seng Contractors (1988) Pte Ltd	✓	Precast manager	✓
3	Construction Technology Pte Ltd	✓	Engineer	✓
4	Eastern Pretech Pte Ltd	✓	Planning engineer	✓
5	ECI Corporation Pte Ltd	✓	Production manager	✓
6	Excel Precast Pte Ltd	✓	Plant engineer	✓
7	Fermold Pte Ltd	✓	Technical director	✓
8	Hanson Precast (S) Pte Ltd	✓	Operations manager	✓
9	HDB Prefabrication Technology Centre	✓	Senior executive engineer	-
10	Hong Leong Asia Ltd	✓	Production engineer	-
11	Hor Kew Pte Ltd	✓	Senior production executive	✓
12	L&M Precast Pte Ltd	✓	Engineer	✓
13	Singapore Precast Pte Ltd	✓	Operations manager	✓
14	Bilcon Industries Pte Ltd	✓	Executive director	✓
15	Precast Technology Pte Ltd	✓	Engineer	✓
16	Eastern Union Trading & Sawmill Co Pte Ltd	-	-	-
17	Grc & Construction Pte Ltd	-	-	-
18	Group Industries Pte Ltd	-	-	-
19	G&W Concrete Products Pte Ltd	-	-	-
20	Sunway Concrete Products (S) Pte Ltd	-	-	-
21	Syscon Pte Ltd	-	-	-
22	Techprecast Pte Ltd	-	-	-
Total	22	15	-	13

Table 3.2: Part of Results from the Questionnaire Survey on Current Practices in Singapore's Prefabrication Industry

	Questions and possible answers	Nos of responses to each answer	% of responses to each answer
Q1.1	Production system(s) adopted in your company		
	(a) Make-to-order (MTO)	15	100%
	(b) Make-to-stock (MTS)	2	13%
Q1.2	Among different types of activities involved in precast production, which one is the critical process?		
	(a) Preparation of materials	0	0%
	(b) Casting of PCs	15	100%
	(c) PC finishing	0	0%
	(d) Others	0	0%
Q1.3	Critical resource(s) in PC production		
	(a) Mould	15	100%
	(b) Labour	15	100%
	(c) Crane	8	53%
	(d) Casting space	1	7%
Q1.5	Time needed to make preparation (including shop drawing preparation, mould fabrication, etc) before production for a newly-received precast project?		
	(a) < 4 weeks	2	13%
	(b) 4~7 weeks	5	33%
	(c) 8~11 weeks	6	40%
	(d) 12~15 weeks	7	47%
	(e) > 15 weeks	3	20%
Q1.6	Time to keep PC in stock before delivery to site (in days)		
	(a) < 1 week	1	7%
	(b) 1~2 weeks	7	47%
	(c) 3~4 weeks	9	60%
	(d) 1~2 months	6	40%
	(e) > 2 months	1	7%
Q1.7	Delivery due dates of PCs are		
	(a) Prescribed by the contractor and must be met by precaster.	15	100%
	(b) Provided by the contractor and negotiable between each other.	6	40%
Q1.8	Curing method in PC production:		
	(a) PCs are cured through a natural process in the open air.	15	100%
	(b) PCs are cured with artificial curing facilities.	0	0%
Q2.1	Mould system adopted in plant		
	(a) Stationary moulds	15	100%
	(b) Movable moulds	0	0%
Q2.2	For a precast project, is it reasonable to assume that a mould can be used through the entire project duration?		
	(a) Yes	15	100%
	(b) No	0	0%

Questions and possible answers		Nos of responses to each answer	% of responses to each answer
Q2.3	Time needed for mould fabrication (in weeks)		
	(a) 1~2 weeks	4	27%
	(b) 3~4 weeks	5	33%
	(c) 5~8 weeks	9	60%
	(d) 9~12 weeks	3	20%
Q2.4	% of sharable moulds in a precast project		
	(a) 0~20	2	13%
	(b) 20~40	7	47%
	(c) 40~60	4	27%
	(d) 60~80	1	7%
	(e) 80~100	1	7%
Q2.5	Mould changeover on sharable mould is		
	(a) Sequence-dependent	15	100%
	(b) Sequence-independent	0	0%
Q2.6	Are identical or similar PCs often produced continuously to reduce mould changeovers?		
	(a) Yes	15	100%
	(b) No	0	0%
Q3.2	In labour planning, do you tend to keep labour size in plant stable?		
	(a) Yes	15	100%
	(b) No	0	0%
Q3.3	Are PCs divided into groups for ease of production?		
	(a) Yes	15	100%
	(b) No	0	0%
Q3.4	How to divide PCs into groups?		
	(a) PCs from one project are grouped together	3	20%
	(b) PCs of similar types are grouped together	15	100%
Q3.5	Do labour sizes in different PC groups need to be adjusted periodically to meet requirement of PC production?		
	(a) Yes	15	100%
	(b) No	0	0%
Q3.6	Number of working shifts used in precast production		
	(a) 1	13	87%
	(b) 2	2	13%
	(c) 3	0	0%
Q3.7	How often do labour work overtime?		
	(a) Always	5	33%
	(b) Frequently	8	53%
	(c) Sometimes	2	13%
	(d) Seldom	0	0%
Q3.8	Do labour work at least 8 hours per day?		
	(a) Yes	15	100%
	(b) No	0	0%
Q3.9	Form of labour organization adopted for PC casting		
	(a) Comprehensive organization	13	87%
	(b) Specialization organization	2	13%

	Questions and possible answers	Nos of responses to each answer	% of responses to each answer
Q4.1	Planning and scheduling method used for precast production		
	(a) Trial-and-error method based on experiences	15	100%
	(b) Others	0	0%
Q4.2	Which one is more significant for precast production? Capacity planning or material planning?		
	(a) Capacity planning	15	100%
	(b) Material planning	0	0%
Q4.4	Is it reasonable to say that final production schedules are satisfying or optimal if all precast demands are fulfilled with a minimum production-related cost?		
	(a) Yes	15	100%
	(b) No	0	0%
Q4.7	Relationship between mould quantity calculation and labour size calculation in production planning		
	(a) Mould quantity and labour size are determined at the same time.	0	0%
	(b) Mould quantity is determined at first. Then, labour size is determined.	15	100%
	(c) Labour size is determined at first. Then, mould quantity is determined.	0	0%
Q4.9	Do you make monthly forecasting of unknown demand in production planning?		
	(a) Yes	9	60%
	(b) No	6	40%
Q4.10	Forecasting of unknown demand can be made		
	(a) For every typical PC type.	0	0%
	(b) In terms of precast volume (m3) in plant.	9	100%
Q4.12	What are the criteria used to determine PC production sequence?		
	(a) PC with least mould changeover is produced first.	12	80%
	(b) PC with earliest due date is produced first.	15	100%
	(c) PC with shortest processing time is produced first.	1	7%
	(d) PC with lowest stock cost is produced first.	1	7%
	(e) PC with least demand volume is produced first.	1	7%

3.2 Distinctive Features of Precast Production

Compared to manufacturing processes in other industries, prefabrication has its own distinctive features, which should be taken into specific account in model development for precast production planning and scheduling. The following characteristics are drawn from Singapore's prefabrication industry. For each characteristic, the supporting results from the investigation are indicated.

3.2.1 Make-To-Order Production and On-Time Delivery

According to the response to Q1.1 in Table 3.2, precast concrete production is normally carried out in a make-to-order (MTO) manner in Singapore. That is, precast components (PCs) are custom-built according to individual customer specifications or project requirements. Before production for a project starts, precasters usually need to prepare shop drawings based on specification requirements provided by the customer (contractor or architect/engineer) and purchase moulds for various PCs involved.

Elements must be delivered to the construction site as required by their erection schedules, which usually overrides all other considerations in production planning (Warszawski, 1990). All the respondents of the questionnaire survey rate on-time delivery as the most important planning objective. This is because precast production in factory and precast erection on site are closely inter-linked. Late production and delivery of PCs or inconsistency between delivery sequence and erection schedule could result in delay to the project progress, and could cause the precaster substantial tardiness penalty and poor reputation. On the other hand, early production can be costly and unreasonable. Precast factories located in urban districts, such as those in Singapore and Japan, are faced with limited production and storage space. Besides, large PCs inventory leads to excessive capital holding cost as precasters cannot get paid until delivery of PCs to site.

3.2.2 Casting Process: the Heart of Precast Production

From the field study, it is learned that production in a prefabrication plant involves several different types of activities, including preparation of materials (such as concrete and reinforcement), casting of PCs (including consecutive operations of demoulding and mould preparation, rebar and cast-in-item fixing, concrete pouring, and curing), finishing of PCs, and their storage. Among them, casting process is the critical activity, which takes control of the pace of the entire production process (refer to Q1.2 in Table 3.2). It is where mould, the most essential resource, is used, and where a majority of man-hours available in plant are consumed. Therefore, as noted by Warszawski (1990), the planning usually focuses on casting of elements, which is perceived as the heart of the production process. Planning of other production activities are derived from a "master plan" of casting process. For this reason, only casting process is considered in the planning and scheduling model to be developed.

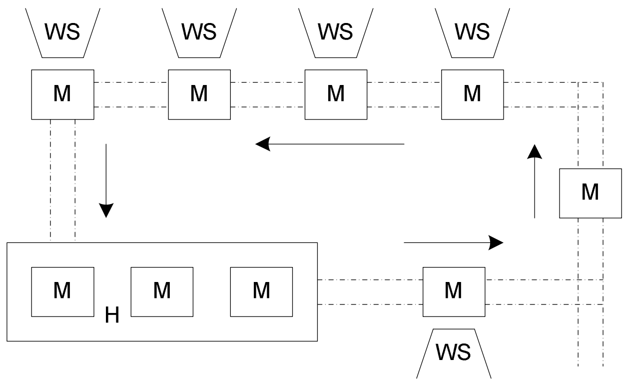
3.2.3 Two Critical Resources: Mould and Labour

Capacity planning in MRP, JIT, or OPT is usually based on one key resource, on which the choice of capacity measure depends. If the key resource is people, then man-hours can be defined as the unit of measure. In other instances, machine hours may be appropriate when a certain machine dominate the production process (Vollmann et al., 1997). Precast production, however, involves two critical resources, mould and labour, as shown in Q1.3 of Table 3.2. They dominate the production pace simultaneously or alternately. Mould is critical because it is used through the entire casting process. It is, however, very expensive so that precaster tends to reduce its quantity and thus purchasing cost. On the other hand, precast production is also a labour-intensive process, and precasters face the shortage of skilled labour. Q3.7 in Table 3.2 shows labour in the local industry usually work overtime in order to meet delivery schedule. Therefore, it would lead to a more accurate and comprehensive production planning if both mould and labour are taken into consideration and production capacity measured in terms of both labour size/hours and mould quantity/hours.

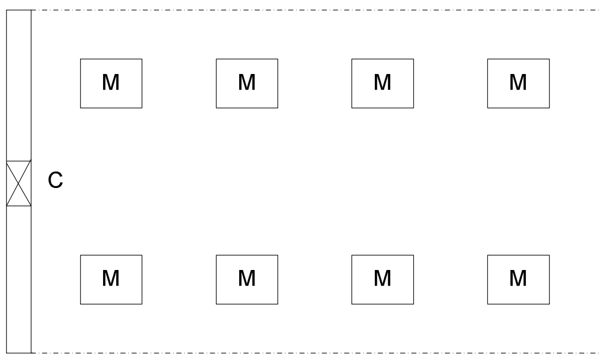
Compared to production materials, such as rebar and concrete, customized moulds and skilled labour are difficult to get, and play a significant role in controlling the production progress. Therefore, precasters agree that capacity planning is more important than material planning in precast production planning and scheduling, as shown in Q4.2 of Table 3.2. In practice, capacity plan and production schedule are first established, from which material plan is derived. For this reason and to simplify the model, material planning is not the focus of this research.

3.2.4 Employment of Stationary Mould System

There are two basic types of mould system employed in precast plants: (1) stationary moulds where every mould is set up in a certain place and all basic casting operations are performed in this place, and (2) movable moulds where the moulds are moved on a rolling line or a conveyor from one work station to another, with different operations performed at each of them (Warszawski, 1990). The two systems are illustrated in Figure 3.1(a) and 3.1(b) respectively, adapted from Warszawski (1990). In general, movable moulds require higher expenses on investment, operation and maintenance, but lower labour size and less working space than stationary moulds. A movable mould system is applicable for MTS production with a steady output and relatively homogeneous product line. On the contrary, a stationary mould system is less sensitive to diversity and continuity of production and can be flexibly employed in both MTS and MTO environments. For this reason, in Singapore context, all precasters adopt stationary mould systems for precast production, as indicated by Q2.1 in Table 3.2.



(a) Movable Moulds



(b) Movable Moulds

Note: M = Mould; WS = Workstation; H = Heating chamber; C = Overhead crane

Figure 3.1: Mould Systems

(Adapted from Warszawski, 1990)

3.2.5 High Percentage of Sharable Moulds and Frequent Mould Changeovers

Depending on whether they are sharable or not among PCs, moulds are generally classified into two categories: exclusive mould and sharable mould. An exclusive mould can only be used to produce one specific PC type, whereas a sharable mould may be used for two or more types of PC types. In PC production, a PC can be produced on an exclusive mould, a sharable mould, or both. In order to reduce mould investment, however, precasters tend to put PCs of similar types together and assign them to a sharable mould. Thus, some exclusive moulds can be replaced with fewer sharable moulds, leading to a high percentage of sharable moulds with lower mould purchasing cost. While the percentage of sharable moulds in precast projects may vary depending on different production requirement, it usually ranges from 20% to 60%, as indicated by Q2.4 in Table 3.2. A large number of sharable moulds inevitably result in more frequent mould changeovers, which are required by production from one PC type to another on a sharable mould. Time and cost for mould changeover depends on PC production sequence on the sharable mould. That is, it is not only affected by the PC to be produced on the mould, but also by the proceeding PC just finished on the mould. Although precasters try to reduce it in planning, mould changeover cannot be completely avoided, especially for urgent demand. Q4.12 in Table 3.2 reveals that precasters normally use EDD (earliest due date) rule followed by LMC (lowest mould changeover) rule in determining PC production sequence on moulds. Therefore, a planning method should be able to efficiently assign PCs to various moulds, as well as allocate time for sequence-dependent mould changeover as needed.

3.2.6 Division of PCs and Labour into Groups

The responses to Q3.3, Q3.4 and Q3.5 in Table 3.2 show that, in order to increase the working efficiency for MTO production, local precasters usually divide various PCs to be produced into several groups, each including same or similar types of PCs. The working skills required to cast PCs in one group are thus alike. During production, labour in the plant are allocated into different PC groups accordingly. Within one group, either comprehensive or specialization organization is adopted, as explained below. Labour size under one group remains unchanged in a short period, say 1 week, so that the labour are devoted to specific PC types during this time period. In this way, working efficiency is improved. Certainly, in order to meet the dynamic demands of various PCs and to fully utilize the labour available in the plant, labour sizes in different PC groups are adjusted on a periodically rolling basis, say weekly, which forms a part of the planning work.

3.2.7 Wide Adoption of Comprehensive Labour Organization

There are two alternatives of casting organization in plant, comprehensive and specialization (Warszawski, 1990). Under comprehensive alternative, all operations are performed by the same crew. After an element is cast, the crew moves to the next mould and starts to work on it from the beginning. Under the specialization alternative, the total process is broken down into several operations which are performed by different crews with specialized tools and work methods.

As a multi-task approach, comprehensive organization may be less efficient than specialization method in terms of labour and equipment utilization. The approach, however, is better adapted to production of heterogeneous (in terms of shape and size) elements. The fact that cross-trained workers can carry out all operations in a casting cycle of various PCs makes "capacity" quite flexible, so that changes in PC demand quantity and PC type are more easily handled. Also, comprehensive organization has the advantages of undivided responsibility of the crew for the total product and independence among different crews during production. On the other hand, as shown in Warszawski (1990), the specialization method usually requires multiple working shifts and artificial curing facilities. This is not the case in the Singapore context, where a warm climate exists all year round and precasters tends to operate under one working shift using natural curing process to avoid excessive investment on special curing facilities. These explain why 13 out of 15 precasters in the questionnaire survey choose to adopt the comprehensive organization for casting PC, as indicated by Q3.9 in Table 3.2. This research focuses on casting process with comprehensive organization, which can be represented by Figure 3.2.

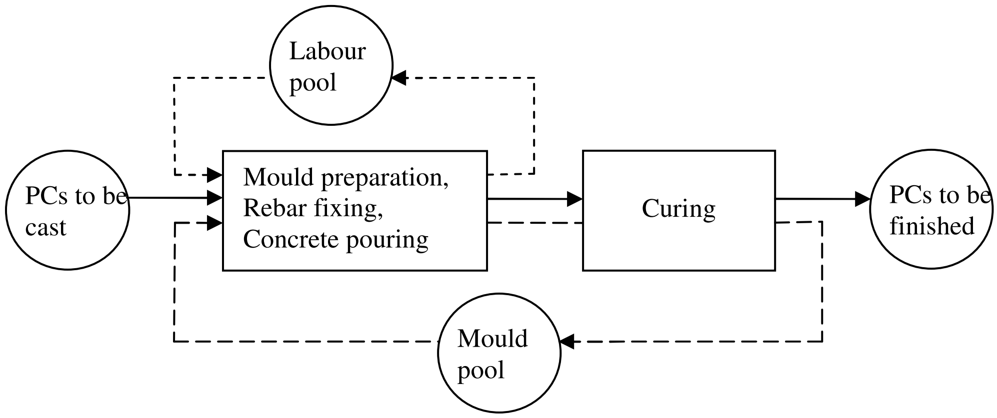


Figure 3.2: PC Casting Process under Comprehensive Organization

3.2.8 Four Categories of PC Demands

Based on the field study and interviews, demands of PCs can be divided into four categories as follows:

1. Existing demands, where PCs' types and quantities are already known, mould needed has been ordered or set up in casting place and the PC production either has been in progress or will start soon;
2. Newly-specified demand, where shop drawing is just finished and detailed PC information is specified and mould planning and purchase will have to be conducted before PC production starts;
3. Newly-received demand, where the order is just received, and the shop drawing development and mould planning has to be done before its production;
4. Unknown demand, whereby the job is not secured yet. The demand is unknown to the precaster.

Since PC types and quantities of existing demand, newly-specified demand, and newly-received demand are actually known, they are jointly called actual demand. On the other hand, volume of unknown demand can be forecast with some forecasting method; therefore the unknown demand can also be referred to as forecast demand.

The timings of various demands vary according to the category of demands, as shown in Figure 3.3. Existing demands can be due anytime from now to some time into the future and therefore could be satisfied by production during the entire planning horizon. As for newly-specified demand and newly-received demand, their production cannot start within a short period (1 ~ 2 months) from now as it takes time to develop shop drawing and order moulds before production. Forecast demand is the latest among the four demand categories in terms of possible production time and delivery schedule. Therefore, it is safe to say that all PCs to be produced within 1 or 2 months in the near future belong to existing demands. As time goes by and new demands emerge, newly-specified demand and newly-received demand will evolve into existing demand, while forecast demand would be progressively consumed by new and existing demand. Certainly, the four categories of demand may overlap one another within the planning horizon, as shown in Figure 3.3.

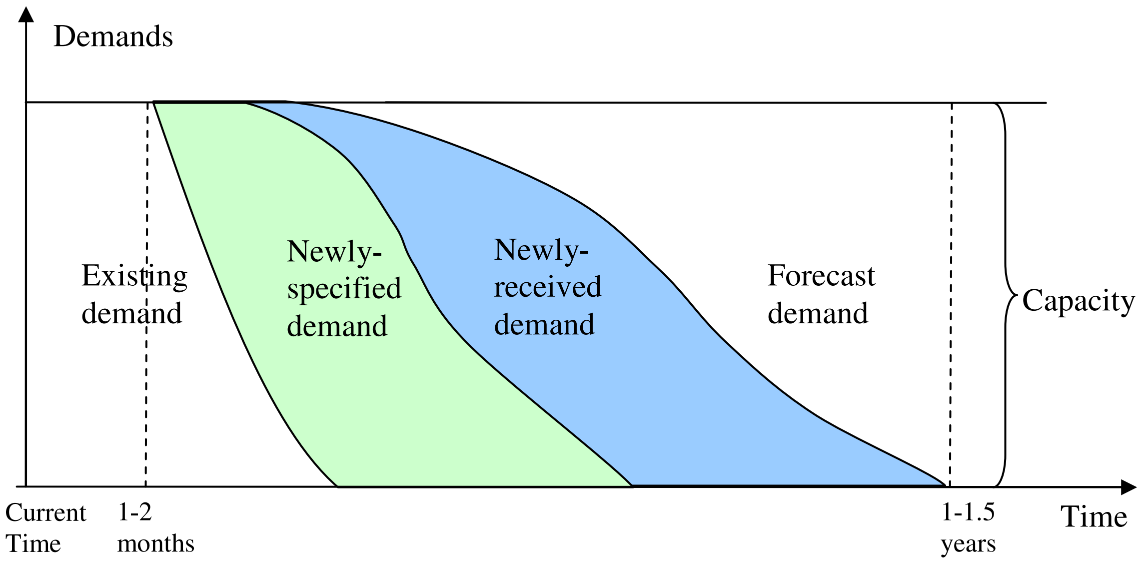


Figure 3.3: Four Categories of PC Demands

When resource plan and production schedule are developed, forecast of unknown demand should be considered together with actual demand, especially for intermediate or long-term planning. Actually in the questionnaire survey, over half the responding precasters make monthly forecast of unknown demand for about one year, as shown by Q4.9 in Table 3.2. The importance of considering unknown demand in production planning is attributed to the fact that unknown demand has a great impact on resource needed and production timings for actual demand both currently and in the future. For example, if the unknown demand is forecast to be a large volume in the next few months, current production for actual demand may need to be done with full capacity and even with overtime to make enough resources available for production of the forecast demand subsequently. On the contrary, if the forecast is a low volume in the near future, the PCs of actual demand should not be produced too early so as to increase PC inventory with no benefit. It might even be favorable to leave labour idle for some time in the case of shortage of forecast demand.

3.3 Planning and Scheduling Method Used in Practice

Dawood (1995) pointed out that, in practice most precasting companies use a simple trial and error approach to develop their production plans. This is also the case in Singapore.

3.3.1 Computer Software Used in Practice

According to the investigation on current practices in Singapore's precast plants, there is no advanced computerized approach for precast production planning and schedule available. Table 3.3 shows the computer software used by Singapore's precasters in precast production planning and scheduling. While precasters here do use computer software, such as MS Excel and MS Project, to assist their planning work, the main functions of the software are in data storage and retrieval, as well as report generation.

While MS Project is a popular project management programme, it cannot fully meet the requirements of planning and scheduling for precast production. For example, MS Project works under the assumption that the required resources (e.g., mould and labour) have been given. It is unable to answer the important questions in mould planning and labour planning, i.e., mould quantity for every mould type and labour size in every planning period. Moreover, when sharable moulds are involved, it, without human's intervention, cannot establish a reasonable plan for PC allocation and production sequence on every mould. Therefore, in practice, the planning and scheduling work is basically a manual work where MS Project, if used, only plays an auxiliary role. Usually, planners first establish a resource plan and production schedule based on experiences, and then input it into MS Project for storage and retrieval, as well as presentation.

Table 3.3: Main Functions of Computer Software Used by Singapore's Precasters

Precaster	Software	Main function		
		Data storage and retrieval	Report generation	Information sharing
C01	MS Project	✓	✓	
C02	MS Project	✓	✓	
C03	Excel	✓	✓	
C04	Intergrated production control system	✓	✓	✓
C05	N/A			
C06	MS Access	✓	✓	
C07	MS Excel	✓		
C08	MS Project	✓	✓	
C09	MS Access	✓		
C10	IMMS	✓		
C11	Exchequer	✓		
C12	MS Excel	✓	✓	
C13	MS Excel	✓		
C14	MS Excel	✓	✓	
C15	MS Project	✓	✓	

3.3.2 Actual Planning and Scheduling Method

Planning and scheduling for precast production is basically a manual work done by planning engineers based on their experiences and some fundamental heuristic rules. Based on the questionnaire survey and interviews with Singapore's precasters, the basic planning and scheduling method used in practice usually contains the following steps:

1. Mould planning: Mould types are determined at first based on shop drawings. Then, for each mould type, mould quantity is estimated based on the average demand rate (the demand quantity on average per period over the planning horizon) of PC types that can be produced on the mould;
2. PC allocation: According to the master construction schedule, PCs are allocated to every mould as early as possible to fully utilize moulds and avoid any delay. PCs with earliest due dates (EDD) or requiring lowest mould changeover

(LMC) are dispatched first. Any mould changeover incurred is identified and mould hours are allocated as needed. Master production schedule is then established. If there is any delay incurred, extra mould(s) will be used, and PCs reallocated and master production schedule adjusted accordingly;

3. Labour planning: Based on the above master production schedule, the labour size in the plant is determined for every planning period, with the idea of keeping labour sizes as steady as possible. If in a certain period man-hours are not enough for production, overtime work will be needed;
4. Labour allocation: For ease of production, PCs are divided into different PC groups according to their similarity in dimension and type. Labour in plant are assigned to each PC group. In each group, comprehensive organization is adopted and it is preferable to keep labour with a particular mould for production of all PCs assigned to it. Certainly, labour sizes are adjusted among different PC groups, say weekly, to meet production requirements and to fully utilize available labour;
5. PC sequencing: PC production sequence on every mould is adjusted when exact PC delivery dates are given. EDD rule and LMC rule are also adopted to sequence PC with EDD being the 1st priority rule and LMC the 2nd. Particular time required for mould changeovers are allocated. Through this process, detailed PC production schedule is generated.

In the above method, steps 1, 2, and 3 are usually done for an intermediate planning horizon, while steps 4 and 5 are conducted for a short-run planning horizon.

3.3.3 Problems with Actual Method

Since in practice the planning and scheduling work is basically carried out on a rule-of-thumb basis, different planners would give different solutions to the same problem. Therefore, it cannot guarantee a good result, let alone an optimal one. Other potential problems with actual planning method are listed below:

- Mould planning, PC allocation and labour planning are done separately to simplify the planning work. It may not achieve a satisfying or good enough solution to the overall planning problem.

- In labour planning, the intention to keep labour size stable over periods may require extra overtime for production, leading to large overtime cost.
- Both master and detailed production schedules are generated with forward scheduling method, which attempts to fully utilize resources and produce PCs as early as possible. Unnecessary OT cost and excessive stock cost may be incurred during the scheduling process.
- Traditional PC dispatching rules may not be able to generate satisfying solution in all occasions. It is worth further exploration to improve the production schedules.

Chapter 4

Conceptual Development of Integrated Planning and Scheduling Model (IPSMPP)

4.1 Objectives of Planning and Scheduling

The research aims to establish a special-purpose planning and scheduling model for MTO precast production where a comprehensive casting organization is adopted. For this purpose, the model, to be called integrated planning and scheduling model for precast production (IPSMPP), should capture the distinctive features of precast production. Also, production planning and scheduling at both mid-term tactical level and short-term operational level should be integrated. In detail, the model should be able to facilitate precasters to accomplish the following objectives of precast production planning and scheduling:

(1) Zero Tardiness

Timely delivery is regarded as the primary objective of production planning and scheduling. Therefore, the production schedules should meet due dates of every PC without any tardiness.

(2) Improvement of Mould Planning

Two critical resources, mould and labour, should be taken into account in capacity planning. Mould can be planned in both mid-term and short-term. In mid-term, proper mould numbers should be determined for every mould type involved in every precast project. In short-term, PC assignment and production sequence on every mould should be such that time and cost incurred in mould changeovers is minimized.

(3) Enhancement of Labour Planning

Likewise, labour planning is also carried out in two stages. In mid-term, the objective is effective determination of labour size for the whole plant. In short-term, it aims to efficiently utilize these labour by properly assigning them to different PC groups, executing PC production with as much normal time as possible, and reducing overtime consumption.

(4) Minimization of PC Inventory

To reduce storage holding cost, the schedule to be developed should keep the PC inventory at a minimum level and within the space constraint.

The significance of the above objectives is justified by the questionnaire survey with precasters in Singapore. In Question 4.3 of the survey, respondents were required to rate relative importance of these objectives in precast production planning and scheduling on a scale of 4 to 0, with 4, 3, 2, 1 and 0 representing "Most Important", "Very Important", "Moderately Important", "Slightly Important" and "Irrelevant" respectively. Based on their ratings, the average importance of each objective was calculated, as shown in Table 4.1. As expected, all precasters cite "on-time delivery" as the most critical objective in precast production, which has the highest score of 3.93. The second significant objective is that production schedules should be feasible in terms of capacity (within resource constraints). It is obvious that should any resource be overburdened in the production schedule, production of certain PCs would have to be postponed, leading to late delivery. Though the other objectives in Table 4.1 have lower scores, they are still "Very Important" or "Moderately Important".

Obviously, accomplishments of some of these objectives may conflict with others. For example, continuous production of same PCs with one mould reduces changeover time on the mould but may increase PC storage. An early production of PCs, in case of a slack in demand, results in excessive inventory though it may take full advantage of available man-hours. These conflicts should be solved by the model in a sensible way.

Table 4.1: Relative Importance of Planning and Scheduling Objectives Rated by Singapore Precasters

Planning and scheduling objectives	Precasters' responses															Average
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Meet the delivery schedule / site demand	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	3.93
Ensure production schedules feasible in terms of capacity (within resource constraints)	3	4	3	3	3	4	4	3	4	3	3	3	4	3	3	3.33
Reduce mould quantity / investment	3	3	4	3	3	3	3	3	3	3	3	4	3	1	2	2.93
Reduce labour cost (for hiring/firing, normal time, overtime)	3	2	2	3	2	3	2	3	4	4	3	4	3	3	2	2.87
Fully utilize labour in plant	2	3	3	3	3	3	3	3	4	3	3	4	4	3	3	3.13
Minimize mould changeovers	3	2	3	2	3	2	3	3	4	2	3	2	3	2	3	2.67
Minimize PC inventory	2	3	2	2	2	3	2	3	3	3	3	3	3	2	2	2.53

4.2 Performance Measurement of Production Schedule

The fundamental requirement of precast planning and scheduling is that precast production schedule must be feasible with respect to capacity and due date, i.e., within capacity constraint and without any tardiness. In addition, economic consequences of alternative feasible schedules should be evaluated so that the best one can be selected for implementation. For this purpose, performance measurement scheme is established for evaluation of feasible schedules.

One major goal of a precast company is making money, i.e., maximizing profit. Under a MTO environment, the production and sale depend on every particular customer demand, and income from sale is basically fixed once an order is accepted, and fulfilled upon delivery of final products. Therefore, in order to accomplish the goal of profit maximization, the final production schedule should be such that demands for PCs are fully satisfied with a minimum production-related cost. This is a point agreed by all respondents in the questionnaire survey, as shown in Q4.4 of Table 3.2.

In practice, precasters usually keep a one- or two-day casting cycle. Therefore, work-in-process (WIP) inventory remains at a very low level and can be negligible, especially under comprehensive casting organization. Besides, it is assumed that material costs, costs of other equipment and tools, and overhead are fixed for a certain amount of demands during the planning horizon. Therefore, the variable costs involved in precast production that need to be measured in planning and scheduling essentially fall into three categories:

(1) Labour Cost

a. Hiring/Firing Cost

Cost incurred to hire or fire labour periodically to accommodate production requirements.

b. Normal Time (NT) Cost

Payment to labour for their working in normal working hours.

c. Overtime (OT) Cost

Costs associated with using manpower beyond normal working hours.

(2) Mould Cost

a. Mould Purchasing Cost

The cost of purchasing moulds for every precast project.

b. Mould Changeover Cost

Costs incurred in mould changeover during precast production, including costs for labour, material, and equipment needed.

(3) Stock Holding Cost

The cost associated with holding PCs in stock, including cost of handling and storage works and cost of capital freezing.

Thus, performance of a feasible schedule can be evaluated in terms of total variable cost incurred during production using the following formula:

Total variable cost = labour cost + mould cost + stock holding cost   Equation (4.1)

4.3 Integrated Planning and Scheduling Model

To achieve the above objectives, the integrated planning and scheduling model for precast production (IPSMPP) is developed as shown in Figure 4.1. The hierarchical levels, various modules and their working mechanisms are explained in the following sections.

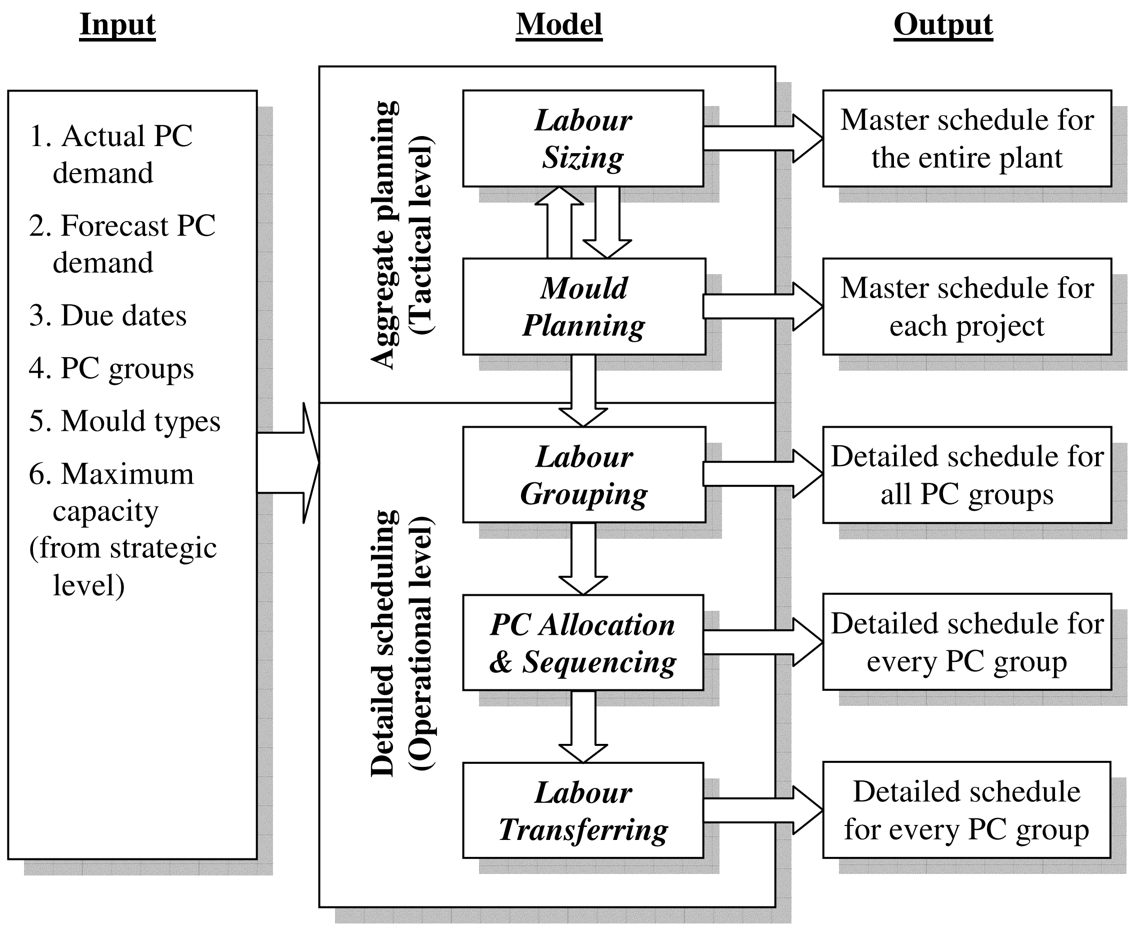


Figure 4.1: Integrated Planning and Scheduling Model for Precast Production (IPSMPP)

4.3.1 Two-Level Hierarchy

Hierarchical production planning (HPP) is adopted to establish the two-level model of integrated planning and scheduling for precast production. Introduced by Hax and Meal (1975), HPP is a planning philosophy and approach that breaks down a large overall planning problem into smaller, more manageable sub-problems according to decision-making levels. The sub-problems to be solved constitute a hierarchy of production planning process. Figure 4.2 gives a generic framework of hierarchical production planning process, adapted from Miller (2001). The higher levels of the hierarchy represent the planning problem in an aggregate, more global manner. In contrast, the lower levels of the hierarchy provide a more detailed description (Mehra, 1995). Problems at each level are solved in order from the top down, and solutions achieved (or decisions made) at one level are used as constraints to problems at the next level. In this way, HPP approach greatly reduces complexity of the planning work. Compared to the original monolithic problem, the sub-problems require significantly less modelling and computational effort. In implementation of HPP approach, production plans which appear feasible at an aggregate level can often contain hidden infeasibilities that only manifest themselves at lower, more disaggregated levels (Miller, 2001). Thus, the "top-down" HPP approach usually employs a "bottom-up" feedback mechanism to communicate and finally remove the potential infeasibility in planning among different levels.

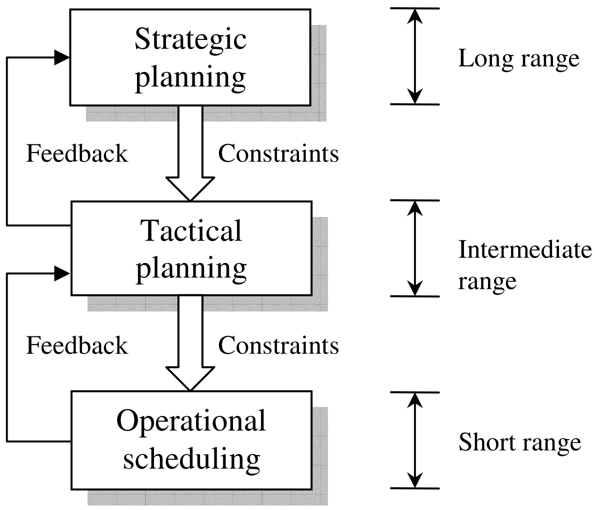


Figure 4.2: Generic Framework of Hierarchical Production Planning

(Adapted from Miller, 2001)

One main principle of HPP is that the planning hierarchy is consistent with decision-making levels in the organization. The generic framework of HPP may span all the 3 levels, namely, strategic planning, tactical planning, and operational planning and scheduling, as shown in Figure 4.2. This relationship between the planning and management hierarchies results in better organization and management of personnel and a clear demarcation of responsibilities in the manufacturing system (Mehra, 1995). In addition, it reduces the need for detailed information at a high level, where only aggregate information appropriate to the decision to be made should be provided.

In IPSMPP, the overall planning and scheduling process is structured into two levels, tactical level and operational level, as shown in Figure 4.1. During planning, mid-range aggregate planning at the tactical level is carried out at first. Then, subject to the constraints imposed by aggregate plan, short-term detailed scheduling is done at the operational level. Table 4.2 gives the general information of the two-level hierarchy. At the tactical level, planning work focuses on effective determination of labour size and mould quantity and development of master production schedule to meet PC demands for a 6~18 month planning horizon. Both actual and forecast demands for PCs falling in the planning horizon are taken into account by the aggregate planning. On the other hand at the operational level, detailed scheduling is concerned with efficiently allocating and utilizing labour and moulds, and reasonably sequencing and scheduling daily production operations. It is done only for a short planning horizon of 4~8 weeks. Only the existing demand from actual demand is considered due to the make-to-order nature of precast production, as explained in section 3.2.8 in Chapter 3.

Table 4.2: Two-Level Hierarchy

	Medium-term aggregate planning	**Short-term detailed scheduling**
Management level	Tactical	Operational
Planning focus	○ Labour size ○ Mould quantity ○ Master production schedule	○ Labour and mould allocation & utilization ○ PC production sequencing & scheduling
Planning horizon	6-18 months	4-8 weeks
Planning period	1~2 months	1 week
Demand	Actual and forecast	Existing

4.3.2 Maximum Capacity Constraint from Strategic Level

Though IPSMPP focuses on production planning and scheduling at the tactical and operational levels, it serves to assure the accomplishment of long-term objectives in a precast plant, and thus is bound by the decisions made at the strategic level. In

IPSMPP, the maximum capacity (PC volume per week/month) represents a collective constraint that is transferred from the strategic level to the tactical level. According to the pilot field study in this research, the maximum capacity a precast plant can achieve is mainly determined by the plant's infrastructure (such as batching plant, casting space, and storage space), long lead-time equipment (such as crane), production technology, material supply network, and financial condition (capital), as shown in Figure 4.3. Decisions on these factors are usually made by the top management and collectively shaped into a maximum capacity restricting the production activities at the lower levels.

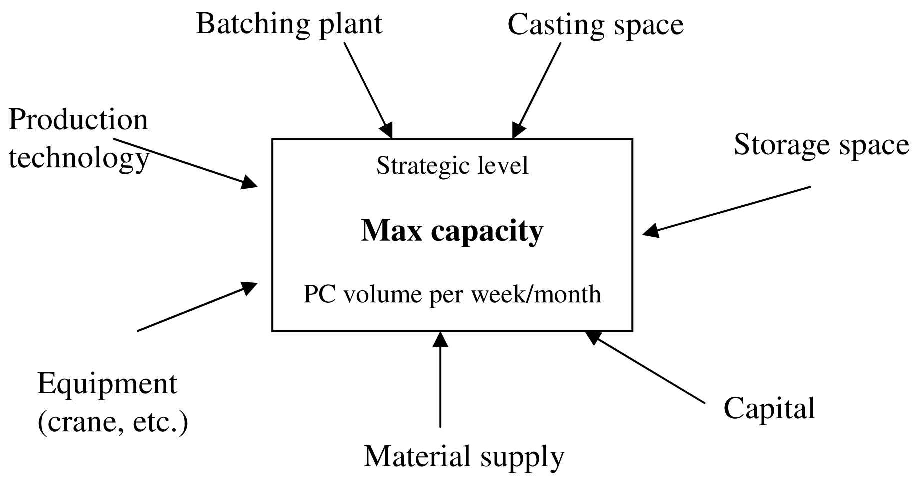


Figure 4.3: Factors Influencing the Maximum Capacity of Precast Plant

4.3.3 Five Modules

For implementation purpose, five modules are developed, (i) *Labour Sizing* (ii) *Mould Planning* at the tactical level, (iii) *Labour grouping*, (iv) *PC Allocation & Sequencing* and (v) *Labour Transferring* at the operation level. Using every module, the corresponding production schedule in Figure 4.1 can be obtained, which is not only feasible with respect to capacity and due date, but also optimal or satisfying in terms of total variable cost. As shown in Figure 4.1, the five modules are arranged in a hierarchical way indicated by directed arrows so that the outputs of one module become the inputs and constraints to the next module.

4.3.3.1 Modules at Tactical Level

As explained in Chapter 3, there are two critical resources, mould and labour, involved in PC production. Therefore, both mould planning and labour planning should be incorporated in aggregate planning. The mould quantity and labour size obtained from aggregate planning should then be efficiently utilized through detailed scheduling.

At the tactical level, *Mould Planning* and *Labour Sizing* have different planning purposes. This research focuses on make-to-order precast production. Different precast projects involve different PCs, requiring customized moulds for their production. Thus, *Mould Planning* is project-based, and aims to determine proper mould quantity for every mould type in a newly-specified project. On the other hand, within a plant, cross-trained labour are used and shared among different projects and different PC groups. Labour size needs to be changed periodically to satisfy PC demands for the whole plant. Therefore, *Labour Sizing* is plant-based, and used to calculate reasonable labour size and maximum allowable OT hours for the entire plant in every planning period along the planning horizon.

4.3.3.2 Modules at Operational Level

PC production is a dual-resource constrained (DRC) system, with mould and labour as critical resources. Two assumptions are made for labour in precast production scheduling:

- Labour in precast plant are cross-trained with multiple skills and can execute all operations in casting process of any PC type;
- There is no time delay in transferring labour from one mould to another.

Thus, labour transfer delay is not considered in this research. In addition to dispatching rule, operating policies for precast production scheduling should include decisions regarding labour flexibility, and “when” and “where” rules for labour transfer. To be specific, *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring* are established to deal with labour flexibility, PC dispatching, and labour transfer, respectively in IPSMPP.

As stated by Treleven (1989), labour flexibility can be modelled in variety of ways, including the machine-staffing level, the efficiency of labour that are transferred, the degree of centralized labour control, and the number of machines to which a labour can be transferred. This research considers labour flexibility mainly in terms of mould-staffing level. In aggregate planning, mould quantity for every precast project and labour size in plant are generated by *Mould Planning* and *Labour Sizing* respectively. Thus, the mould-labour ratio for the entire plant is established. Furthermore, as discussed in Chapter 3, in order to increase the working efficiency, labour in plant are usually assigned into different PC groups periodically, and engaged in PC production in one group until they are reassigned to other groups. In fact, the periodical assignment of labour is an effective way to control mould-stuffing levels in every PC group, and thus to adjust labour flexibility, for a short period. *Labour Grouping* module is established to model this kind of labour flexibility. In addition to assigning suitable labour sizes to different PC groups, *Labour Grouping* determines maximum allowable OT hours for each group in every planning period.

In precast production, the “when” and “where” rules regulate the way labour in a PC group are transferred to every mould involved. Between the two basic versions of “when” rules (centralized rule and decentralized rule), centralized rule clearly is more flexible than decentralized rule in transferring worker to other worker centers (Kher and Fry, 2001). Studies have been made to measure their efficiency in DRC systems and Hottenstein and Bowman (1998) concluded that centralized control marginally reduces flow-time mean and variance as compared to decentralized control. Therefore, centralized rule is adopted in this research for detailed scheduling for PC production.

Compared to the question of when to transfer an eligible cross-trained worker, where the worker should be transferred has a greater impact on shop performance (Hottenstein and Bowman, 1998). Thus, the “where” labour transfer decision is one major concern in this research for detailed scheduling. Although quite a few “where” rules have been proposed in DRC literature, such as the longest queue (LQ) rule and the earliest due date (EDD) rule, there is still possibility for schedule performance improvement. *Labour Transferring* is designed, aiming to generate a reasonable priority for transferring labour to moulds in every PC group.

In PC production, after labour are transferred to a certain mould, decisions have to be made to dispatch PCs waiting for processing on the mould. Various job dispatching rules have been established for DRC systems. Specifically for precast production scheduling, EDD/LMC rule seems to be the most suitable dispatching rule, as it has been recommended by several researchers (such as Warszawski, 1990 and Chan and Hu, 2002) and justified by the questionnaire survey (see Q4.12 in Table 3.2). Nevertheless, *PC Allocation & Sequencing* is proposed in this research to further explore the potential of better PC production sequencing on every mould. Before dispatching production on each mould, all PCs need to be properly assigned to every eligible mould, which is also one of the functions of *PC Allocation & Sequencing*. The objective of *PC Allocation & Sequencing* is to establish a good balance between mould changeover and PC stock, and finally achieve a lower total variable cost.

4.4 Working Mechanism of Every Module

Having been designed with different functions, the five modules on the two-level hierarchy have similar internal working mechanisms.

4.4.1 Simulation-GA Based Approach

All the five modules are based on simulation and genetic algorithm (GA), as shown in Figure 4.4. Simulation and GA are different techniques for modelling and optimization respectively. They are integrated together to form a specialized approach for precast production planning and scheduling.

The power of simulation lies in its capability to accurately represent capacity and current status of a system. Therefore, it has experienced widespread use as a finite capacity approach to remedy the weakness of MRP (Ying and Clark, 1994). More importantly, it allows to model and investigate real-world systems that are too complex to be studied by a mathematical model, as noted by Law and Kelton (2000). In IPSMPP, two discrete-event simulation engines, Simulation(A) and

Simulation(D), are designed for production schedule development at the tactical level and the operational level respectively. Special priority rules are developed and imbedded in the two engines for considerations of mould requirements and availability during the scheduling process. Moreover, in contrast to traditional scheduling models based on single-pass forward simulation, both Simulation(A) and Simulation(D) take multiple (forward and backward) scheduling passes to reduce excessive OT usage and PC stock.

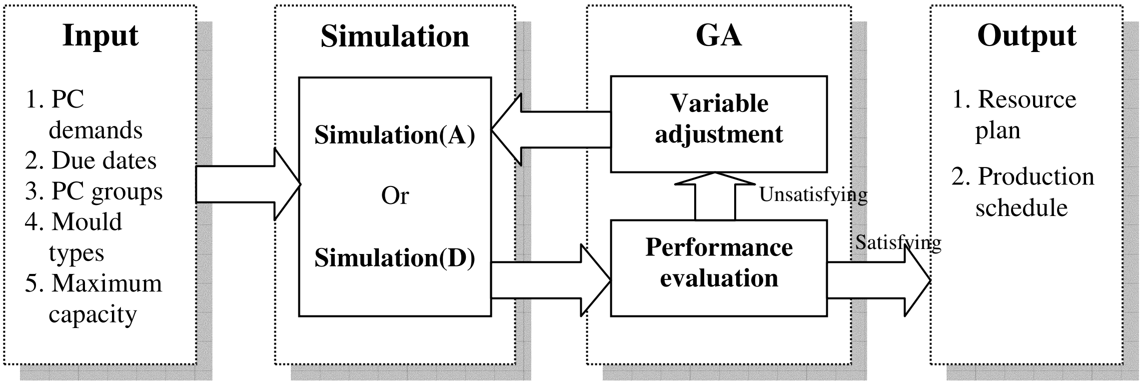


Figure 4.4: Simulation-GA Based Approach for Every Module

Genetic algorithms (GA) are powerful and broadly applicable stochastic search and optimization techniques based on the principles from evolution theory (Gen and Cheng, 1997). They have been successfully applied in many areas to solve complex problems that are difficult to solve by conventional optimization techniques. The general procedure of GA is explained in Chapter 2.

Different modules involve different decisions variables, as discussed above. However, during planning process in every module, even if values of the relevant decision variables (e.g., mould quantity and labor size) are given, the correpsonding production schedule still cannot be determined automatically. Some questions (e.g., in what sequcne PCs should be allocated and to which mould) still remain open. Particular operating rules or heursitics, have to be applied in a scheduling process to finally generate the production schedule. To overcome this difficulty, the approach of combining simulation and GA is adopted in this researh to solve all the sub-problems involved in each module.

The scheduling process of each module is an iterative procedure of progressive improvement, as shown in Figure 4.4. During one scheduling iteration, Simulation(A) or Simulation(D) arrives at production schedules with given values of a set of decision variables involved, while GA evaluates the performance of the resultant schedules, and based on this, adjusts values of the decision variables for the simulation and selects the better ones for the next iteration. The scheduling cycle is repeated until a satisfying or optimal solution is achieved.

While a pure GA could be adopted for problem-solving, it would not work as efficiently as the Simulation-GA based approach. In this case, all the planning burdens, i.e., determination of both the main decision variables and the operating policies, would be placed on GA. Thus, the planning focus of the module (to give the values of the main decision variables) would be diverted. More importantly, there would be too many variables involved. The searching space would become too large for GA to get a feasible schedule, let alone a satisfying one.

4.4.2 Differences between Simulation(A) and Simulation(D)

Both Simulation(A) and Simulation(D) belong to discrete-event simulation. Designed to apply to aggregate planning and detailed scheduling respectively, Simulation(A) and Simulation(D) work differently in terms of level of modelling detail, simulation clock advancing, priority rules adopted, mould and labour requirements, and scheduling pass, as shown in Table 4.3.

Determining at what level of detail a complex system should be modelled is very important in development of a simulation model. It has a direct impact on effectiveness and efficiency of the model. To answer this question, a tradeoff would have to be made between creating a credible model for effective decision making and making it efficient to develop and run such a model. Generally, the level of modelling detail should depend on project objectives, performance measures, data availability, computer constraints, time and money constraints (Law and Kelton, 2000). In this research, aggregate planning focuses on developing a master schedule for PCs within an intermediate planning horizon (6~18months), whereas detailed planning aims to establish a detailed schedule for operations involved in every PC production in a short-term horizon (1~2 months). Therefore, it is reasonable to set the minimum modelling detail of Simulation(A) and Simulation(D) as individual PCs and operations respectively.

Table 4.3: Differences between Simulation(A) and Simulation(D)

	Simulation(A)	**Simulation(D)**
Planning level	Tactical	Operational
Level of modelling detail	Precast component (PC)	Operation
Means of advancing simulation clock	Fixed-increment algorithm (FIA)	Next-event algorithm (NEA)
Labour requirement	Man-hours per PC	Labour quantity and hours per operation
Mould requirement	Mould hours of a certain mould per PC	Mould hours of a certain mould per operation
Priority rule	Single rule to assign PC to mould together with labour	Double rules for labour transfer and PC dispatching
Scheduling pass	Multiple passes: forward → backward	Multiple passes: forward → backward → forward

There are two approaches to advancing simulation clock in discrete-event simulation, next-event algorithm (NEA) and fixed-increment algorithm (FIA), as introduced in Chapter 2. With NEA, simulation clock is advanced only at the times of event occurrences. In simulation-based production system modelling and scheduling, NEA can accurately process events and capture dynamics of shop status, such as execution of individual operations of every job and job queuing on every machine. Therefore, NEA is used in Simulation(D) for detailed scheduling at the operational level. On the other hand, Simulation(A) adopts FIA for simulation clock advancing. With this approach, the simulation clock is advanced in increments of exactly Δt time units, and any events that have occurred during a certain time interval of Δt are considered to occur at the end of the interval (Law and Kelton 2000). Since aggregate planning for precast production is carried out for an intermediate time period (6~18 months), it makes no sense to consider individual operations and PC queuing on every mould, which would complicate the problem modelling and solving process. With an appropriate choice of Δt (e.g., one week), FIA allows aggregate planning to be performed at the PC level.

With different levels of modelling detail, Simulation(D) and Simulation(A) consider resource requirements for PC production in different ways. To accurately represent production at the operational level, Simulation(D) needs to model resource requirements by every single operation in terms of labour quantity and hours, as well as mould hours of a certain mould. On the other hand, resource requirement can be compactly represented in terms of mould hours and man-hours per PC in Simulation(A), corresponding to the PC level of modelling detail.

Proper priority rules need to be set up in order to run a discrete-event simulation. PC production scheduling is actually a DRC problem with mould and labour as critical resources. Therefore, as in conventional DRC scheduling, two sets of priority rules are used in Simulation(D) for transferring labour to moulds and dispatching PCs on every mould respectively. On the other hand, in order to simplify the modelling process, a single priority rule is used in Simulation(A) to assign PCs to every mould together with labour needed. This treatment is similar to that in traditional machine-limited scheduling, which uses the same rule for labour assignment and job dispatching decisions (Holstein and Berry, 1972).

In addition, while both Simulation(A) and Simulation(D) take multiple scheduling passes, the numbers of scheduling passes are different. Simulation(A) takes two scheduling passes, including a forward simulation to generate a feasible schedule, and a backward simulation to improve the forward schedule. On the other hand, Simulation(D) has three scheduling passes, including two forward simulations and one backward simulation. The 1st forward simulation is conducted first to generate a feasible detailed schedule. Then the backward simulation proceeds with the aim to improve the 1st forward schedule. Finally, the 2nd forward simulation is used to repair the backward schedule and make it applicable. How Simulation(A) and Simulation(D) work will be explained in detail in Chapters 5 and 6 respectively.

4.5 Transferring Feasibility from Aggregate Planning to Detailed Scheduling

As stated by Mehra (1995), the planning hierarchy seeks a detailed production plan which is: (1) consistent with the aggregate plan, i.e., it satisfies the target aggregate production volumes provided by the top level, (2) feasible for implementation, i.e., it satisfies all the constraints of the lowest level model, and (3) optimal in minimizing costs. Sometimes, an apparently feasible schedule that is produced at a high level can become infeasible at a lower level. In this case, the schedule should not be used for implementation since it would lead to capacity conflict or missing of due dates during the shop-floor production.

4.5.1 Aggregate Planning with Feedback Mechanism

In this research, in order to ensure the transferring feasibility from the tactical level to the operational level, a feedback mechanism is established and embedded in aggregate planning modules (*Labour Sizing* and *Mould Planning*). In addition, a large unit penalty cost is introduced into performance measurement for both master production schedule and detailed production schedule to take into account production delay so that a feasible schedule without delay would have a smaller fitness value than an infeasible schedule with delay. The scheduling procedure of aggregate planning with a feedback mechanism is given in Figure 4.5.

First, Simulation(A) in aggregate planning (*Labour Sizing* and/or *Mould Planning*) is carried out. Feasibility of the resultant master schedule is then measured in terms of the total variable cost $F(A)_c$ and the penalty cost for delay $F(A)_p$. If the schedule is infeasible, then the sum of $F(A)_c$ and $F(A)_p$, is transferred to GA as its fitness value. If it is a feasible schedule, Simulation(D) in *Labour Grouping* is implemented based on the parameters/constraints transferred from the master schedule. Then, the feasibility is checked for the detailed schedule. If it is infeasible with some delay, the sum of the penalty cost of the detailed schedule and the total variable cost of the master schedule, $F(D)_p + F(A)_c$, is used as the fitness value. Otherwise, the fitness value is set to $F(A)_c$. In the next step, performance of every master schedule is evaluated in GA according to its fitness value. The lesser the fitness value that a master schedule achieves, the more likely it is selected for the next generation. That is, the schedule that is feasible at both tactical and operational levels has better chances to survive and to finally evolve into the final solution than the schedule that is infeasible at either tactical or operational level. In this way, the final master schedule is guaranteed to be feasible at both tactical and operational levels, once it is found by GA.

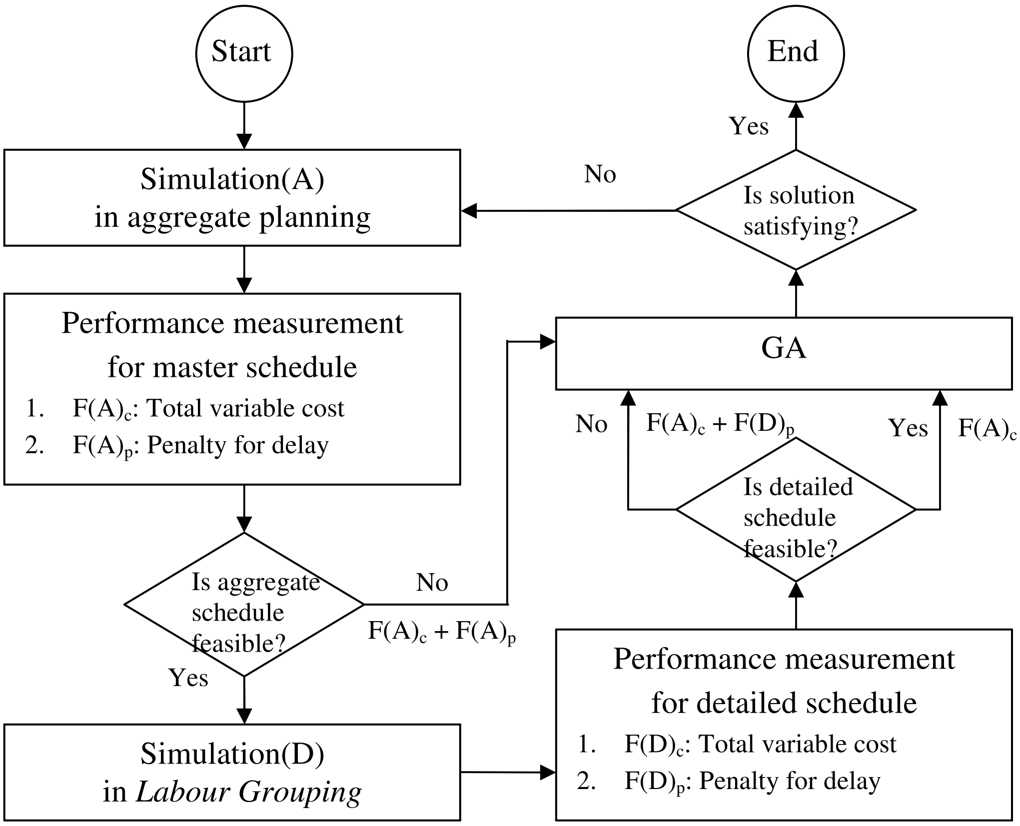


Figure 4.5: Scheduling Procedure of Aggregate Planning with Feedback Mechanism

4.5.2 Parameters from Aggregate Planning to Detailed Scheduling

In the scheduling procedure of aggregate planning with feedback mechanism, *Labour Grouping* is only carried out for a short-range planning horizon, which is usually equal to the first planning period of aggregate planning. Some parameters of the master production schedule during this period should be transferred as constraints to the operational level to launch *Labour Grouping*, as listed below:

1. PC types and quantity produced in the master production schedule.
2. PC assignment to every exclusive mould type and individual mould of every sharable mould type is transferred from aggregate planning to *Labour Grouping*. It should be noted that due dates of PCs used in *Labour Grouping* are more accurate than, and thus probably a little different from those in the aggregate

planning. PC production sequence on any individual mould of every sharable mould type given by a master schedule may not be reasonable anymore in a detailed schedule according to EDD/LMC rule. Therefore, it needs to be rescheduled in detailed scheduling based on the adjusted due dates.

3. In *Labour Grouping*, the max OT hour of every PC group in every planning period is set to the max OT hour in the corresponding period in the master production schedule. In a certain period, labour size in every PC group in *Labour Grouping* can be roughly determined based on the ratio of man-hours consumed in every PC group in the master production schedule, as shown in Equation (4.2).

$$L_{ij} = L_i^{all} \times \frac{H_{ij}}{H_i^{all}} \qquad \text{Equation (4.2)}$$

The parameters in Equation (4.2) are defined as follows:

- L_{ij} : Labour size of PC group j in Period i for *Labour Grouping*;
- L_i^{all} : Overall labour size in plant available in period i in the master production schedule;
- H_{ij} : Man-hours consumed by PC group j in period i in the master production schedule;
- H_i^{all} : Overall man-hours consumed by all PC groups in period i in the master production schedule.

Chapter 5

IPSMPP: Modelling for Aggregate Planning

5.1 Integrated Aggregate Planning

Aggregate planning focuses on planning work at the tactical level for an intermediate planning horizon. It contains two modules, namely *Labour Sizing* and *Mould Planning*, as shown in Figure 4.1. Both of the two modules are based on Simulation-GA approach, as explained in Chapter 4, and should be executed together to achieve a better performance.

5.1.1 Simulation(A)-GA Based Planning

Figure 5.1 presents a detailed structure of Simulation-GA based approach for *Mould Planning* and *Labour Sizing* at the tactical level in IPSMPP.

In this model, *Mould Planning* and *Labour Sizing* are combined together with master schedule development. As shown in Figure 5.1, Simulation(A) can generate master production schedules, based on inputs from GA. Then performances of the schedules are measured and transferred to GA. GA, in turn, selects a new set of schedules based on their fitness values, and adjusts values of various decision variables in *Mould Planning* (i.e., mould quantity) and *Labour Sizing* (i.e., labour size and max OT hour) for further schedule development.

5.1.1.1 Bidirectional Simulation(A)

Instead of a single-pass forward simulation, Simulation(A) uses a bidirectional process to produce master production schedules. In an iteration of Simulation(A), a forward simulation and a backward simulation are conducted consecutively. First, the forward simulation generates a feasible production schedule. Then, the schedule is improved by the backward simulation, as shown in Figure 5.1. How the forward simulation and the backward simulation work in Simulation(A) will be presented in detail respectively in the following sections.

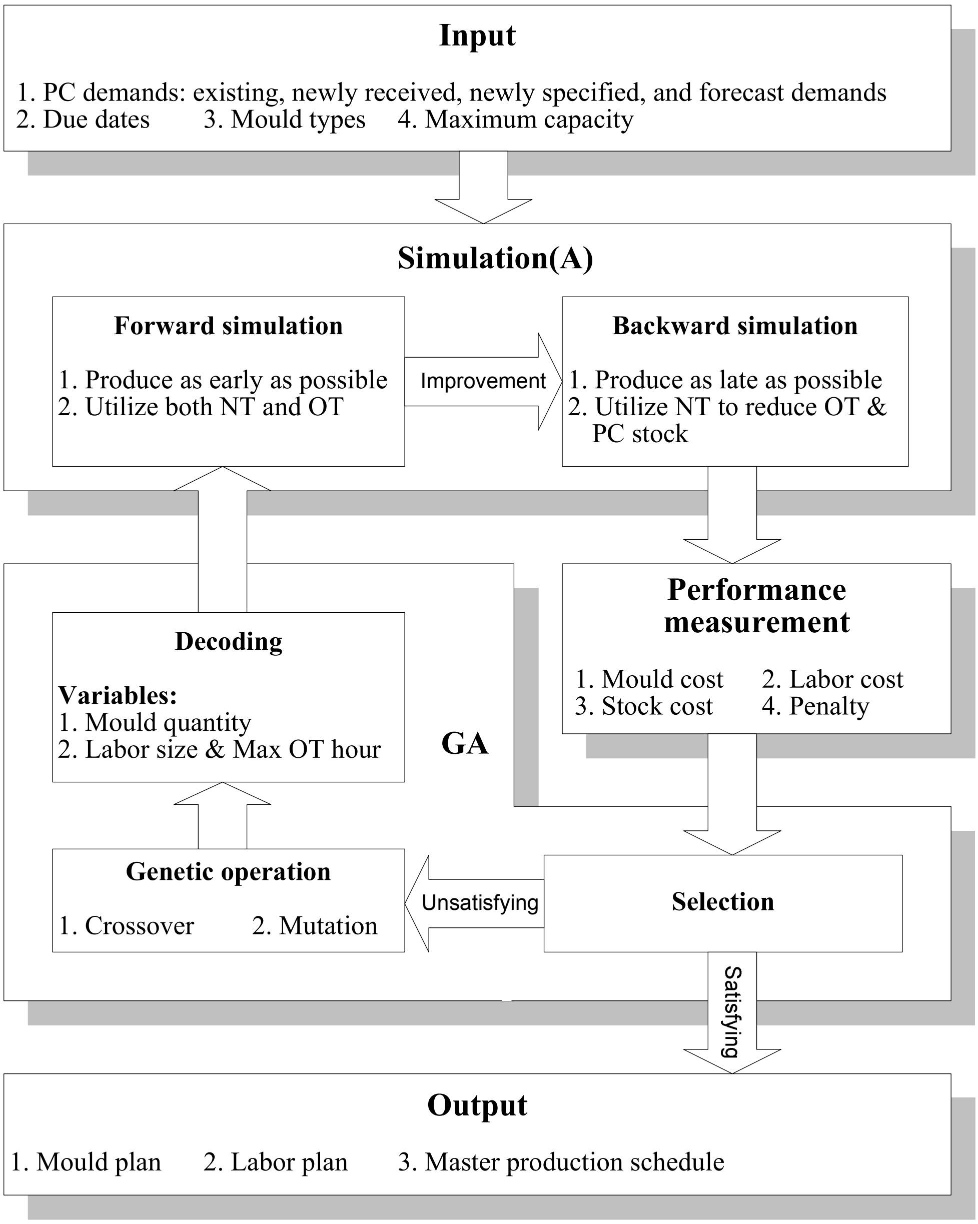


Figure 5.1: Simulation(A)-GA Based Approach for Aggregate Planning

As mentioned in Chapter 4, Simulation(A) for aggregated planning adopts FIA for simulation clock advancing. It should be noted that, two different time lengths are used in both the forward and backward simulations of Simulation(A) and defined as follows.

- Loading bucket (1 day ~ 2 weeks). It is a time interval for advancing system clock in Simulation(A). It is also used for setting PC due dates, i.e., PCs are assumed to be due for delivery at the end of a certain loading bucket. Since *Mould Planning* is very sensitive to PCs' due dates, loading bucket should not be too large (e.g., 1~2 months) to denote due dates accurately.
- Planning period (1 ~ 2 months): It is a time interval for labour planning. Labour size and maximum allowable OT hours are kept constant within one planning period and can only be adjusted over different periods. A planning period includes several loading buckets.

5.1.1.2 Three Subsystems in GA

The procedure of GA has been described in Chapter 2. GA applied for aggregate planning contains three consecutively executed subsystems, namely selection, genetic operation, and decoding, as shown in Figure 5.1. After a set of production schedules has been generated by Simulation(A), the objective costs of the schedules are calculated and then transferred to GA as fitness values of the corresponding chromosomes. From the chromosomes (both parents and offspring) in the current generation, some chromosomes are selected with selection subsystem based on their fitness values and form a new generation. If GA reaches the predetermined terminating condition(s), usually in terms of maximum number of generations, the entire planning process stops. Otherwise, genetic operation subsystem in GA starts to create offspring chromosomes in the new generation with two operators: crossover and mutation. At last, decoding subsystem is used to translate the chromosomes into values of the decisions variables (i.e., mould quantity in *Mould Planning*, and labour size and max OT hour in *Labour Sizing*), based on which the new schedules can be derived with Simulation(A) accordingly. The inner workings of GA will be further explained below.

5.1.1.3 Performance Measurement

The objective of production planning and scheduling is to meet the PC demand on time with a minimum total variable cost. As explained in Chapter 4, the total variable cost of a production schedule includes mould cost, labour cost and PC stock cost. Besides, a penalty cost is introduced to take into account production delay in an infeasible schedule. Thus, the sum of the total variable cost and penalty cost is set as objective cost, and used to measure performance of a schedule at both tactical level and operational level. The objective cost of a master schedule at the tactical level, C(A), can be calculated using the following objective function:

$$Min: \quad C(A) = C_{labor} + C_{mould} + C_{stock} + C_{penalty} \qquad \text{Equation (5.1)}$$

In Equation (5.1), C_{labor}, C_{mould}, C_{stock} and $C_{penalty}$ represent labour cost, mould cost, PC stock cost, and penalty cost for delay respectively and can be obtained as follows:

$$C_{labor} = \sum_{t=1}^{T} (c^L \alpha w_t L_t + c^O O_t + c^H H_t + c^F F_t) \qquad \text{Equation (5.2)}$$

$$C_{mould} = \sum_{m=1}^{M} c_m^D D_m \qquad \text{Equation (5.3)}$$

$$C_{stock} = \sum_{t=1}^{T} \sum_{p=1}^{P} c_p^I v_t I_{t,p} \qquad \text{Equation (5.4)}$$

$$C_{penalty} = N \sum_{t=1}^{T} \sum_{p=1}^{P} v_t U_{t,p} \qquad \text{Equation (5.5)}$$

The definitions of variables and parameters in Equations (5.2) ~ (5.5) are given below:

$t = 1, 2, ..., T$: loading bucket in the planning horizon;

$p = 1, 2, ..., P$: type of PCs;

$m = 1, 2, ..., M$: type of mould in *Mould Planning*;

α : normal working hours per man day;

w_t : number of working days in bucket t;

v_t : number of days in bucket t;

c^L : cost of normal working time per man-hour;

c^O : cost of overtime working per man-hour;

c^H : hiring cost per worker;

c^F : firing cost per worker;

c_m^D : purchasing cost of mould type m per mould;

c_p^I : inventory cost of PC type p per PC per day;

L_t : number of workers available in plant in bucket t;

H_t : number of workers hired at the beginning of bucket t;

F_t : number of workers fired at the beginning of bucket t;

O_t : overtime hours consumed by all workers in bucket t;

D_m : quantity of mould type m;

$I_{t,p}$: inventory level of PC type p at the beginning of bucket t;

$U_{t,p}$: Quantity of PCs from PC type p that are due before or in bucket t but have not been produced by bucket t;

N : large penalty cost for delay per PC per day;

It should be noted that in precast production costs incurred for mould changeover may include costs for labour, material and equipment needed. To simplify the modelling work, only labour cost is considered in the model for mould changeover.

5.1.2 Integration of *Mould Planning* and *Labour Sizing*

In Figure 5.1, *Mould Planning* and *Labour Sizing* can be done separately as different planning problems and at different points of time. That is, *Mould Planning* is carried out whenever the shop drawing preparation for a precast project is finished and PCs involved are specified, while *Labour Sizing* is executed periodically for the entire plant. By contrast, *Mould Planning* and *Labour Sizing* can be integrated and conducted together to achieve a satisfying solution to the problems as a whole. In this case, decision variables in both *Mould Planning* and *Labour Sizing* are all determined by GA. When *Mould Planning* or *Labour Sizing* is conducted alone, final resource plan and master schedule are obtained under the constraints of the other resource. The plan is only a locally good solution and could be improved when the constraints of the other resource are changed. On the other hand, when the two planning problems are integrated and solved together, many more production alternatives under various combinations of mould quantities and labour sizes can be explored and evaluated. Thus, the integrated aggregate planning has a better chance to achieve a satisfying solution in a broad sense than individual *Mould Planning* and *Labour Sizing*. Table 5.1 presents different roles that mould type, labour size and max OT hour play in *Mould Planning*, *Labour Sizing*, and integrated planning respectively.

Table 5.1 Roles of Parameters in Individual and Integrated Planning

Parameters	*Mould Planning*	*Labour Sizing*	Integrated Planning
Mould quantity for every mould type	V	C	V
Labour size & max OT for the plant in every period	C	V	V

Note: "V" represents variables in GA;
"C" represents predetermined constraints.

5.1.3 Consideration of Various Demands

According to Section 3.2.8 in Chapter 3 and Section 4.3.1 in Chapter 4, PC demands involved in aggregate planning include existing demand, newly-specified demand, newly-received demand, and unknown demand. Based on their own characteristics, these demands are dealt differently in aggregate planning in terms of PC used to represent each demand, resource considered and *Mould Planning* needed, as shown in Table 5.2.

Table 5.2: Consideration of Various Demands in Aggregate Planning

Demands		**Representative PC**	**Resource considered**	***Mould planning***
Actual	Existing	Real individual PC	Mould & labour	No
	Newly-specified	Real individual PC	Mould & labour	Yes
	Newly-received	Typical PC for PC category	Labour	No
Forecast	Unknown	Typical PC for plant	Labour	No

Since detailed information of individual PCs has been disclosed through shop drawing development for existing demand and newly-specified demand, real individual PC can be used in aggregate planning to represent the demands. On the contrary, "Typical PC" is defined to represent newly-received demand and unknown demand respectively in aggregate planning, since detailed information of individual PCs is not completely known for these two demands at the time of planning. A "Typical PC" can be thought of as, on average, consuming the same amount of resource (man-hours) and having the same stock holding cost as every single PC in a demand to represent.

When a new project is received, the exact PC types have not been identified for production and shop drawing has to be conducted to specify individual PCs. Nevertheless, design drawings from the client do provide some general PC information, such as preliminary PC types and dimension. PCs of similar PC types and dimensions can be grouped together as a specific PC category. In this research, "Typical PC for PC category" is used to represent every PC category involved in a newly-received project. As for unknown demand, it is difficult to make an accurate forecast in terms of PC types or categories due to the make-to-order nature of PC production. The forecasting accuracy, however, can be considerably increased when the demand is forecast in an aggregate way (Vollmann et al., 1997). For this purpose, unknown demand is forecast for the entire plant collectively and "Typical PC for plant" is used as its representative in the planning. This treatment is consistent with the fact that precasters tend to make monthly forecast of unknown demand in terms of PC volume (m3), instead of PC types, as indicated by Q4.10 in Table 3.2.

The mould type and quantity cannot be determined until shop drawing for a new project is finished and PCs involved specified. Therefore, both labour and mould can be used in planning as resources needed by existing demand and newly-specified demand. Furthermore, *Mould Planning* has been finished for existing demand and needs to be carried out for newly-specified demand only. On the other hand, for newly-received demand and unknown demand, *Mould Planning* cannot be done due to lack of detailed PC information and labour is used in planning as a single resource for their production.

5.2 The Forward Simulation

In this process, the master production schedule is generated with forward simulation with fixed-increment time advance. Therefore, PCs can be produced as early as possible by fully utilizing resources available.

In the simulation, priority rules are heuristics used to determine PC loading sequence due to scarce resources. The commonly used traditional rules and a novel priority rule, the critical PC (CP) rule, for forward simulation are given below.

5.2.1 Traditional Rules

There are several traditional priority rules that have been widely accepted in the literature (e.g., Warszawski 1984, Warszawski 1990, Dawood, 1995, Chan and Hu 2002) and adopted for precast production in practice. Three main rules are listed below:

1. Earliest due date (EDD) rule: PCs are loaded based on their due dates and those with earliest due dates are loaded first. This is to ensure PC demand is satisfied without any delay.
2. Lowest mould changeover (LMC) rule: PCs requiring low mould changeovers get high priority in the simulation process. It aims to minimize mould changeover cost.
3. Lowest stock cost (LSC) rule: PCs are loaded based on their unit stock-holding costs, and those with lowest stock-holding cost are produced first. It is used to reduce PC stock-holding cost.

In the forward simulation, the above three rules are usually used consecutively, with EDD being the 1^{st} rule, followed by LMC and LSC. The order corresponds to the relative importance of their planning objectives.

5.2.2 CP Rule

In PC production, moulds are a most critical resource. A mould is only dedicated to PCs of one type or a few similar types, and a PC could be produced on an exclusive mould, a sharable mould, or both at the same time. In such an environment, mould requirements and availability should be carefully considered in deciding on PC production sequence and allocation to moulds. Traditional rules may not work well due to the lack of such considerations. The CP rule is designed to solve this potential problem with the traditional rules.

5.2.2.1 Three PC Classes with Different Criticalities

The underlying principle of CP rule is that PCs should be loaded in a sequence of criticality. With CP rule, all PC types to be loaded are divided into 3 classes according to their criticalities:

1. Due date-related critical PCs (D_PC). D_PC is those PC types with PC due dates earlier than or equal to current loading bucket (CB). They are most urgent PCs and should be loaded in CB first, otherwise delays will be incurred or increased;
2. Mould-related critical PCs (M_PC). M_PC is defined as PC types that are potentially critical due to the lack of moulds. If they are not loaded at CB, there would probably not be enough mould hours available for their production at later buckets;
3. Non-critical PCs (N_PC). The PC types other than D_PC and M_PC are N_PC and could be produced at a bucket later than CB without incurring any delay.

D_PC can be easily identified according to its definition. M_PC are recognized by a special backward loading of PCs, where the mould is used as a single resource, as explained in the following section. It should be noted that mould is not used as resource in the proposed model for PC production for newly-received demand and forecast demand. Therefore, M_PC belong to either existing demand or newly-specified demand.

5.2.2.2 M_PC Identification Procedure

The idea of identifying M_PC is based on loading PCs onto corresponding moulds backward from their due buckets to CB+1. During the backward loading, for every bucket from the last bucket to CB, the amount of PCs with their due dates later than the bucket, but with their production to be incurred at the bucket and earlier bucket(s), is defined as "PC Gap" at the bucket. PC_Gap@CB is used to represent PC Gap at CB. After the backward loading, if there is any amount of PC left to be loaded at CB (i.e., PC_Gap@CB is greater than zero), it indicates that PC demand cannot be satisfied with the mould at all the buckets later than CB and some PCs should be loaded at CB to avoid any delay. Actually, PC_Gap@CB result from the backward loading can be regarded as the minimum PC value that should be loaded at CB in the subsequent forward simulation in Simulation(A) to avoid any potential delay due to the lack of mould. Therefore, a PC type with a positive PC_Gap@CB is identified as M_PC and the PC_Gap@CB is used as its critical value (CV). It should be noted that, labour is not considered in the backward loading, as M_PC are used to signify PC criticality in terms of mould requirements and availability. Thus, the backward loading can be simplified with mould as a single resource, and represented by BLWMO (Backward Loading with Mould Only) in this research. There are two types of BLWMO in M_PC identification as follows:

- BLWMO_E: BLWMO that is conducted on an exclusive mould type;
- BLWMO_S: BLWMO that is conducted on a sharable mould type.

For M_PC identification, PC types from existing and newly-specified demands can be broken into 3 categories according to the mould type used:

- E_PC: PC type that can only be produced on an exclusive mould type;
- S_PC: PC type that can only be produced on a sharable mould type;
- B_PC: PC type that can be produced on both an exclusive mould type and a sharable mould type.

Parameters involved in M_PC identification are defined in Table 5.3, and an algorithm for M_PC identification is given in detail in Figures 5.2 to 5.6. Typically, M_PC identification is carried out in the following 5 consecutive procedures.

1. For every PC type p ($p = 1, 2, ..., P$), initialize PC demands for BLWMO_E and BLWMO_S, as shown in Figure 5.2;
2. On every exclusive mould type e ($e = 1, 2, ..., E$), conduct BLWMO_E for the corresponding PC type, resulting in PC_Gap@CB, as shown in Figure 5.3;

3. For every exclusive mould e ($e = 1, 2, ..., E$), if the corresponding PC type is B_PC with a positive PC_Gap@CB resulted from BLWMO_E, calculate PC transfer demand to be loaded on its sharable mould, as shown in Figure 5.4;
4. On every sharable mould s ($s = 1, 2, ..., S$), conduct BLWMO_S for all S_PC and B_PC types that can be produced with the mould, resulting in PC_Gap@CB, as shown in Figure 5.5;
5. For every sharable mould s ($s = 1, 2, ..., S$) with a positive PC_Gap@CB resulted from BLWMO_S, calculate max contribution amount and determine PC criticality for every related S_PC or B_PC type, as shown in Figure 5.6.

Table 5.3: Parameters for M_PC Identification

○ $t = 1, 2, ..., T$: loading bucket in planning horizon;
○ CB : current loading bucket. $1 \le CB \le T$;
○ $p = 1, 2, ..., P$: type of PCs;
○ $e = 1, 2, ..., E$: type of exclusive mould;
○ $s = 1, 2, ..., S$: type of sharable mould;
○ p_e^E : the PC type that can be produced with exclusive mould type e;
○ b_s : the number of PC types that can be produced with sharable mould type s;
○ $a = 1, 2, ..., b_s$: the serial number of PC types that can be produced with sharable mould type s;
○ $p_{s,a}^S$: the corresponding PC type of the a th PC type that can be produced with sharable mould type s;
○ m_p^E : exclusive mould type that can be used for production of PC type p.
○ m_p^S : sharable mould type that can be used for production of PC type p.
○ For every PC type p, if $m_p^E > 0$ and $m_p^S = 0$, then the PC type p is E_PC; if $m_p^E = 0$ and $m_p^S > 0$, then the PC type p is S_PC; if $m_p^E > 0$ and $m_p^S > 0$, then the PC type p is B_PC.
○ m_p^T : mould hours needed per PC of PC type p (excluding hours for mould changeover). It is assumed that every PC type in a PC family sharing a certain sharable mould s needs the same amount of mould hours for production, i.e., $m_{p_{s,1}^S}^T = m_{p_{s,2}^S}^T = ... = m_{p_{s,b_s}^S}^T$.
○ α_s : the multiplier to account for mould changeover time needed for PC production on a sharable mould type s. $\alpha_s \ge 1.0$. $\alpha_{m_p^S} m_p^T$ is the total mould hours needed for production of one PC p on sharable mould m_p^S (including hours for mould changeover).

- $d_{p,t}$: demand of PC type p at the end of bucket t.
- $d^E_{p,t}$: demand of PC type p at the end of bucket t to be loaded on exclusive mould.
- $d^S_{p,t}$: demand of PC type p at the end of bucket t to be loaded on sharable mould.
- For every PC type p, $d_{p,t} = d^E_{p,t} + d^S_{p,t}$; If $m^E_p = 0$, then $d^E_{p,t} = 0$ and $d^S_{p,t} = d_{p,t}$; if $m^S_p = 0$, then $d^S_{p,t} = 0$ and $d^E_{p,t} = d_{p,t}$;
- $e_{e,t}$: working hours of exclusive mould type e available at bucket t;
- $s_{s,t}$: working hours of sharable mould type s available at bucket t;
- g_t : PC Gap at bucket t on a certain mould type obtained from BLWMO. If $g_t = 0$, it is called g^0 and the corresponding bucket t is t^0. The minimum g_t among several consecutive buckets is represented by $g^{\min}$, and the bucket with $g^{\min}$ is $t^{\min}$. $g_{e,t}$, g^0_e, $g^{\min}_e$, t^0_e and $t^{\min}_e$ are for exclusive mould e, and $g_{s,t}$, g^0_s, $g^{\min}_s$, t^0_s and $t^{\min}_s$ are for sharable mould s.
- v^E_p (CV for E_PC type p): the amount of E_PC type p that is critical and should be tried for loading in CB, otherwise some delay is expected to be incurred due to lack of mould.
- $c^{\max}_p$ (MCA for S_PC or B_PC type p): the maximum amount that S_PC or B_PC type p would contribute to CV of its PC family.
- v^F_s (CV for PC family s): the amount of all related PC types $p^S_{s,a}$ ($a = 1,2,...,b_s$) in PC family s that is critical and should be tried for loading in CB, otherwise some delay is expected to be incurred due to lack of mould.

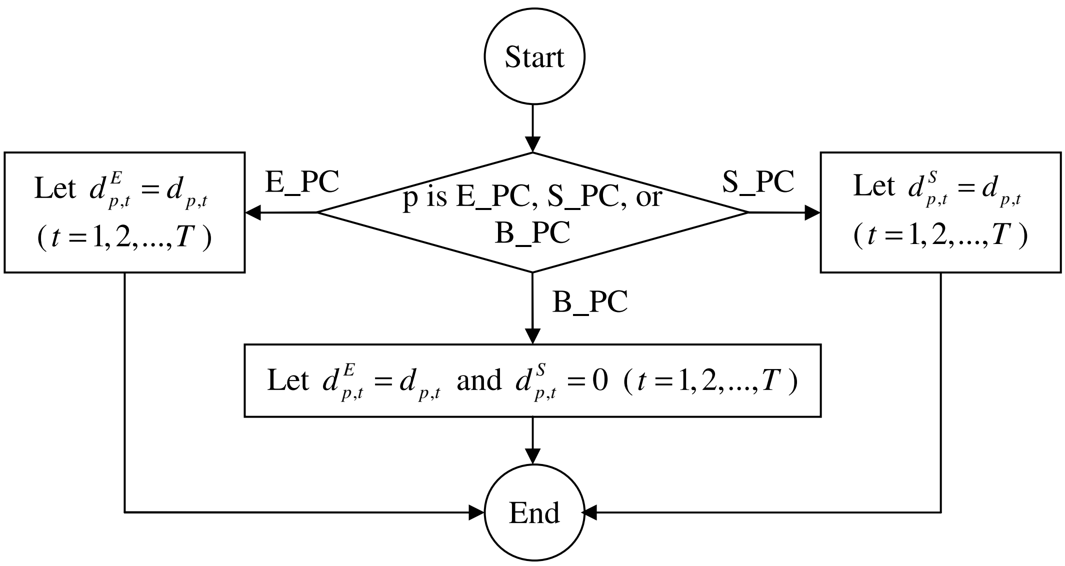


Figure 5.2: Demand Initialization of PC Type p for BLWMO_E and BLWMO_S

Before BLWMO_E and BLWMO_S, as revealed in Figure 5.2, PC demands need to be initialized such that all demands for an E_PC or S_PC type will be loaded on its exclusive mould or sharable mould respectively. For a B_PC type, on the other hand, all the demands should be loaded on its exclusive mould before part of the demands could be transferred to its sharable mould, as explained below.

For E_PC, the PC criticality and its CV can be easily identified with BLWMO_E, as shown in steps [1] ~ [13] of Figure 5.3. By contrast, for S_PC and B_PC, the M_PC identification process becomes a little complicated. All related PC types that can be produced on a certain sharable mould type form a PC family, and should be identified for M_PC together. A PC family with a particular sharable mould type may include S_PC and B_PC. Therefore, both BLWMO_E and BLWMO_S are performed to identify M_PC for all related PC types in a PC family.

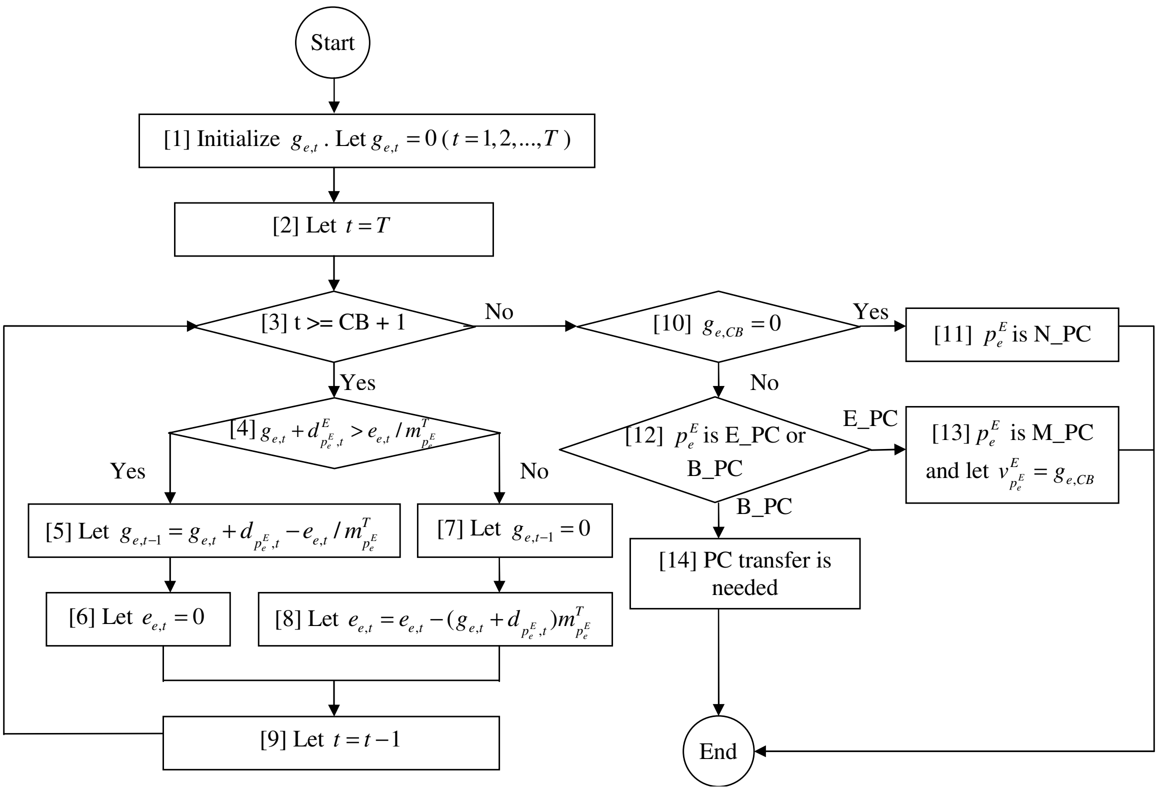


Figure 5.3: BLWMO_E on Exclusive Mould Type e

First, if there exists any B_PC in a PC family, BLWMO_E should be conducted for these PC types at first. As indicated by steps [10] ~ [14] in Figure 5.3, if no PC_Gap@CB is resulted for a PC type of B_PC, then the PC type is non-critical and identified as N_PC. On the other hand, if there is a positive PC_Gap@CB, the PC type is not necessarily critical because it can also be produced on the sharable mould type. Some PC demand has to be transferred to the sharable mould type to see if it can result any further CV.

The rules for transferring part of B_PC demand from an exclusive mould type to a sharable mould type are listed below:

- Rule 1: Any transferred demand should have contributed to a positive PC_Gap@CB in BLWMO_E, and total amount of the transferred demand is equal to the PC_Gap@CB.

  The rule aims to utilize the exclusive mould as much as possible, and transfer to the sharable mould only the part of PC demand that would lead to PC_Gap@CB in BLWMO_E and thus might be potentially critical in terms of mould requirements.

- Rule 2: The transferred demand, if any, should be distributed, within the planning horizon, as late as possible.

  This rule is used to minimize any potential PC_Gap@CB in the following BLWMO_S for the transferred demand by fully utilizing sharable mould hours available along the planning horizon. With a certain total amount, the transferred demand may vary in terms of its distribution along the planning horizon. Since BLWMO is carried out backward in time from the due dates of a demand, a demand with early due dates can utilize mould hours available only on the early stage, while a demand with late due dates can be assigned with mould hours on both early and late stages. Therefore, the later a transferred demand is distributed within the planning horizon, the more mould hours available after CB could be utilized and the lesser PC_Gap@CB would be incurred.

Based on the above rules, Figure 5.4 presents how to calculate PC transfer demand $d^S_{p_e^E,t}$ for a B_PC type p_e^E after BLWMO_E is finished on the corresponding exclusive mould type e. PC Gap at bucket t, g_t, is defined as the amount of PCs with their due dates later than bucket t, but with their production incurred no later than bucket t in BLWMO. This definition indicates that g_t is actually is the maximum PC amount that can be reduced from g_{t-i} ($i \geq 0$) by transferring production for any PC demand at any bucket $t+j$ ($j>0$) from one mould type to other mould types. Therefore, step [1] starts to search, from CB onwards, for the first bucket where $g_t = 0$, t^0 . PC demand at any bucket later than t^0 has no contribution to g_{CB} . That is , t^0 is, in the planning horizon, the latest bucket at which some PC demand have contribution to g_{CB}, and thus should be transferred to the sharable mould type to reduce g_{CB}. This is consistent with the 2nd rule for PC demand transferring. The amount of PC demand at t^0 to be transferred is set as the minimum PC Gap from CB to t^0-1, $g^{\min}$ at $t^{\min}$, as in steps [2] and [3]. This is because $g^{\min}$ at $t^{\min}$ will be reduced to zero after the demand transferring, and any extra reduction of PC demand at the later bucket t^0 would not have any influence on $g^{\min}$ and g_{CB}. Then, step [4] reduces g_t by $g^{\min}$ for every bucket from CB to t^0-1. $g^{\min}$ is reduced to zero and $t^{\min}$ becomes t^0. The process of PC demand transferring repeats until $t^{\min}$ is equal to CB, and g_{CB} is reduced to zero, i.e., the requirement of the above 1st rule is satisfied.

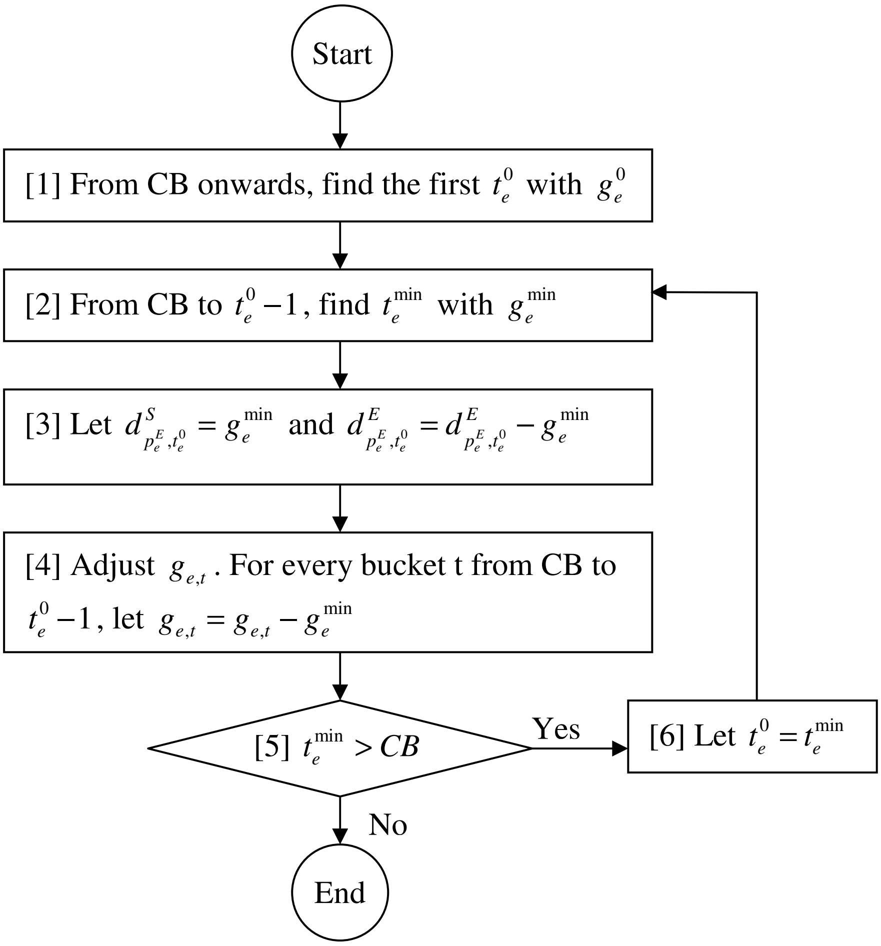


Figure 5.4: Calculation of PC Transfer Demand from Exclusive Mould e to Sharable Mould

After deciding on the transferred amount for every PC type of B_PC in a PC family, BLWMO_S is conducted for all PC types in the family, as shown in Figure 5.5. In BLWMO_S, only the transferred demand is loaded for a B_PC, while all demand is loaded for a S_PC. If there is no PC_Gap@CB result from BLWMO_S, then all related PC types are non-critical. On the contrary, if PC_Gap@CB is greater than zero, then the PC family can be identified as "critical" and the CV for the entire family is PC_Gap@CB. Final analysis needs to be made to determine which PC type in the family has contribution to the CV in BLWMO_S and which not.

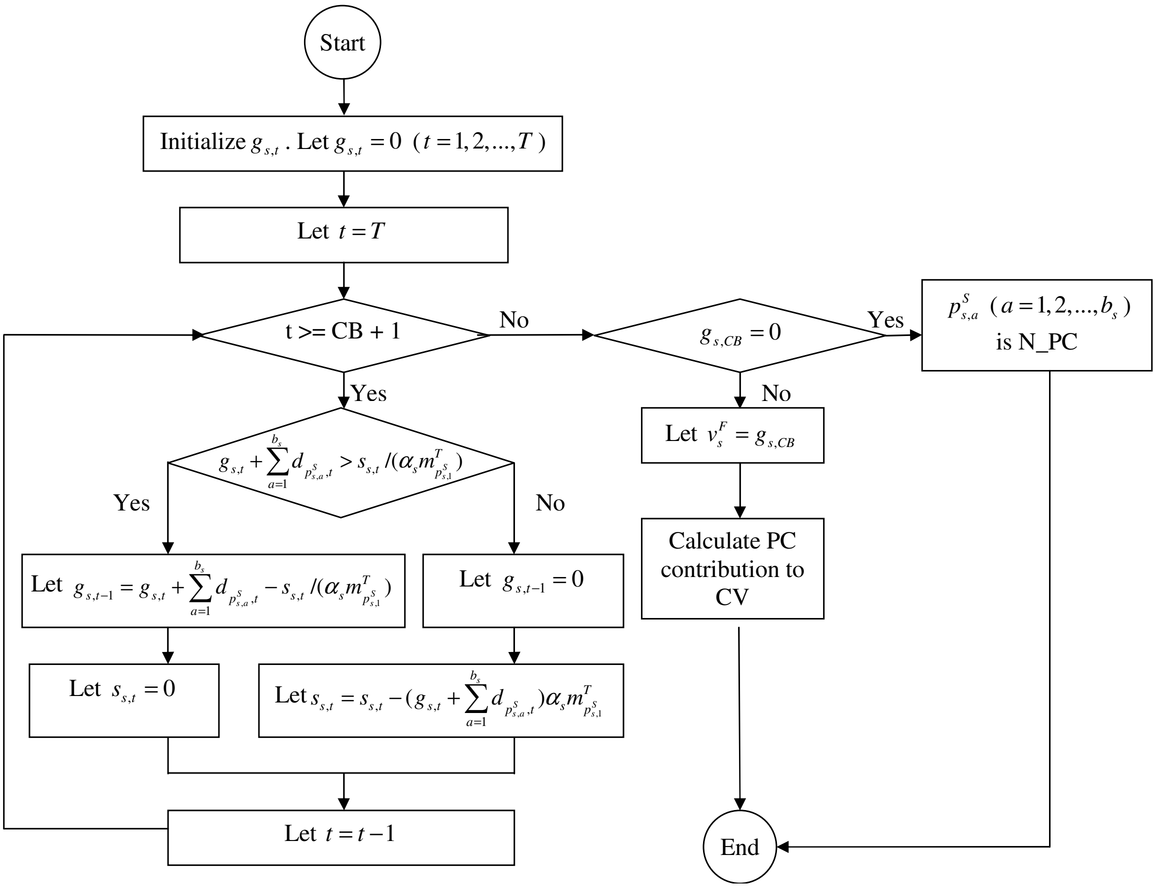


Figure 5.5: BLWMO_S on Sharable Mould Type s

If a PC type has contributed to the CV of the PC family, then it is regarded as M_PC. Also, the maximum amount the PC type could contribute to the CV, the max contribution amount (MCA), is calculated. On the other hand, if a PC type has nothing to do with the CV of the PC family, then it is identified as N_PC. Figure 5.6 shows the procedure to determine MCA for every PC type in a PC family with a positive PC_Gap@CB. In the procedure, the MCA of a PC type is calculated under three conditions as follows:

1. The MCA is less than or equal to the CV of the PC family;
2. The MCA is dependent on demands of the PC type allocated to the corresponding sharable mould type;
3. The MCA is subject to PC Gap at bucket t ($t \geq CB$) in that the contribution that PC demands at all the buckets later than t can make to PC_Gap@CB is not greater than PC Gap at bucket t.

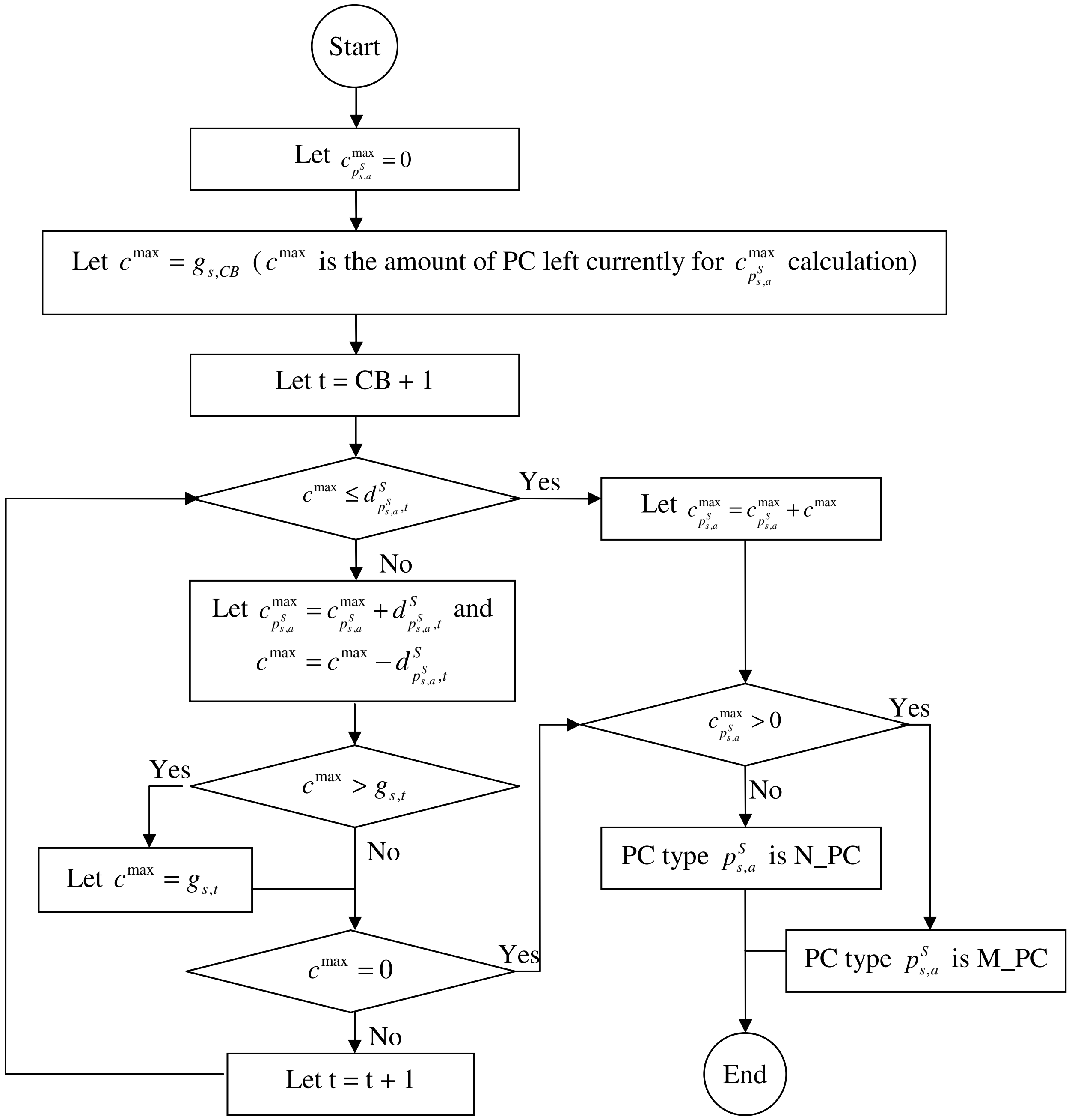


Figure 5.6: Determination of MCA and PC Criticality for PC Types on Sharable Mould s

It should be noted that the above-discussed M_PC identification algorithm is based on the assumption that every PC type in a PC family sharing a certain sharable mould needs the same amount of mould hours for production. When PC types in the PC family need different amounts of mould hours for production, a minor adjustment should be made to the algorithm for M_PC identification, as shown in Appendix D.

5.2.2.3 An Example for M_PC Identification

A simple example is given to illustrate the M_PC identification procedure, especially the PC demand transferring process in a PC family, as shown in Table 5.4. In this example, there are two PC types (P1 and P2) in a PC family, one exclusive mould (E1) and one sharable mould (S1). E1 is used for P1 only, while S1 is shared by both P1 and P2. Demand of P1 and P2 in the four buckets along the planning horizon is shown in the table. Mould changeover time on S1 is not considered in the example, and E1 and S1 have the same production capability (6 PCs per bucket). Assume the current bucket is bucket 1. Initial BLWMO_E is carried out to load all P1 demand onto E1, resulting in PC_Gap@CB equal to 10. Therefore, 10 P1 should be transferred to S1 to further identify criticality and MCAs for P1 and P2. Typically, the following three alternative plans could be used to transfer 10 P1 demand to S1, and then load P1 and P2 onto S1 with BLWMO_S.

First in Plan I, 10 P1 demand at the last bucket, bucket 4, is transferred onto S1. This plan is infeasible as there is still 6 PC_Gap@CB left in the adjusted BLWMO_E on E1 after demand transferring. According to the 1st rule of PC transferring, not only the total transferred demand should be equal to PC_Gap@CB in BLWMO_E, but also only the demand that has contributed to the PC_Gap@CB should be transferred. In the initial BLWMO_E, 4 PC_Gap at bucket 2 indicate that at most 4 out of 10 PC_Gap@CB are attributed to P1 demand at bucket 4. Therefore, it is useless to transfer more than 4 PC demand at bucket 4 for PC_Gap@CB reduction.

In Plan II, 10 P1 demand at bucket 2 is transferred on to S1, resulting in zero PC_Gap@CB in the adjusted BLWMO_E. BLWMO_S on S1 is conducted for P1 and P2, resulting in 14 PC_Gap@CB. It exceeds the overall capacity of E1 and S1 at CB, which is 12. Therefore, the 2 demand cannot be met at CB in the following Simulation(A), and Plan II is infeasible too. The problem with Plan II lies in that the transferred demand did not distribute as late as possible along the four planning buckets, as required by the 2nd rule for PC transferring. Therefore, S1 cannot be fully utilized in BLWMO_S.

Table 5.4: An Example of M_PC Identification

	Mould type	PC type for BLWMO	Demand, prodduction & PC Gap	Bucket 1	2	3	4
Input	E1&S1	P1	Demand	0	12	0	16
	S1	P2	Demand	0	0	16	0
	E1	P1	Capacity	6	6	6	6
	S1	P1&P2	Capacity	6	6	6	6
Initial BLWMO_E	E1	P1	Demand	0	12	0	16
		Initial	Production	0	6	6	6
		BLWMO_E	PC Gap	10	4	10	0
Plan I	E1	P1	Adjusted demand	0	12	0	6
		Adjusted	Adjusted production	0	6	0	6
		BLWMO_E	Adjusted PC Gap	6	0	0	0
	S1	P1	Transferred demand	0	0	0	10
Plan II	E1	P1	Adjusted demand	0	2	0	16
		Adjusted	Adjusted production	0	6	6	6
		BLWMO_E	Adjusted PC Gap	0	4	10	0
	S1	P1	Transferred demand	0	10	0	0
		P2	Demand	0	0	16	0
		BLWMO_S	Production	0	6	6	0
			PC Gap	14	10	0	0
		P1	Max contribution	0	10	0	0
		P2		0	0	10	0
Plan III	E1	P1	Adjusted demand	0	6	0	12
		Adjusted	Adjusted Production	0	6	6	6
		BLWMO_E	Adjusted PC Gap	0	0	6	0
	S1	P1	Transferred demand	0	6	0	4
		P2	Demand	0	0	16	0
		BLWMO_S	Production	0	6	6	4
			PC Gap	10	10	0	0
		P1	Max contribution	0	6	0	0
		P2		0	0	10	0

Finally, Plan III transfers 6 P1 at bucket 2 and 4 P1 at bucket 4 onto S1, leading to zero PC_Gap@CB in adjusted BLWMO_E on E1. Further loading P1 and P2 onto S1 through BLWMO_S creates a 10 PC_Gap@CB, which is within the capacity of E1 and S1 at CB. Therefore, Plan III is a feasible alternative for transferring P1 demand from E1 to S1. CV for the PC family is 10. Calculate MCAs of P1 and P2 respectively from CB onwards. The 4 P1 demand at bucket 4 gives a zero PC_Gap at bucket 3 in BLWMO_S and thus provides no contribution to the family's CV. P1 at most contributes 6 to the CV with its 6 demand at bucket 2. On the other hand, P2 may contribute up to 10 to the CV with its 16 demand at bucket 3. Therefore, both P1 and P2 are identified as M_PC, with MCA being 6 and 10 respectively.

5.2.3 Simulation Procedure Based on CP Rule

In forward simulation of Simulation(A) based on CP rule, CP rule is used as the 1st priority rule. At a certain loading bucket, PCs are loaded in order of their criticality, i.e., D_PC is loaded at first, next M_PC, at last N_PC. For PCs of the same criticality, the traditional priority rules, EDD/LMC/LSC are adopted as subordinate rules.

The procedure of the forward simulation based on CP rule is given in Figure 5.7. At CB, D_PC is identified and loaded at first. Then, for PC types with their earliest due dates later than CB, and from existing demand and newly-specified demand, M_PC is identified based on BLWMO. If an E_PC type is identified as M_PC, it should be loaded to consume all its CV. On the other hand, for S_PC and B_PC, the loading of all M_PC types in PC a family should use up the CV of the family, subject to MCA of each PC type involved. At last, PC types other than D_PC and M_PC are identified as N_PC and loaded.

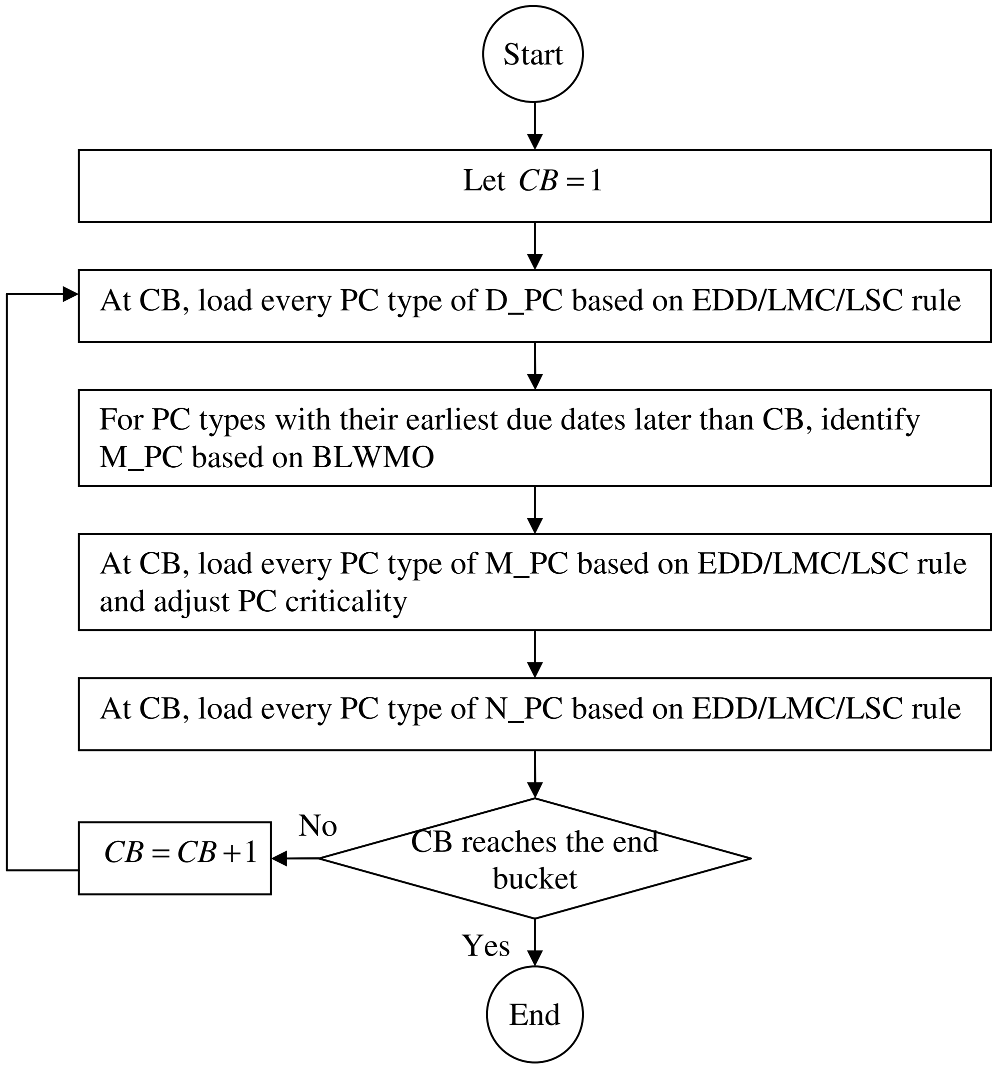


Figure 5.7: Procedure of Forward Simulation Based on CP Rule in Simulation(A)

5.3 The Backward Simulation

In an attempt to avoid any delay and resource idleness, traditional forward simulation tends to produce as early as possible by fully utilizing available resources in both NT and OT. This method may not generate a satisfying production schedule for two reasons. Firstly, certain PCs can be produced much earlier than their due dates, leading to overstock. Secondly, some OT may be overused for the PC production that otherwise could be carried out at a later stage with NT, resulting in unnecessary OT cost. To solve this problem, a bidirectional simulation is adopted instead, where a specialized backward simulation is carried out after a forward simulation based on CP rule is finished. The purpose of the backward simulation is to get a feasible production schedule with smaller PC stock and OT cost. The backward simulation is executed based on the result of the proceeding forward simulation. It tries to utilize the NT unused at a certain bucket to reduce the OT overused at earlier buckets in the forward schedule, thus leading to smaller stock cost and OT cost.

To make sure the performance of the backward simulation is always better than that of the preceding forward simulation, some principles are established as follows:

1. The backward simulation is carried out from the due dates backward in time to obtain a non-delay schedule;
2. Production time (bucket) of a PC in the backward simulation must not be earlier than that in the forward simulation;
3. The backward simulation keeps the same profile of PC assignment and production sequence on moulds as the forward simulation;
4. At every bucket, backward simulation loads PCs until all PCs produced at the same bucket in the forward schedule have been loaded and until as many NT hours available have been utilized as possible.

Priority rules applied in the backward simulation are also established accordingly:

1. The 1^{st} rule: Production time (bucket) of PC in the forward schedule. The larger production time a PC has in the forward schedule, the sooner it is loaded in the backward simulation;
2. The 2^{nd} rule: due date of PC. The larger due date a PC has, the sooner it is loaded;
3. The 3rd rule: Stock cost. The larger stock cost a PC has, the sooner it is loaded.

Based on the above principles and priority rules, procedure of backward simulation in Simulation(A) is presented in Figure 5.8.

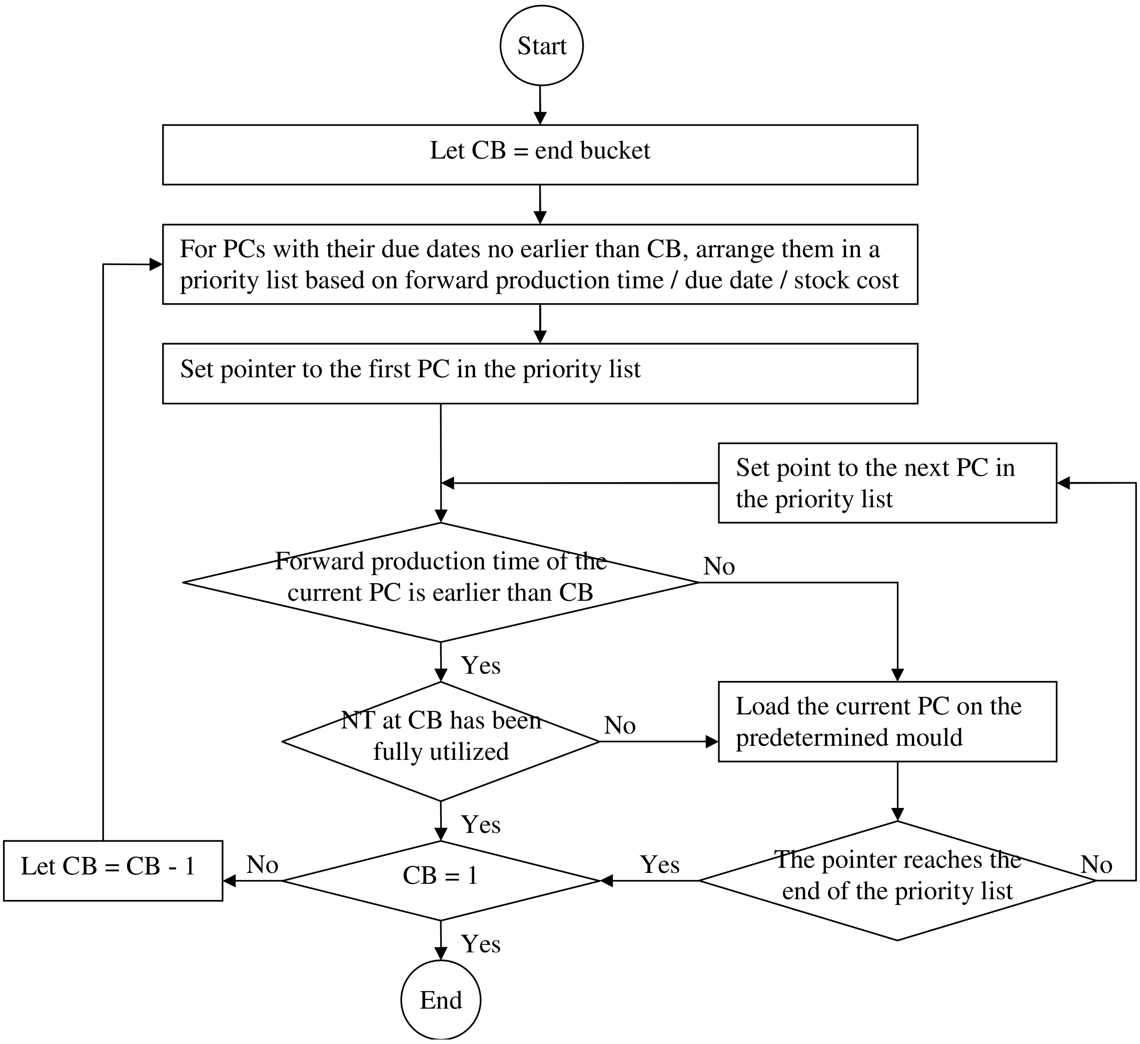


Figure 5.8: Procedure of Backward Simulation in Simulation(A)

5.4 Implementation of GA

Three main subsystems are included in GA for aggregate planning, as mentioned above. The implementation of these subsystems is explained below.

5.4.1 Encoding and Decoding

A chromosome in GA stands for a solution of the problem at hand. The way to encode a solution of the problem into a chromosome, or choosing an appropriate chromosome representation of a solution of the problem, forms the basis for GA application. Initially, most GA applications simply used a binary string representation. However, the binary string is not a natural coding, and thus is not suited for many complex real-world problems. To deal with this limitation, various non-string encoding techniques have been created for particular problems, such as real number representation for constrained optimization problems and integer representation for combinatorial optimization problems (Gen and Cheng, 1997).

As for *Labour Sizing* and *Mould Planning* in this research, labour size and max OT hour for every planning period, and mould quantity for every mould type, are the decision variables. Considering different properties of these variables, integer representation is used for labour size and mould quantity, and real number representation is used for max OT hour. A chromosome representation can be illustrated in Figure 5.9 for an aggregate planning of integrated *Labour Sizing* and *Mould Planning* with 4 planning periods and 3 mould types. In this chromosome, each gene corresponds to a decision variable in question.

	L_1	L_2	L_3	L_4	O_1	O_2	O_3	O_4	M_1	M_2	M_3	Variable
Chromosome	45	50	54	60	3.5	2.0	4.3	1.5	2	1	3	Gene value

Note: L_i -- Labor size in period i; O_i -- Max OT hours in period i; M_j -- Mould quantity of Mould type j.

Figure 5.9: Example of Chromosome Representation for Integrated *Labour Sizing* and *Mould Planning*

Decoding a chromosome representation for aggregate planning into a solution is straightforward. As shown in Figure 5.9, the values of genes can be directly assigned to the corresponding decision variables, which will be used in Simulation(A) for schedule development.

5.4.2 Crossover

Crossover is a primary genetic operator, which performs on two parent chromosomes at a time and generates offspring by combining both chromosomes' features (Gen and Cheng, 1997). Traditional two-cut-point crossover is used in this research for both aggregate planning and detailed scheduling, as illustrated in Figure 5.10.

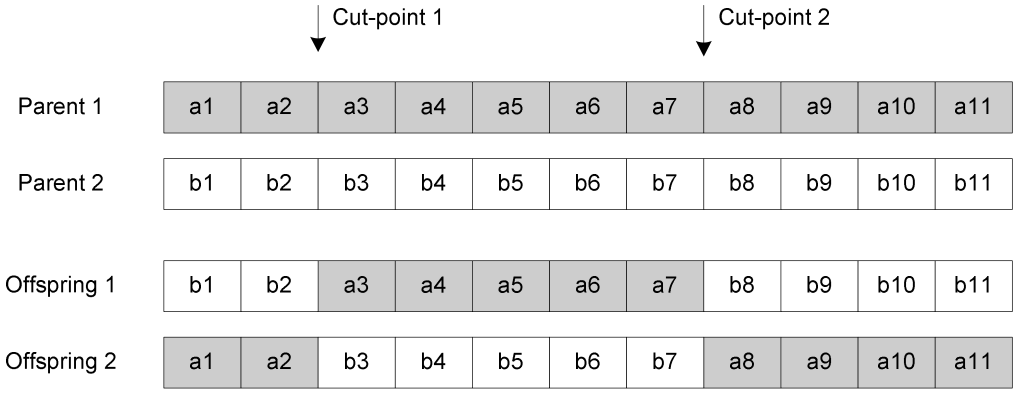


Figure 5.10: Illustration of Two-Cut-Point Crossover

In the crossover, two cut-points are first chosen randomly for parent 1 and 2. Then, the substrings of parent 1 and 2 within the two cut-points are exchanged to create two new chromosomes: offspring 1 and 2.

5.4.3 Mutation

Mutation is a secondary genetic operator, which acts on a single parent chromosome and generates a new offspring chromosome by randomly changing values of one or more genes. A simple uniform mutation is adopted in this research for both aggregate planning and detailed scheduling, as illustrated in Figure 5.11.

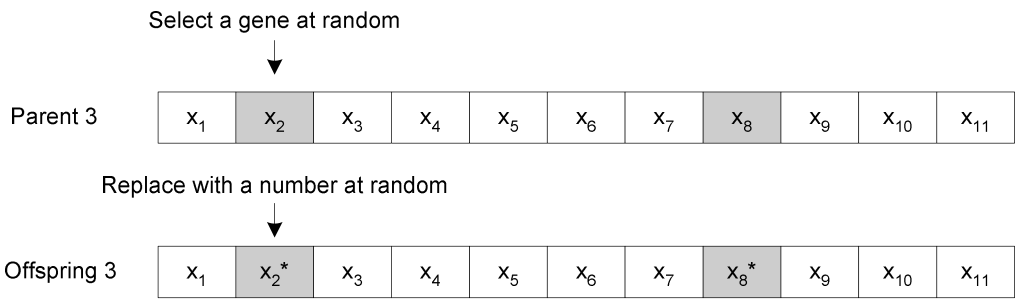


Figure 5.11: Illustration of Uniform Mutation

Before execution of the uniform mutation, every gene in a chromosome should be assigned with a specific range where its value belongs. During the mutation, some genes are first selected at random from a parent chromosome. Then, the value of every selected gene is replaced with a randomly generated number within its predetermined range. In Figure 5.11, let the range of selected gene, x_k, be $[x_k^L, x_k^M]$, where x_k^L and x_k^M are actually lower and upper bonds of x_k. To generate the offspring chromosome, x_k is replaced with x_k^*, which is produced randomly with a uniform probability distribution from the range $[x_k^L, x_k^M]$. Certainly, the variable x_k can be set as a real number or an integer, as per request. Specifically in aggregate planning, labour size and mould quantity are integer variables, and max OT hour is a variable of real number.

5.4.4 Selection

Selection is an evolution operation, which directs a genetic algorithm search toward promising regions in the search space. During selection, a new population for the next generation is created from parents and offspring chromosomes of the current generation based on their fitness values. Fitter chromosomes have higher probabilities of survival to the next generation.

This research simply uses $(\mu + \lambda)$ selection (Fogel, 1994), which has been adopted by many researchers to deal with combinatorial optimization problems. With this method, μ parents and λ offspring of the current generation complete for survival and the μ best chromosomes are finally selected as parents of the next generation. In this case, the objective costs of schedules generated by simulation can be simply used as fitness values of the corresponding chromosomes, and $(\mu + \lambda)$ selection sorts chromosomes according to their fitness values for chromosome selection.

Chapter 6

IPSMPP: Modelling for Detailed Scheduling

6.1 Integrated Detailed Scheduling

Detailed scheduling is concerned with planning work at operational level for a short-run planning horizon. It contains three modules, namely *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring*. During scheduling, they are conducted one by one for better resource allocation and production schedule improvement, as shown in Figure 4.1.

6.1.1 Simulation(D)-GA Based Scheduling

The common feature shared by all the three modules is that they are all based on Simulation(D) and GA. Figure 6.1 provides a detailed structure of Simulation-GA based approach for detailed scheduling. Simulation(D) is used to generate detailed production schedules, based on inputs from GA. Then performance of the schedules are measured and transferred to GA. GA, in turn, selects a new set of schedules based on their fitness values, and adjusts values of various decision variables for further schedule development.

Unlike FIA used in Simulation(A), NEA is adopted in Simulation(D) for advancing the simulation clock. Simulation(D) takes three scheduling passes, including two forward simulations and one backward simulation, to get a production schedule. As shown in Figure 6.1, during one simulation process, at first the 1st forward simulation tries to generate a feasible production schedule by producing as early as possible with both NT and OT available. Then the backward simulation is conducted to improve the schedule by pulling back the production for lower stock and utilizing NT available to reduce OT usage. Finally, the 2nd forward simulation is done for schedule repair. As the schedule generated by the backward simulation is usually inconsistent with practice, the 2nd forward simulation aims to repair it and make it applicable for implementation in practice.

Similar to GA in aggregated planning, GA applied in detailed scheduling also contains three subsystems of selection, genetic operation, and decoding, which are executed in sequence, as shown in Figure 6.1. The implementation of GA for the three modules at the operational level will be explained in detail in Section 6.7.

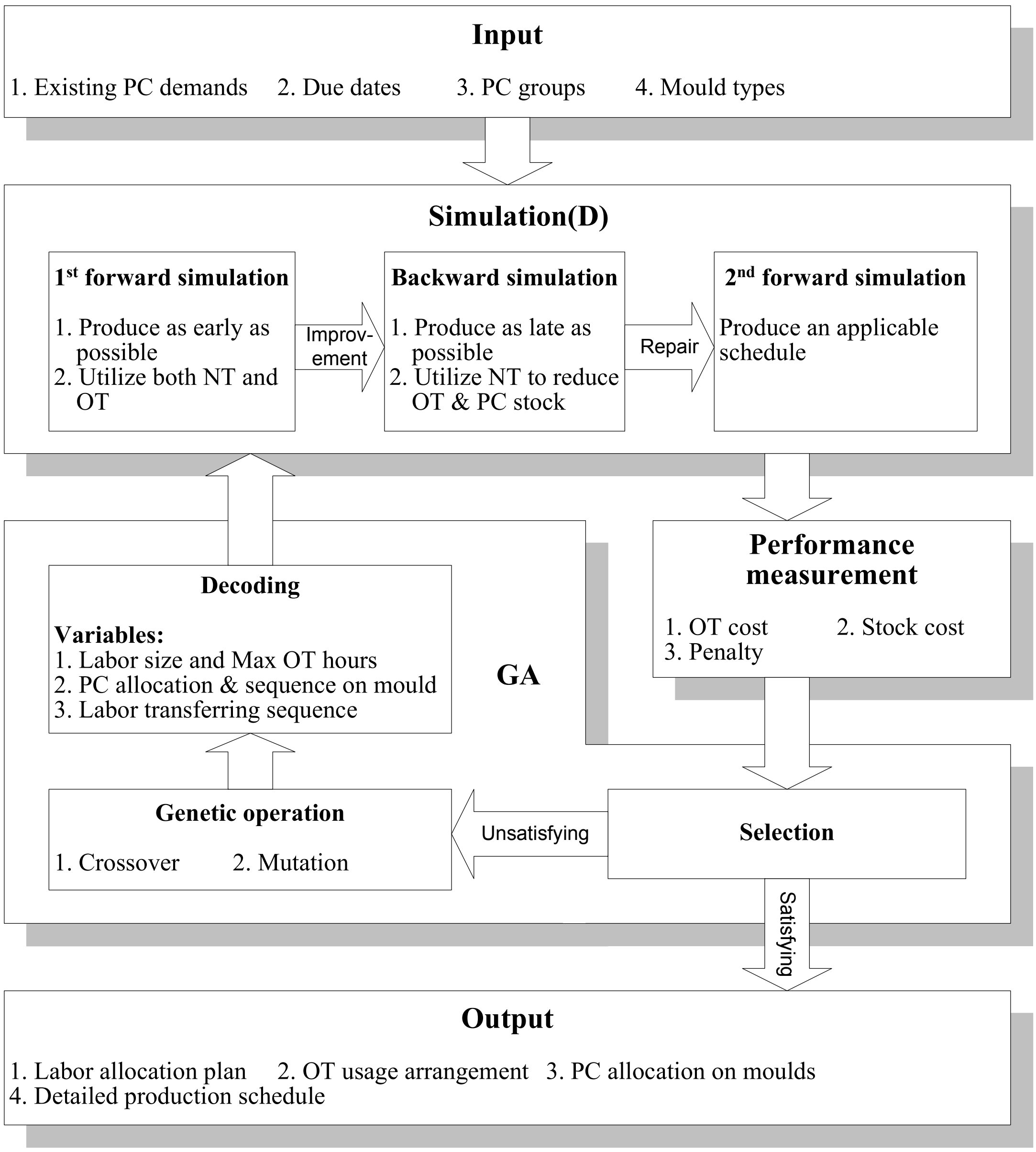


Figure 6.1: Simulation(D)-GA Based Approach for Detailed Scheduling

6.1.2 Decision Variables, Constraints, and Priority Rules

The decision variables, constraints, and priority rules in the three modules are given in Table 6.1. Different modules involve different decisions to make, which is represented by the decision variables in GA. Subject to a fixed labour size in plant, *Labour Grouping* aims to assign suitable labour sizes to different PC groups for every planning period and to determine maximum allowable OT hour for each group per period. On this basis, proper allocation of PC onto exclusive and sharable moulds and PC production sequence on individual sharable mould are resolved using *PC Allocation & Sequencing*. Finally, *Labour Transferring* generates a reasonable sequence to transfer labour among all moulds in every PC group.

Table 6.1: Decision Variables, Constraints, and Priority Rules in Detailed Scheduling

Module			***Labour Grouping***	***PC Allocation & Sequencing***	***Labour Transferring***
GA	Decision variable		Labour size and max OT in every group	PC assignment among exclusive & sharable moulds; PC sequence on individual sharable mould	Labour transfer sequence among all moulds
Bi-directional simulation (D)	Predetermined constraint		PC assignment among exclusive & sharable moulds	Labour size and max OT in every group	Labour size and max OT; PC assignment & sequence on moulds
	1^{st} Forward Simulation	Labour transfer rule	CM	CM	From GA
		PC dispatch-ing rule	EDD/LMC	From GA	From constraint
	Backward Simulation	PC dispatch-ing rule	FT of PCs in 1^{st} forward schedule		
	2^{nd} Forward Simulation	PC dispatch-ing rule	ST of PCs in backward schedule		

It should be noted that one major concern of *PC Allocation & Sequencing* is mould changeovers on sharable moulds. The module tries to achieve a good balance among mould changeover reduction, resource utilization, and stock minimization by reasonably assigning PCs onto moulds, and sequencing their production on each mould. As described in Chapter 5, PC Types can be broken into 3 categories according to the mould type used, namely E_PC, S_PC and B_PC. For simplicity of the model, allocation and sequencing of E_PC on corresponding exclusive moulds is not considered in *PC Allocation & Sequencing*, as production on an exclusive mould does not involve any mould changeover. In simulation, all moulds of an exclusive mould type used for an E_PC type can be simply regarded as a work center. Once there is any mould available in the work center, the corresponding PCs can be allocated for production in an ascending sequence of their due dates. Similar treatment is also adopted for a B_PC type, which can be produced with both exclusive mould and sharable mould. Once some of PCs of a B_PC type is decided to be assigned to the corresponding exclusive mould type, allocation and sequencing of these PCs on the exclusive mould can be determined in the same way as E_PC, and thus is not a concern of *PC Allocation & Sequencing* any more. Therefore, the module of *PC Allocation & Sequencing* only focuses on allocation of PCs (both B_PC and S_PC) among exclusive mould types and individual sharable moulds, as well as PC production sequence on every single sharable mould.

Furthermore, there may be a lot of PCs of B_PC and S_PC in one PC group within the planning horizon. It would be difficult to conduct *PC Allocation & Sequencing* at one time for a PC group due to the vast solution space. For this reason, all related PCs (B_PC or S_PC) that can be produced on a certain sharable mould type is defined as a PC family. *PC Allocation & Sequencing* for a PC group can be done in steps with each step for one PC family only. In this way, the computation burden is reduced. Since *PC Allocation & Sequencing* concentrates on mould changeover reduction on sharable moulds and each PC family corresponds to one sharable mould type, mould changeovers can be used to determine the sequence of executing *PC Allocation & Sequencing* for PC families in a PC group. The larger mould changeover that could be incurred on a sharable mould type, the earlier *PC Allocation & Sequencing* should be conducted for the corresponding PC family.

Similar to *PC Allocation & Sequencing*, *Labour Transferring* considers all moulds of every exclusive mould type a work center for simplicity of the model. Thus, the labour transfer decision in simulation is made to transfer labour to either any exclusive mould type or individual sharable mould. Furthermore, *Labour Transferring* is conducted, PC allocation to moulds and PC production sequence on every mould have been established by *PC Allocation & Sequencing*. In the simulation of *Labour Transferring,* labour transferred to a mould must be used for production of PCs allocated to the mould according to the predetermined sequence. Thus, to be exact, the decision variable in GA for *Labour Transferring* is the sequence of transferring labour to PCs on every exclusive mould type and individual sharable mould.

Besides inputs from GA, some predetermined constraints and priority rules are used to run Simulation(D). Part of the constraints of a certain module is usually the decisions made by preceding planning module(s). To be exact, PC assignment among exclusive and sharable moulds determined in the aggregate planning form a constraint to *Labour Grouping*; Labour size and max OT hour in every group are produced by *Labour Grouping* and then become constraints to *PC Allocation & Sequencing* and *Labour Transferring*; PC assignment & sequence on moulds decided by *PC Allocation & Sequencing* finally restrains execution of *Labour Transferring*.

Certain "where" labour transfer rule and PC dispatching rule are also needed for the 1st forward simulation in any of the three modules if they are not generated by GA or set by predetermined constraints. At a certain point of simulated time, "where" rule dictates to which mould among all available moulds labour should be transferred, and then PC dispatching rule chooses a PC from all PCs allocated to the mould for PC loading. A new labour transfer rule, critical mould (CM) rule, is specially designed in this research and used in the 1st forward simulation of two modules, *Labour Grouping* and *PC Allocation & Sequencing*. On the other hand, priority for transferring labour is input from GA in module of *Labour Transferring*. As for PC dispatching, popular EDD/LMC rule is used for *Labour Grouping*. In *PC Allocation & Sequencing*, PC dispatching sequence on a certain mould is determined by GA as its decision variables. It is then transferred as a constraint to *Labour Transferring*, as mentioned above.

In order to simplify the simulation process, only one type of priority rule, the PC dispatching rule, is used to decide PC loading sequence in both the backward simulation and the 2nd forward simulation for all the three scheduling modules. In the backward simulation, PC dispatching rule is constructed based on PCs' finish times (FTs) in the 1st forward schedule, whereas in the 2nd forward simulation, PCs are loaded according to their start times (STs) in the backward schedule.

6.1.3 Performance Measurement

In aggregate planning, performance for a master schedule is measured in terms of the objective cost, including total variable cost and penalty cost for production delay, as shown in Equations (5.1) ~ (5.5). Similarly, the objective cost could be used to measure the performance for a detailed schedule. For simplicity of the model, however, the objective cost is adjusted for detailed scheduling.

In the proposed model, the planning horizon for detailed scheduling is set to be the first planning period in aggregate planning, which is about 4~8 weeks. For the planning horizon, labour size available in the entire plant has already been planned, and no unexpected change in labour size is supposed to happen during this short time. Therefore, the cost for labour hiring/firing is fixed for the planning horizon. Given that daily NT payment is a constant for a worker regardless how long he works a day, the NT cost of all labour in plant is also fixed for the planning horizon. It can be calculated by multiplying daily NT payment per worker, working days in the planning horizon, and labour size in plant. Besides, the planning horizon only covers existing PC demand, for which *Mould Planning* has already finished. Thus, mould purchasing cost is known at the time of planning. To simplify performance evaluation process for detailed scheduling, the fixed labour hiring/firing cost, NT working cost, and mould purchasing cost are removed from the total variable cost of a detailed schedule for performance measurement. Thus, a detailed schedule can be measured based on the adjusted objective cost, including OT working cost and PC stock cost, and penalty cost for production delay, as shown in Figure 6.1.

6.2 Execution of Various Operations in Simulation(D)

Detailed scheduling focuses on scheduling at the operational level, i.e., how to arrange every operation in precast production. Casting process of a PC involves several operations with different characteristics. They need to be modelled properly in different scheduling directions and working time zones.

6.2.1 Time Zones in a Working Day

Basically, there are three continuous time zones in a working day, namely normal time (NT) zone, overtime (OT) zone, and break time (BT) zone, as shown in Figure 6.2. It is assumed in this research that a working day starts with NT zone, goes through OT zone, and ends with BT zone. Durations of NT, OT, and BT zones in hours are represented by T_N, T_O, and T_B respectively. T_N is determined by management and fixed for every working day, T_O is a decision variable in GA of *Labour Grouping*, and $T_B = 24 - T_N - T_O$.

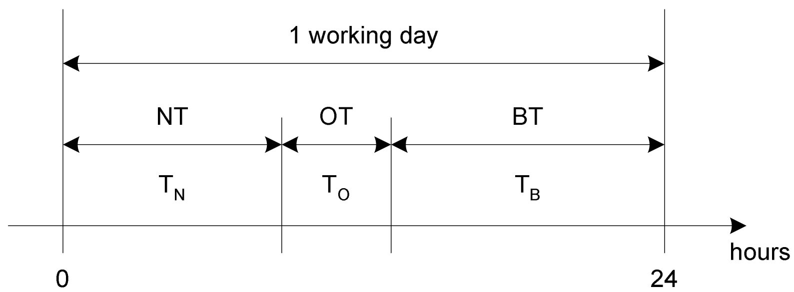


Figure 6.2: Time Zones in a Working Day

6.2.2 Characteristics of Casting Operations

Casting process of a PC is composed of sequentially executed operations, including mould changeover, preparation (mould preparation and rebar fixing), concrete pouring, and curing. These operations vary from each other in terms of resource needed, working time zone, preemptive nature, and duration, as given in Table 6.2. Mould changeover, preparation, and concrete pouring need both labour and mould and thus can proceed at NT and OT zones except BT zone, while curing may be conducted any time of a day as it only uses mould as a single resource. As in Graves et al. (1993), if the process of an operation can be interrupted and resumed at a later time, the operation is preemptive. Otherwise if an operation cannot be interrupted until it is completed, it is non-preemptive. Based on this definition, mould changeover and preparation are preemptive, whereas concrete pouring and curing are non-preemptive. Clearly, durations of preparation, concrete pouring, and curing are fixed for a certain PC. On the contrary, time needed for mould changeover for a PC on a sharable mould may change, depending on both the current PC to produce and the proceeding PC that has been finished.

Table 6.2: Characteristics of Casting Operations

Operation		Resource needed	Working time	Preemptive	Duration
0	Mould changeover	Labour & Mould	NT & OT	Yes	Sequence-dependent
1	Preparation (Mould preparation and Rebar fixing)	Labour & Mould	NT & OT	Yes	Fixed
2	Concrete pouring	Labour & Mould	NT & OT	No	Fixed
3	Curing	Mould	Any time (NT, OT & BT)	No	Fixed

In Simulation(D) for detailed scheduling, mould changeover, preparation, concrete pouring, and curing are represented by operation 0, 1, 2, and 3 respectively. Thus, the casting process of a PC in Simulation(D) can be illustrated by Figure 6.3.

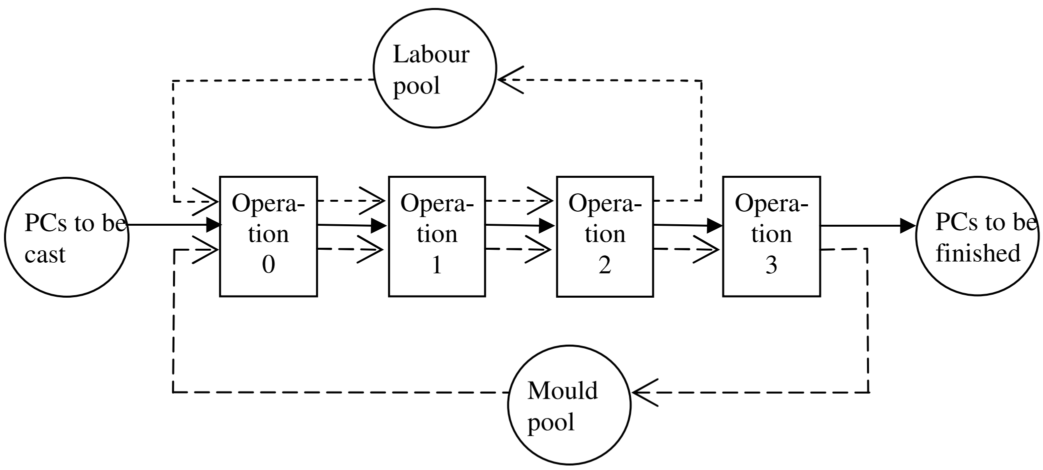


Figure 6.3: PC Casting Process under a Comprehensive Organization

6.2.3 Operation Time Calculation in Simulation(D)

In Simulation(D), the production times of various casting operations need to be calculated. They form a basis not only for allocating and releasing resources, but also for advancing system clock during simulation process. As mentioned above, Simulation(D) is composed of two forward simulations and one backward simulation. Different simulation directions require different algorithms for calculating operation time. Furthermore, the production time of an operation may also differ due to its preemptive nature and the time zone(s) at which it is allowed to proceed. In precast production, there are 3 possible alternatives of time zone(s) used for an operation, namely (1) NT and OT zones, (2) NT zone, and (3) anytime in a day. Alternative 1 and 3 are used for all the three simulations in Simulation(D), while alternative 2 is only for the backward simulation and the 2^{nd} forward simulation.

In forward simulation, simulation clock is increased as the simulation proceeds, and operations are executed from start to end in a natural way consistent with the real world. Therefore, the function *Plus* is established to calculate finish time (FT) of an operation when it is tried for execution at a certain point of time, as shown in Table 6.3. On the other hand, simulation clock decreases during backward simulation, and operations are conducted from end to start in the direction opposite to the reality. Therefore, function *Minus* , is established to calculate start time (ST) of an operation when it is tried for execution at a certain point of time, as shown in Table 6.4. In Table 6.3 and 6.4, the parameters and functions used in *Plus* and *Minus* are explained. Parameter is given in the form of "(type of the parameter) name of the parameter", while function is given in the form of "(type of the function) name of the function ((type of parameter 1 used in the function) name of parameter 1, …, (type of parameter n used in the function) name of parameter n))". Types of parameter and function used in this research are *integer*, *double*, *boolean*, *string*, and *character*, as those in commonly used programming languages.

For function *Plus* and *Minus* to work, the following assumptions are made:

- NT zone is long enough to do the operation if it cannot be interrupted. That is, $t2 \le T_N$ if $preemptive = false$;
- Both the time to try to execute the operation and the duration of the operation are not negative, i.e., $t1 \ge 0$ and $t2 \ge 0$.

6.2.3.1 FT Calculation in Forward Simulation

Function *Plus* is given in Table 6.3 and explained below:

- Step [1]: If the duration of the operation is equal to zero (such as of mould changeover of a PC on an exclusive mould), then the FT is equal to ST of the operation.
- Step [2]: If the operation can be loaded anytime in a day (such as curing of a PC), then the FT is equal to the ST plus the duration.
- Step [3]: In the case that the operation can be done in both NT and OT zones, and cannot be interrupted (such as the case of concrete pouring), the FT calculation depends on what time zone t1 falls into. If t1 lies in BT zone, the operation cannot start until the next working day. If t1 is at NT or OT zone, a judgement has to be made to see whether the working hours available in the current day of t1 are enough to finish the operation. If it is enough, then let the FT be equal to the ST plus the duration. Otherwise, the operation will be finished in the next working day.
- Step [4]: In the case that the operation can only be done in NT zone and cannot be interrupted, calculation of the FT is similar to Step [3], except that the working time is changed from both NT and OT zones to NT zone only.
- Step [5]: In the case that the operation can be done in both NT and OT zones, and can be interrupted (such as mould changeover and preparation), the FT calculation depends on what time zone t1 falls into. If t1 lies in BT zone, the operation will start on the next working day, and end when all its duration has been used up by NT and OT from that day forward. On the contrary, if t1 is at NT or OT zone, a judgement has to be made to see whether the working hours available in the current day are enough to finish the operation. If it is enough,

then let the FT be equal to the ST plus the duration. Otherwise, the remaining part of the operation will be executed from the next working day forward.

- Step [6]: In the case that the operation can only be done in NT zone and can be interrupted, calculation of the FT is similar to Step [5], except that the working time is changed from both NT and OT zones to NT zone only.

Table 6.3: Function *Plus* for Calculating FT of an Operation in Forward Simulation

$(double)\ Plus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,$
$(boolean)\ preemptive)$

Parameters:

- $(double)\ t1$: the point of time in hours when the operation is tried for execution;
- $(double)\ t2$: the duration in hours of the operation to execute;
- $(double)\ t3$: the FT in hours of the operation;
- $(string)\ time$: indicates at what time zone the operation can proceed; $"N"$: NT zone; $"N+O"$: NT and OT zones; $"N+O+B"$: all the three time zones;
- $(boolean)\ preemptive$: indicate whether the operation is preemptive (true) or not (false).
- $(integer)\ g$: the group where the PC of the operation belongs;
- $(double)\ T_N$: NT hours in a working day;

Referenced functions:

- $(double)\ T_O((integer)\ d,\ (integer)\ g)$: Max OT working hours on day d in PC group g;
- $(character)\ Zone((double)\ t,\ (integer)\ g)$: indicates which time zone that point of time t falls into in PC group g. Zone = 'N', 'O', or 'B' represent that t falls into NT, OT, or BT zone respectively;
- $(integer)\ Day((double)\ t)$: return the day where t falls into; it is equal to $\text{int}(t/24)$;
- $(integer)\ Hour((double)\ t)$: return the hours that t has on the day where t falls into; it is equal to $t-24\times\text{int}(t/24)$;

Procedure:

[1] If $t2=0$, then let $t3=t1$;
[2] Else if $time="N+O+B"$, let $t3=t1+t2$;
[3] Else if $time="N+O"$ and $preemptive=false$, then
  [3.1] If $Zone(t1,\ g)='B'$, then let $t3=24(Day(t1)+1)+t2$;

[3.2] Else if $Zone(t1,\ g) = 'N'$ or $'O'$, then

[3.2.1] If $Hour(t1) + t2 \le T_N + T_O(Day(t1),\ g)$, let $t3 = t1 + t2$;

[3.2.2] Else then let $t3 = 24(Day(t1) + 1) + t2$;

[4] Else if $time = "N"$ and $preemptive = false$, then

[4.1] If $Zone(t1,\ g) = 'B'$ or $'O'$, then let $t3 = 24(Day(t1) + 1) + t2$;

[4.2] Else if $Zone(t1,\ g) = 'N'$, then

[4.2.1] If $Hour(t1) + t2 \le T_N$, let $t3 = t1 + t2$;

[4.2.2] Else then let $t3 = 24(Day(t1) + 1) + t2$;

[5] Else if $time = "N + O"$ and $preemptive = true$, then

[5.1] If $Zone(t1,\ g) = 'B'$, then

[5.1.1] Let $d = Day(t1) + 1$;

[5.1.2] While $t2 > T_N + T_O(d,\ g)$, do

[5.1.2.1] Let $t2 = t2 - (T_N + T_O(d,\ g))$;

[5.1.2.2] Let $d = d + 1$;

[5.1.3] Let $t3 = 24d + t2$;

[5.2] Else if $Zone(t1,\ g) = 'N'$ or $'O'$, then

[5.2.1] If $Hour(t1) + t2 \le T_N + T_O(Day(t1),\ g)$, then let $t3 = t1 + t2$;

[5.2.2] Else then

[5.2.2.1] Let $t2 = Hour(t1) + t2 - (T_N + T_O(Day(t1),\ g))$;

[5.2.2.2] Let $d = Day(t1) + 1$;

[5.2.2.3] While $t2 > T_N + T_O(d,\ g)$, do

[5.2.2.3.1] Let $t2 = t2 - (T_N + T_O(d,\ g))$;

[5.2.2.3.2] Let $d = d + 1$;

[5.2.2.4] Let $t3 = 24d + t2$;

[6] Else if $time = "N"$ and $preemptive = true$, then

[6.1] If $Zone(t1,\ g) = 'B'$ or $'O'$, then

[6.1.1] Let $d = Day(t1) + 1$;

[6.1.2] While $t2 > T_N$, do

[6.1.2.1] Let $t2 = t2 - T_N$;

[6.1.2.2] Let $d = d + 1$;

[6.1.3] Let $t3 = 24d + t2$;

[6.2] Else if $Zone(t1,\ g) = 'N'$, then

[6.2.1] If $Hour(t1) + t2 \le T_N$, then let $t3 = t1 + t2$;

[6.2.2] Else then

[6.2.2.1] Let $t2 = Hour(t1) + t2 - T_N$;

[6.2.2.2] Let $d = Day(t1) + 1$;

[6.2.2.3] While $t2 > T_N$, do

[6.2.2.3.1] Let $t2 = t2 - T_N$;

[6.2.2.3.2] Let $d = d + 1$;

[6.2.2.4] Let $t3 = 24d + t2$;

[7] Return $t3$;

6.2.3.2 ST Calculation in Backward Simulation

Function *Minus* is given in Table 6.4 and explained below.

- Step [1]: If the duration of the operation is equal to zero (such as of mould changeover of a PC on an exclusive mould), then the ST is equal to the FT of the operation.
- Step [2]: If the operation can be loaded anytime in a day (such as curing of a PC), then the ST is equal to the FT minus the duration.
- Step [3.1]: In the condition that the operation is conducted either in NT and OT zones or in NT zone only (such as all the casting operations except curing), t1 may have to be adjusted at first before calculation of the ST. To be exact, when t1 happens to be the point of time separating BT and NT zones of two consecutive days, it needs to be reset to the ending time of OT zone of the previous working day. This is to get the proper value for $Day(t1)$ in the following calculations. Since the operation is not allowed to proceed in BT zone, the adjustment of t1 from the end of a BT zone to the end of the previous nearest OT zone won't have any negative effect on getting a correct answer for the ST.
- Step [3.2]: In the case that the operation can be done in both NT and OT zones, and cannot be interrupted (such as concrete pouring), the ST calculation depends on what time zone t1 falls into. If t1 lies in BT zone, the operation cannot proceed until the end of OT zone of the current day. If t1 is at NT or OT zone, a judgement has to be made to see whether the working hours available in the current day are enough to finish the operation. If it is enough, then let the ST be equal to the FT minus the duration. Otherwise, the operation will be executed in the previous working day.
- Step [3.3]: In the case that the operation can only be done in NT zone and cannot be interrupted, calculation of the ST is similar to Step [3.2], except that the working time is changed from both NT and OT zones to NT zone only.

- Step [3.4]: In the case that the operation can be done in both NT and OT zones, and can be interrupted (such as mould changeover and preparation), the ST calculation depends on what time zone t1 falls into. If t1 lies in BT zone, the operation will begin from the end of OT zone in the current working day, and end when all its duration has been used up by OT and NT from the day backward. On the contrary, if t1 is in NT or OT zone, a judgement has to be made to see whether the working hours available in the current day are enough to finish the operation. If it is enough, then let the ST be equal to the FT minus the duration. Otherwise, the remaining part of the operation will be executed from the previous working day backward.
- Step [3.5]: In the case that the operation can only be done in NT zone and can be interrupted, calculation of the ST is similar to Step [3.4], except that the working time is changed from both NT and OT zones to NT zone only.

Table 6.4: Function *Minus* for Calculating ST of an Operation in Backward Simulation

$(double)\ Minus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,$ $(boolean)\ preemptive)$ ***Parameters and referenced functions:***   Same as those in Table 6.3.   ***Procedure:***   [1] If $t2 = 0$, then let $t3 = t1$;   [2] Else if $time = "N+O+B"$, let $t3 = t1 - t2$;   [3] Else if $time = "N+O"$ or $"N"$, then   [3.1] If $Hour(t1) = 0$, let $t1 = 24(Day(t1)-1) + T_N + T_O(Day(t1)-1,\ g)$;   [3.2] If $time = "N+O"$ and $preemptive = false$, then   [3.2.1] If $Zone(t1,\ g) = 'B'$, then let $t3 = 24Day(t1) + T_N + T_O(Day(t1),\ g) - t2$;   [3.2.2] Else if $Zone(t1,\ g) = 'N'$ or $'O'$, then   [3.2.2.1] If $Hour(t1) - t2 \geq 0$, let $t3 = t1 - t2$;   [3.2.2.2] Else then let $t3 = 24(Day(t1)-1) + T_N + T_O(Day(t1)-1,\ g) - t2$;   [3.3] If $time = "N"$ and $preemptive = false$, then   [3.3.1] If $Zone(t1,\ g) = 'B'$ or $'O'$, then let $t3 = 24Day(t1) + T_N - t2$;   [3.3.2] Else if $Zone(t1,\ g) = 'N'$, then

[3.3.2.1] If $Hour(t1) - t2 \geq 0$, let $t3 = t1 - t2$;
[3.3.2.2] Else then let $t3 = 24(Day(t1) - 1) + T_N - t2$;
[3.4] Else if $time = "N + O"$ and $preemptive = true$, then
[3.4.1] If $Zone(t1,\ g) = 'B'$, then
[3.4.1.1] Let $d = Day(t1)$;
[3.4.1.2] While $t2 > T_N + T_O(d,\ g)$, do
[3.4.1.2.1] Let $t2 = t2 - (T_N + T_O(d,\ g))$;
[3.4.1.2.2] Let $d = d - 1$;
[3.4.1.3] Let $t3 = 24d + T_N + T_O(d,\ g) - t2$;
[3.4.2] Else if $Zone(t1,\ g) = 'N'$ or $'O'$, then
[3.4.2.1] If $Hour(t1) - t2 \geq 0$, then let $t3 = t1 - t2$;
[3.4.2.2] Else then
[3.4.2.2.1] Let $t2 = t2 - Hour(t1)$;
[3.4.2.2.2] Let $d = Day(t1) - 1$;
[3.4.2.2.3] While $t2 > T_N + T_O(d,\ g)$, do
[3.4.2.2.3.1] Let $t2 = t2 - (T_N + T_O(d,\ g))$;
[3.4.2.2.3.2] Let $d = d - 1$;
[3.4.2.2.4] Let $t3 = 24d + T_N + T_O(d,\ g) - t2$;
[3.5] Else if $time = "N"$ and $preemptive = true$, then
[3.5.1] If $Zone(t1,\ g) = 'B'$ or $'O'$, then
[3.5.1.1] Let $d = Day(t1)$;
[3.5.1.2] While $t2 > T_N$, do
[3.5.1.2.1] Let $t2 = t2 - T_N$;
[3.5.1.2.2] Let $d = d - 1$;
[3.5.1.3] Let $t3 = 24d + T_N - t2$;
[3.5.2] Else if $Zone(t1,\ g) = 'N'$, then
[3.5.2.1] If $Hour(t1) - t2 \geq 0$, then let $t3 = t1 - t2$;
[3.5.2.2] Else then
[3.5.2.2.1] Let $t2 = t2 - Hour(t1)$;
[3.5.2.2.2] Let $d = Day(t1) - 1$;
[3.5.2.2.3] While $t2 > T_N$, do
[3.5.2.2.3.1] Let $t2 = t2 - T_N$;
[3.5.2.2.3.2] Let $d = d - 1$;
[3.5.2.2.4] Let $t3 = 24d + T_N - t2$;
[4] Return $t3$;

In real simulation system, special considerations have to be given under the boundary condition, i.e., when working time available between t1 and the end time of simulation is not enough for execution of the operation. Moreover, in practice labour in precast plants take public holidays when they do not need to work. Thus, to make the model consistent with practice, the calendar needs to be incorporated in *Plus* and *Minus* functions to distinguish holiday and working day. These modifications are easy to make and are not discussed here.

6.2.4 Resource Examination for Operation Execution

For an operation to be executable from certain time through its entire duration, resource needed by the operation has to be examined to ensure it is available for use in this period. In regular simulation, the quantity of every resource for production is assumed to remain constant during the entire simulation process. Therefore, examination on resource availability is only carried out at the beginning of the operation. If resource needed is available at certain time t, then it could be occupied by the operation from t on, which means the operation is executable.

This, however, is not the case in Simulation(D) of the research. In production of a PC under a comprehensive labour organization, labour is occupied continuously from operation 0 to operation 2, while mould is kept occupied along the entire casting process. Therefore, resource examination should make sure that there are enough resources available for the whole process using the resource. That is, enough labour are available for operations 0 to 2 and required mould is available for operations 0 to 3. More importantly, availability of mould and labour for precast production may change within the planning horizon in detailed scheduling. Mould may be introduced into the plant any day based on *Mould Planning*, whereas labour size in a group can also vary due to periodical labour reassignment within plant via *Labour Grouping* and change of labour size in plant via *Labour Sizing*. In this case, resource examination at the beginning of a process is not sufficient to guarantee the process is executable, since the resource occupied at the beginning may not be available at some other time within the process.

This problem can be illustrated by an example given in Figure 6.4, showing changes of resources needed by a PC during a 4-week planning horizon. It can be seen that the mould is only available for use from the 3rd week on, while labour size also decreases at the beginning of the 3rd week. Time needed for operation 0 to 2 using labour is $(t_b - t_a)$, while time for operation 0 to 3 using mould is $(t_c - t_a)$. In forward simulation, assume that when the PC is tried for loading at t_a, there are enough labour for its production. However, the production may not proceed to t_b in the 3rd week since these labour needed are reassigned to other PC groups and not available for the current PC. On the other hand, in backward simulation, it seems there is no problem to start the PC production at t_c as the mould needed is available. Nevertheless, the PC cannot be finished at t_a in the 2nd week because the mould is not ready for use at that time.

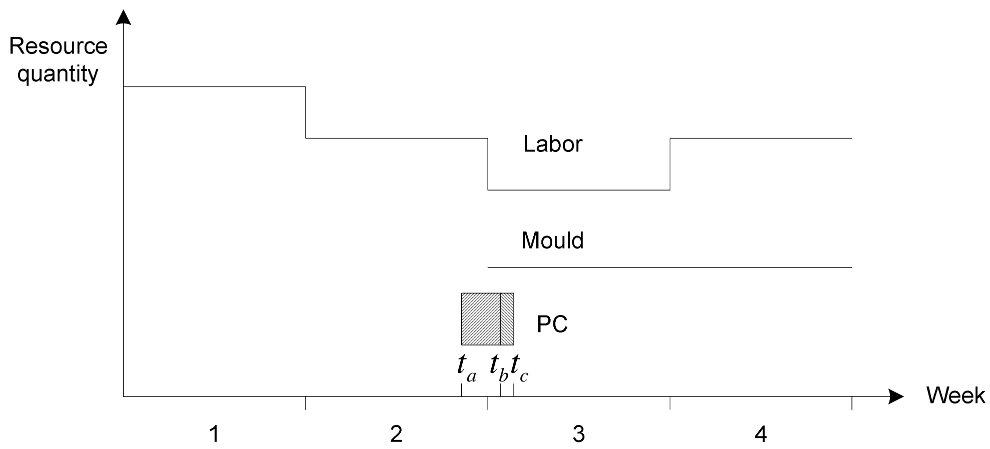


Figure 6.4: An Example of Changes of Resources Needed by a PC

To take into account changes of resource availability within the planning horizon and to make sure that the process can be executed during its entire duration with corresponding resource, a more comprehensive resource examination should be conducted. It usually takes 1 or 2 days to produce a PC, which is much less than the period within which labour size in a PC group or mould quantity is kept constant. This means at most one time of change in labour size or mould quantity could happen during a PC's production. Therefore, two examinations on each resource can be applied to guarantee a process using the resource is executable in its entire duration, one is for the beginning of the process and the other is for the end, as shown in Table 6.5. Assume t1 is the simulation clock in a simulation. If a process can be started at t1, then the end time of the process, t2, can be calculated based on t1 and the process's duration. The condition that the process can be started at t1 is that the resource quantity currently available is no less than that needed by the process, which is the same as that in regular simulation. The underlying principle of resource examination for the end of the process is that, there should be still enough resource available to execute the process at t2, even if all the resource quantity occupied before t1 is not released till t2. Therefore, resource originally available at t2 minus resource quantity occupied before t1 should be greater than or equal to the resource quantity needed by the process.

A process is executable as long as both the two conditions for resource examinations in Table 6.5 have been met. The resource mentioned here is referred to as mould or labour. If the resource is labour in Figure 6.4, then t1 and t2 stand for t_a and t_b respectively in forward simulation, and for t_b and t_a in backward simulation. On the other hand, if the resource is mould, then t1 and t2 correspond to t_a and t_c separately in forward simulation, and to t_c and t_a in backward simulation.

Table 6.5: Two Conditions for Resource Examinations for Executing a Process in Simulation(D)

Parameters:

- $(double)\ t1$: ST of the process using mould or labour in PC production;
- $(double)\ t2$: FT of the process using mould or labour in PC production;
- $(integer)\ n\_Res\_Ndd$: resource quantity needed by the process in PC production;

Referenced functions:

- $(integer)\ n\_Res\_All((double)\ t)$: return the resource quantity initially available at the point of time t.
- $(integer)\ n\_Res\_Cur((double)\ t)$: return the resource quantity available when simulation clock is equal to t during simulation.

Condition for executing a process at the beginning of the process

- $n\_Res\_Cur(t1) \geq n\_Res\_Ndd$

Condition for executing a process at the end of the process

- $n\_Res\_All(t2) - (n\_Res\_All(t1) - n\_Res\_Cur(t1)) \geq n\_Res\_Ndd$

6.3 The 1st Forward Simulation

The 1st forward simulation tries to generate a feasible production schedule by producing as early as possible with both NT and OT available. It works in a manner similar to general discrete-event simulations that are widely adopted in literature.

6.3.1 Priority Rules

As explained above, two types of priority rule, "where" labour transfer rule and PC dispatching rule, may be needed for the 1st forward simulation.

6.3.1.1 CM Rule for Labour Transfer

Quite a few "where" rules have been proposed for DRC systems. Among them, the longest queue (LQ) rule and the earliest due date (EDD) rule are typical ones. In the case of precast production, LQ rule mainly focuses on the overall loading burden in future on different moulds, and assigns workers to the mould with the longest queue. On the other hand, EDD rule focuses on urgency of immediate PC demand, and allocates workers to the mould that is assigned the PC with the earliest due dates. Though widely adopted, LQ rule and EDD rule are not without limitations. In fact, the strength of one is the weakness of the other. That is, LQ rule does not consider the urgency of immediate demand, while EDD rule ignores the overall burden of mould. Therefore, a novel "where" labour transfer rule, critical mould (CM) rule, is established in the research to take into account the overall PC demands and their requirement on a mould. CM rule is supposed to possess the strengths of LQ and EDD rules and avoid their weaknesses.

6.3.1.1.1 The Basis for CM Rule

The motive of CM rule is to identify the criticality of every mould in terms of their requirement by PCs and to transfer labour to moulds according to such criticality. To identify the criticality of every mould, a special backward loading with mould only (BLWMO) is conducted before the 1st forward simulation. It should be noted that labour is not considered in BLWMO, since CM rule focuses on mould requirement by overall PC demands. For every exclusive mould type and individual sharable mould, BLWMO loads backwards from due dates the PCs that have been assigned to the mould but yet to be produced in the 1st forward simulation. As a result, possible latest ST and FT can be obtained for every PC to ensure a feasible schedule without any delay. During the following 1st forward simulation, latest ST of the next PC to be loaded on a mould can be taken as a signal of urgency of mould requirement by all the PCs left to load. At a certain simulation clock, CT, during the 1st forward simulation, the smaller the latest ST is, the lesser time interval between CT and the latest ST, thus the bigger chance delay would be incurred if the PC is not loaded onto the mould at CT. Therefore, criticality of a mould for PC loading can be established according to the latest ST of the next PC to load onto the mould. The smaller the latest ST of the next PC to load is, the more critical the mould is. During the 1st forward simulation, of all moulds in a PC group, the most critical mould with the next PC to load with the smallest latest ST should be selected first for labour transfer.

The basis of CM rule is similar to that for M_PC identification in CP rule used for aggregate planning, as explained in Chapter 5. Both CM rule and CP rule adopt BLWMO as a means for criticality identification. The main difference lies in that CM rule is applied after every PC is allocated to an exclusive mould type or individual sharable mould, and it only cares about every single mould requirement by PCs allocated to the mould. On the other hand, when CP rule is used, PC allocation to every mould has not been done, and BLWMO may be carried out for a PC type on both exclusive and sharable moulds. In addition, BLWMO in CM rule is carried out based on next-event time advance simulation, whereas BLWMO in CP rule is based on fixed-increment time advance simulation.

6.3.1.1.2 BLWMO in CM Rule

A general description of forward simulation based on the next-event time-advance approach is given by Law and Kelton (2000). First, the simulation clock is initialized and the times of occurrence of future events are determined and stored in Event List. Then the simulation clock is advanced to the time of the most imminent event, the state of the system is updated, and future event times are determined and added to Event List. This process of advancing the simulation clock from one event time to another is continued until eventually some specified stopping condition is satisfied. Backward simulation is actually reverse version of a regular forward simulation. The time advance and Event List processing mechanisms employed by the two simulations are the same (Watson et al., 1993). The basic idea of backward simulation is to start jobs at their due dates, represent reversed job routes, and use the job completion times as the order release times (Ying and Clark, 1994).

In this research, the following definitions are used for Simulation(D).

- Min_T: the minimum simulated time in Simulation(D). Min_T is the start time of the 1st and 2nd forward simulations and the end time of the backward simulation and BLWMO;
- Max_T: the maximum simulated time in Simulation(D). Max_T is the end time of the 1st and 2nd forward simulations and the start time of the backward simulation and BLWMO;
- CT: Current simulated time (simulation clock) during simulation;
- Event List: A list containing the next time when each type of event will occur (Law and Kelton, 2000).

Figure 6.5 presents the procedure of BLWMO used for mould criticality identification in CM rule. At first, initialize Event List, i.e., add Min_T, Max_T, and PCs' due dates into Event List. Then, advance the simulation clock, CT, to the next latest time in Event List, as the simulation is conducted backward in time. Initially, CT is equal to Max_T. At certain CT, if any event ends, i.e., any PC is finished, then the mould occupied by the PC is released and the profile of mould availability updated. Then, PC loading is tried for every exclusive mould type and individual sharable mould at CT. For a particular mould, PCs assigned to the mould is tried for loading in the sequence opposite to that for the 1st forward simulation. Therefore, of all PCs to be loaded on the mould, try to load the last PC at CT, which will be discussed in detail below. If the PC can be loaded, one mould of the corresponding exclusive mould type or the individual sharable mould is occupied and the mould availability profile is updated. The ST of the PC is inserted into Event List since it is the time when the mould occupied would be released. The PC is removed from the queue of the mould. After PC loading has been tried for all moulds, CT is advanced to the next latest time in Event List, and a new run of resource update and PC loading begins. The process continues until CT reaches Min_T, and the simulation stops.

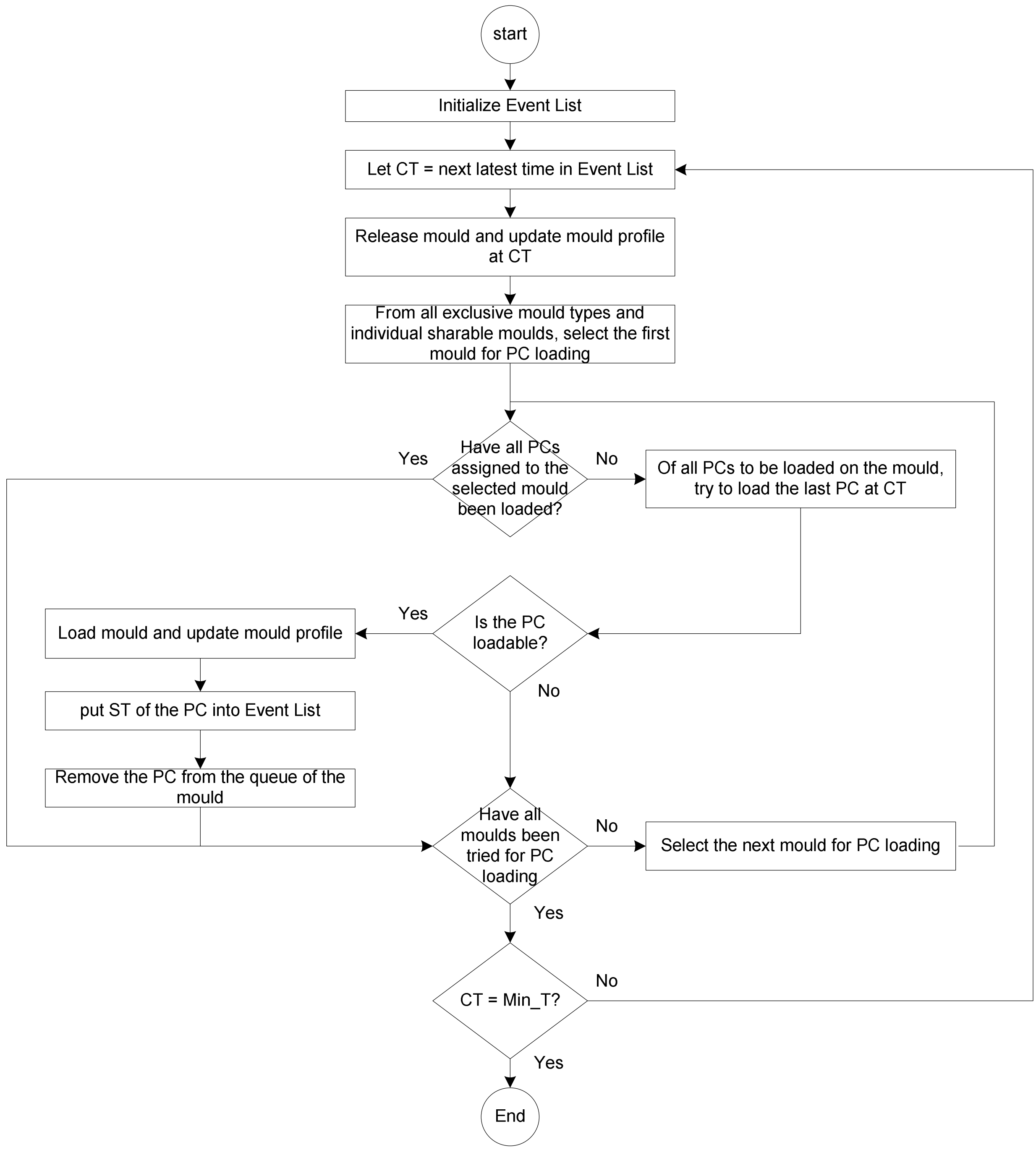


Figure 6.5: Procedure of BLWMO in CM Rule

Table 6.6 shows part of parameters and functions used for PC loading processes in BLWMO, the 1st forward simulation, the backward simulation and the 2nd forward simulation of Simulation(D). The procedure of trying for PC loading in BLWMO is presented in Figure 6.6 and the detailed algorithm given in Table E.2 of Appendix E. First, the two preconditions have to be met before a PC can be loaded to the corresponding mould. One is that the simulation clock must be no later than the PC's due date, while the other is that there must be at least one mould available at CT for the PC loading. With these preconditions, ST of every operation and the PC can be calculated using *Minus* function introduced in Table 6.4. It should be noted that different values of parameters should be used in *Minus* to reflect characteristics of operation 3, 2, 1, 0 in terms of duration, time zone used and preemption. In order to be consistent with the following 1st forward simulation, BLWMO allows operation 0, 1 and 2 to proceed in both NT and OT zones. After the ST of PC and operation 0 is calculated, the mould availability has to be checked to see if the PC production can proceed to the ST of PC. If yes, the PC is loadable; otherwise, the PC is non-loadable.

Table 6.6: Part of Parameters and Functions Used for PC Loading in Simulation(D)

Parameters:

- $(integer)\ g$: the PC group of a PC;
- $(integer)\ p$: the PC type in a PC group;
- $(integer)\ i$: the serial number of a PC in a PC type;
- $PC_{g,p,i}$: represents the ith PC of PC type p in PC group g;
- $(integer)\ a$: the serial number of operations for a PC production; a = 0 stands for mould changeover, 1 for preparation before concrete pouring, 2 for concrete pouring, and 3 for curing;
- $(double)\ ST^{B}_{g,p,i}$, $FT^{B}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the backward simulation;
- $(double)\ ST^{B}_{g,p,i,a}$, $FT^{B}_{g,p,i,a}$: ST and FT of the a th operation of $PC_{g,p,i}$ production in the backward simulation;
- $(double)\ ST^{BLWMO}_{g,p,i}$, $FT^{BLWMO}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in BLWMO;
- $(double)\ ST^{BLWMO}_{g,p,i,a}$, $FT^{BLWMO}_{g,p,i,a}$: ST and FT of the a th operation of $PC_{g,p,i}$ production in BLWMO;
- $(double)\ ST^{F1}_{g,p,i}$, $FT^{F1}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the 1st forward simulation;
- $(double)\ ST^{F1}_{g,p,i,a}$, $FT^{F1}_{g,p,i,a}$: ST and FT of the a th operation of $PC_{g,p,i}$ production in the 1st forward simulation;
- $(double)\ ST^{F2}_{g,p,i}$, $FT^{F2}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the 2nd forward simulation;
- $(double)\ ST^{F2}_{g,p,i,a}$, $FT^{F2}_{g,p,i,a}$: ST and FT of the a th operation of $PC_{g,p,i}$ production in the 2nd forward simulation.

Referenced functions:

- $(double)\ Plus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,\ (boolean)\ preemptive)$ see Table 6.3;
- $(double)\ Minus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,\ (boolean)\ preemptive)$ see Table 6.4.

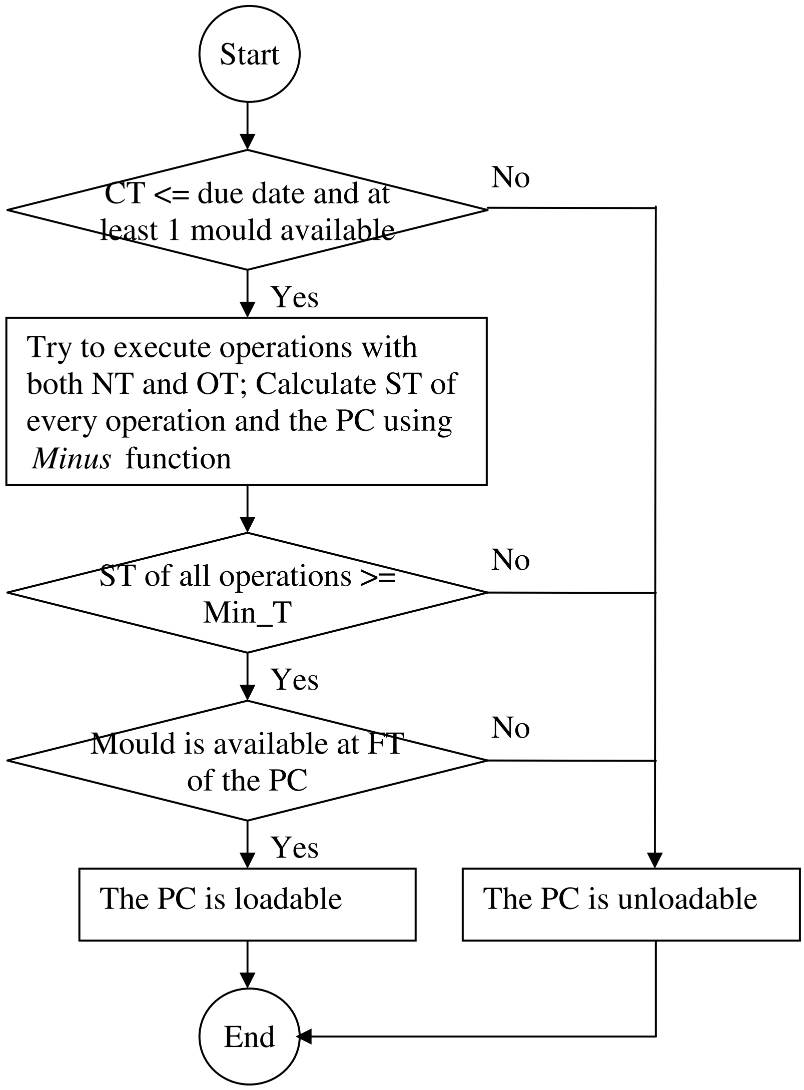


Figure 6.6: Procedure of Trying for PC Loading in BLWMO

6.3.1.2 EDD/LMC Rule for PC Dispatching

In the module of *Labour Grouping,* certain PC dispatching rule has to be used to perform the 1st forward simulation, as GA and predetermined constraint do not provide the basis for dispatching PCs assigned to every exclusive mould type and individual sharable mould. Many dispatching rules have been proposed for DRC shops, as summed up by Treleven (1989) and Hottenstein and Bowman (1998). Studies indicate that the dispatching rules which perform well in DRC systems are SOT (shortest operation time), EDD (earliest due date) and SPR (slack per remaining operation) (Treleven, 1989). Elvers and Treleven (1985) compared these rules and found that if lateness criteria are most important, the EDD and SPR rules are good. The EDD rule prioritizes jobs in each queue based on orders' due dates and has been commonly used in prior studies on due dates management (Kher and Fry, 2001). SPR is in fact a variant of EDD that divides the slack time by the number of remaining operations, and sequencing jobs in the order of the smallest value first (Vollmann et al., 1997).

In precast production, delivery on time is the key objective. It explains why EDD rule has been adopted by several studies on precast scheduling, such as Warszawski (1990) and Chan and Hu (2002). When a comprehensive labour organization is applied, casting operations are performed continuously and thus can be regarded as a whole in PC dispatching process. In this case, SPR rule would have a similar effect with EDD rule. In addition, reduction of mould changeovers is another important factor in determining the PC production sequence on a mould in practice, as illustrated by Q4.12 in Table 3.2 from the questionnaire survey. Based on these considerations, EDD/LMC rule is used in this research to dispatch PCs in *Labour Grouping*, with EDD being the primary rule and LMC the secondary.

6.3.2 Simulation Procedure

The procedure of the 1st forward simulation is given in Figure 6.7, where 'G', 'S' and 'T' stand for the module of *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring* respectively. For *Labour Grouping* and *PC Allocation & Sequencing*, BLWMO is conducted first to calculate the latest ST of every PC. If any PC cannot be loaded in BLWMO, then the schedule is infeasible, and simulation has to stop. Otherwise, the 1st forward simulation begins.

At first, Event List is initialized. Basically, Event List needs to include Min_T, Max_T, and PCs' due dates. Besides, the ST of NT zone on every working day within the planning horizon is added into Event List for two reasons. One is that labour become available when BT zone of a day finishes and a new working day starts, and the other is that labour size in every PC group may change on certain days. These points of time are used to update the profile of labour availability as the simulation proceeds. Furthermore, the time when availability of any mould changes also need to be put into Event List to update the mould profile during simulation.

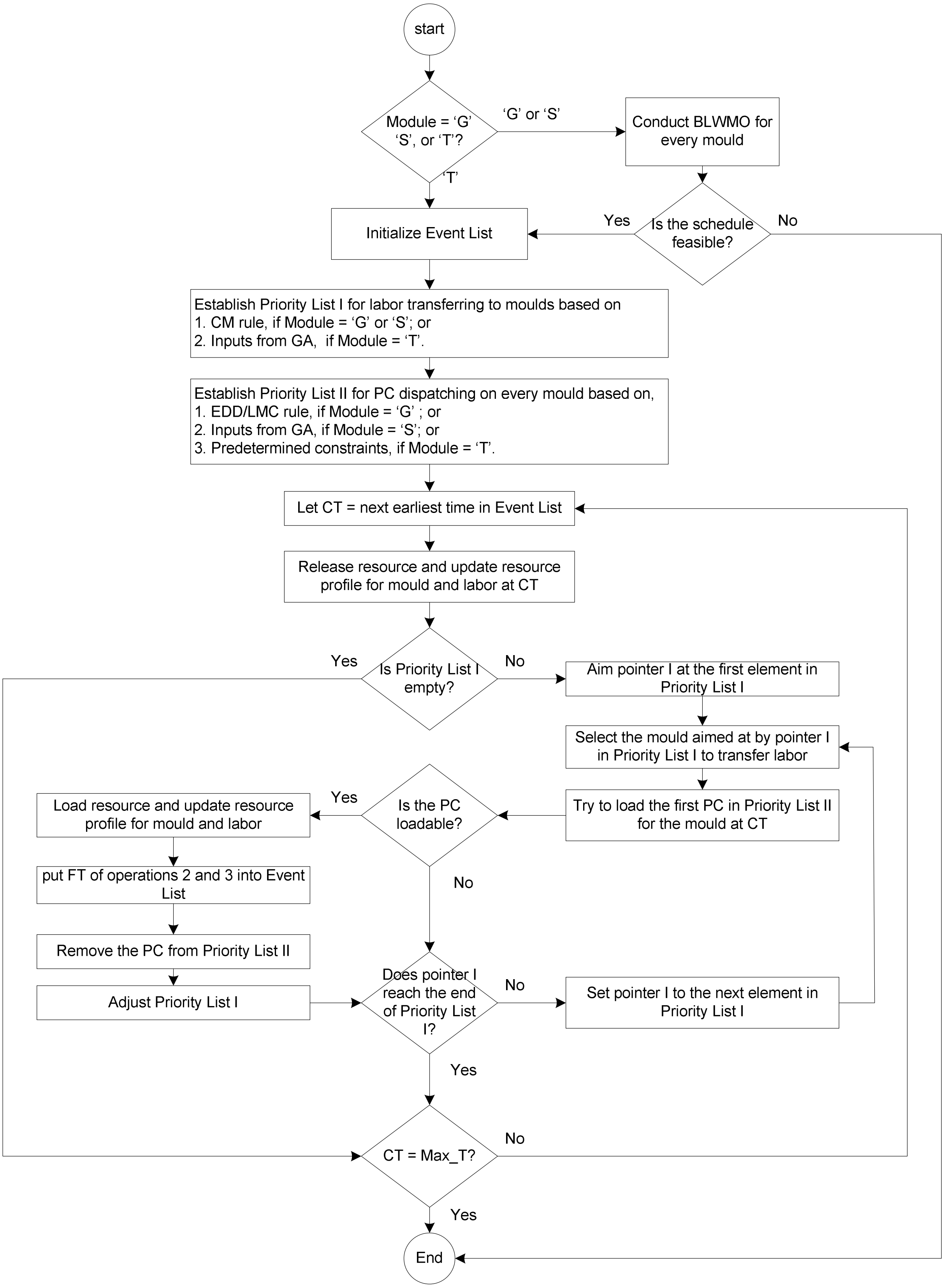


Figure 6.7: Procedure of the 1st Forward Simulation

Priority List I and a set of Priority List II are established for transferring labour to moulds and dispatching PC on every mould respectively. As discussed before, Priority List I is set up based on CM rule for *Labour Grouping* and *PC Allocation & Sequencing*, and on inputs from GA for *Labour Transferring*. Elements in Priority List I includes all exclusive mould types and individual sharable moulds. On the other hand, EDD/LMC rule, inputs from GA, and predetermined constraints form the basis for Priority List II for *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring* respectively. Every mould in Priority List I corresponds to a Priority List II, which include all the PCs to be loaded on the mould.

Next, advance the simulation clock, CT, to the next earliest time in Event List, as the simulation is conducted forward in time. Initially, CT is equal to Min_T. At certain CT, if any event ends, i.e., operation 2 or 3 of any PC is finished, then the labour or mould occupied by the PC is released. Besides, profile of resource availability is also updated if CT is equal to ST of NT zone on a working day or any time when mould quantity changes. A judgement is then made to see if Priority List I is empty. If Priority List I is not empty, transfer labour to every mould according to their order in Priority List I. Of all PCs to be loaded on a mould, try to load the first PC in Priority List II at CT, which will be discussed in detail below. If the PC is loadable, one mould of the corresponding exclusive mould type or the individual sharable mould, and the labour needed are occupied and the profiles of mould and labour availability are updated. The STs of operation 2 and 3 of the PC are inserted into Event List since they are times when the labour and the mould occupied would be released respectively. The PC is then removed from the Priority List II for the mould. If there is no PC left to be loaded on the mould, then the mould should be removed from Priority List I. Otherwise, if there is any PC left on the mould, then the sequence of elements (moulds) in Priority List I may need to be adjusted based on the updated PC information. After PC loading has been tried for all moulds in Priority List I, CT is advanced to the next earliest time in Event List, and a new run of resource update and PC loading begins. The process continues until CT reaches Max_T, and the simulation stops.

The procedure of trying for PC loading in the 1st forward simulation is presented in Figure 6.8 and the detailed algorithm given in Table E.3 of Appendix E.

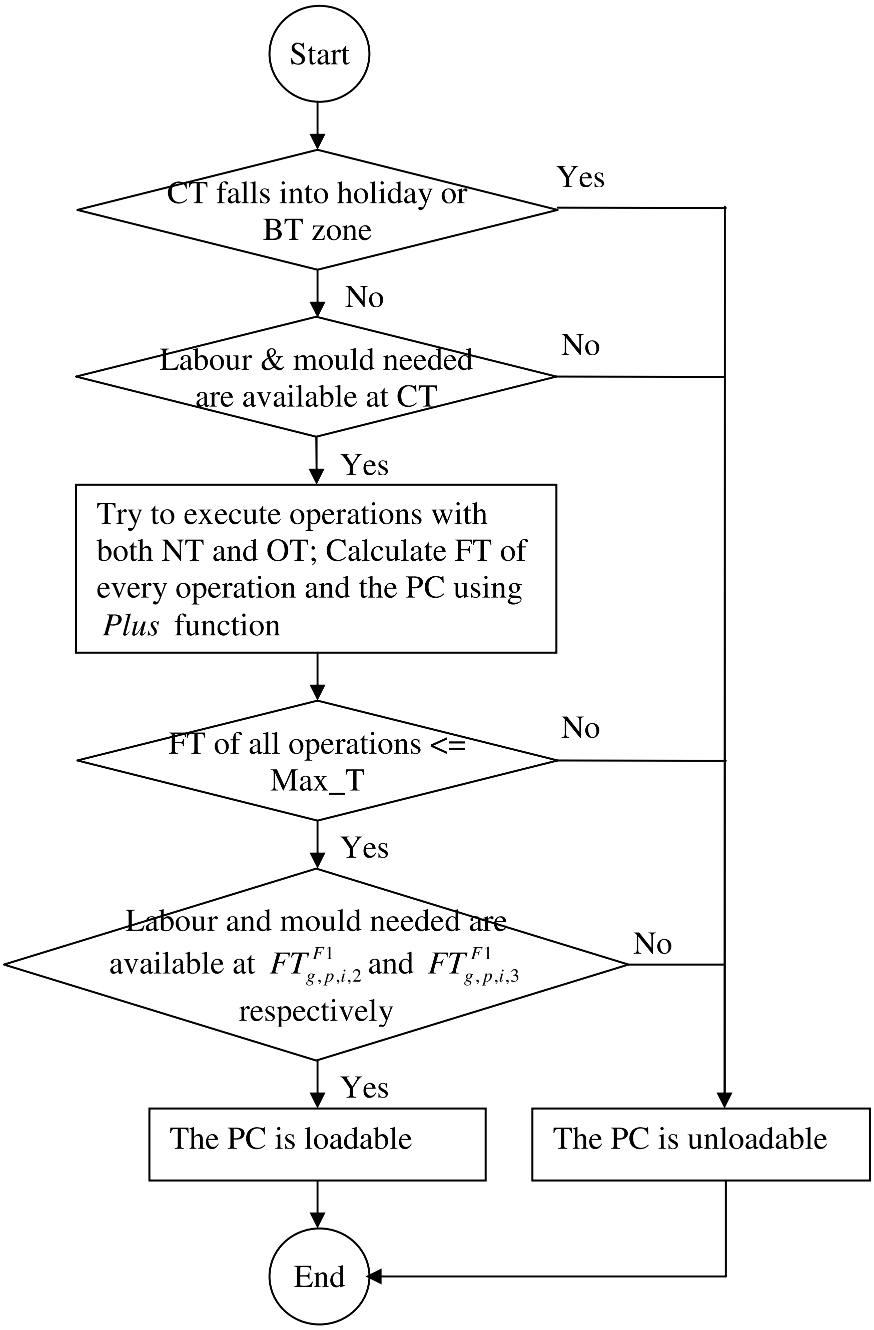


Figure 6.8: Procedure of Trying for PC Loading in the 1st Forward Simulation

First, the following four preconditions have to be met before a PC can be loaded at CT:

1. CT does not fall into any holiday;

2. CT does not fall into BT zone;
3. Labour available at CT are equal to or greater than that needed by the PC;
4. There is at least one mould available at CT for the PC loading.

With these preconditions, FT of every operation and the PC can be calculated using *Plus* function introduced in Table 6.3. It should be noted that the 1st forward simulation allows operation 0, 1 and 2 to proceed in both NT and OT zones. Different values of parameters should be used in *Plus* to reflect characteristics of operation 0, 1, 2 and 3 in terms of duration, time zone used and preemption. The PC is unloadable if FT of any operation from 0 to 3 exceeds Max_T. After FTs of all operations are calculated, labour and mould availability have to be checked to see if the PC production can proceed to FTs of both operation 2 and 3. If yes, the PC is loadable; otherwise, the PC is non-loadable.

6.4 The Backward Simulation

The 1st forward simulation expedites PC production as soon as possible by fully utilizing both NT and OT available. The resultant schedule may not be of good performance for two reasons. Firstly, some PCs may be produced much earlier than their due dates leading to excessive PC stock. Secondly, OT hours at the early stage of the planning horizon may be overused, while labour are left idle during certain NT hours at the late stage. Given these thoughts, backward simulation is conducted to “improve” the 1st forward schedule. In the backward simulation, PCs is pulled back close to their due dates to reduce PC stock. In addition, the backward simulation tries to utilize NT that is unused in the 1st forward schedule to release the overused OT, thus avoiding unnecessary OT cost.

6.4.1 Relationship between the Backward Simulation and the 1st Forward Simulation

Backward simulation is closely related to the 1st forward simulation. The main relationships between the backward simulation and the 1st forward simulation are given below:

- The backward simulation aims to improve the schedule result from the 1st forward simulation;
- The backward simulation is conducted after the 1st forward simulation. Only when a feasible schedule is obtained from the 1st forward simulation can the backward simulation proceed;
- To simplify the simulation process, the backward simulation keeps the same PC assignment to moulds and production sequence on every mould as those in the 1st forward schedule;
- Production time of every PC in the feasible 1st forward schedule forms a basis for operation execution in the backward simulation.

The last point of the above relationships can be explained in more detail. ST and FT of every operation in a PC production generated from the 1st forward simulation may be the minimum ST and FT that could probably be achieved for the PC. Thus, attempt should be made in backward simulation so that the resultant ST and FT are no earlier than the minimum ST and FT from the 1st forward schedule respectively. Otherwise, PC demand may not be fully satisfied and an infeasible backward schedule incurred. In the research, this is achieved in two ways. One way is to establish priority lists for PC dispatching in the backward simulation on a basis of FTs result from the 1st forward simulation, which will be discussed in the following section. In addition, FT of an operation in the 1st forward schedule is used to control NT and OT use by the operation in the backward simulation. When operation a (a = 0, 1 or 2) of $PC_{g,p,i}$ is tried for execution at CT in the backward simulation, if $CT > FT^{F1}_{g,p,i,a}$, it means there is chance that $ST^{B}_{g,p,i,a} \geq ST^{F1}_{g,p,i,a}$ even if the operation is executed with NT only. Thus, the operation is first tried for execution with NT only. If $ST^{B}_{g,p,i,a} \geq ST^{F1}_{g,p,i,a}$, then any OT used by the operation in the 1st forward schedule is saved, and the schedule performance improved. Otherwise, if the execution with NT only leads to $ST^{B}_{g,p,i,a} < ST^{F1}_{g,p,i,a}$, the operation is conducted the operation with both NT and OT to make sure $ST^{B}_{g,p,i,a} \geq ST^{F1}_{g,p,i,a}$. On the other hand, if $CT \leq FT^{F1}_{g,p,i,a}$ when trying to execute the operation at CT, it means

$FT^{B}_{g,p,i,a} \le FT^{F1}_{g,p,i,a}$. In the case, $ST^{B}_{g,p,i,a} \le ST^{F1}_{g,p,i,a}$ is bound to happen. Thus both NT and OT should be used in the backward simulation as so to pull back $ST^{B}_{g,p,i,a}$ as close to its minimum value, $ST^{F1}_{g,p,i,a}$, as possible, thus lowering the risk of causing an infeasible schedule with unfinished operations or PCs.

6.4.2 Two Priority Lists for PC Dispatching

In the backward simulation, production of one PC includes two points of time when resource occupation starts. One is the end of operation 3 when mould is occupied, while the other is the end of operation 2 when labour is taken up. Use of mould and labour continues till the front of operation 0 when they are released together. Therefore, $FT^{F1}_{g,p,i,3}$ and $FT^{F1}_{g,p,i,2}$ are used to form two priority lists, Priority List I and Priority List II, based on which operation 3 and operation 2~0 can be executed respectively in the backward simulation. The larger $FT^{F1}_{g,p,i,3}$ ($FT^{F1}_{g,p,i,2}$) is, the sooner the corresponding operation (operations) is (are) tried for execution.

In the backward simulation, the priority list based on $FT^{F1}_{g,p,i,2}$ or $FT^{F1}_{g,p,i,3}$ may be applied in the following two forms:

1. Relative application, where every PC in a priority list is tried for execution in turn at a certain CT, whether the preceding PC can be loaded or not. Finally, the actual loading sequence may be different from that initially in the priority list;
2. Absolute application, where actual execution of different PCs in the backward simulation strictly follows the PC order in the priority list. At certain CT, if a PC cannot be loaded, other PCs left in the priority list are not tried for loading as long as their corresponding $FT^{F1}_{g,p,i,2}$ or $FT^{F1}_{g,p,i,3}$ are earlier than that of the current PC.

Relative application and absolute application have different effects on operation execution and thus schedule performance. In particular, exploration should be made into such effects on execution of those operations using common resources, which are referred to as operations 2~0 of different PCs sharing labour among each other. The advantage of relative application is that every PC in the priority list gets a chance of being tried for loading, as long as resources needed are available. Thus, resources can be fully utilized and PCs are pulled back as close to their due dates as possible. On the other hand, absolute application may not lead to good utilization of resource and low PC stock due to its rigid requirement on PC loading sequence.

Figure 6.9 gives an example to illustrate the advantage of relative application over absolute application. The example focuses on part of the backward simulation process where the simulation clock is advanced from a certain time, t1, to the end time of the simulation, Min_T. There are totally 6 labour available for production of 7 PCs (PC 1~7). 2 labour are needed for PC 1, 2, 3, 6 and 7, and 3 labour for PC 4 and 5. Assume each PC use different mould, which is available along the planning horizon. Thus mould does not constitute a constraint for PC production. All the 7 PCs are due at the end of the planning horizon so that their productions can be pulled back as long as the labour needed are available. As shown in Figure 6.9(a), when the simulation proceeds at t1, PC 6 and 7 have been loaded while the other 5 PCs, PC 1~5, are waiting for loading. The positions of PC 1~5 in Figure 6.9(a) stand for their production times in the 1st forward simulation. As mentioned above, a priority list can be established for PC loading at t1, where PCs are sequenced from PC 5 to PC 1 in a decreasing order of their $FT^{F1}_{g,p,i,2}$. Relative application or absolute application of the priority list can be used to load PCs at t1. PC 5 and 4 are tried for loading in both of the two applications. But they cannot be loaded at t1 since only two labour are available, which are less than those needed for their production, 3. If the priority list is applied relatively, the next PC in the list, PC 3, is tried for loading at t1 though PC 5 and 4 cannot be loaded. This time, PC 3 can be loaded since it only needs 2 labour. On the other hand, if the absolute application is used, PC loading is not tried for PC 3, 2 and 1, because their $FT^{F1}_{g,p,i,2}$ are less than those of the unloadable PC 5 and 4. The simulation clock is then advanced to the next latest time in Event List, t2, for a new turn of PC loading. The simulation continues to Min_T and stops. The two resultant schedules based on relative and absolute applications of the priority list are presented in Figure 6.9(b) and 6.9(c) respectively. It can be seen that the actual PC loading sequences with relative application is PC 3, 5, 4, 2, and 1, which is different from that in the priority list. On the contrary, absolute application loads PCs strictly following the PC sequence in the priority list. Obviously, the schedule based on relative application has a better performance than that based on absolute application. With PC 3 loaded at t1, Figure 6.9(b) has a lower PC stock than Figure 6.9(c), as well as avoids labour idling from t1 to t2, as happens in Figure 6.9(c).

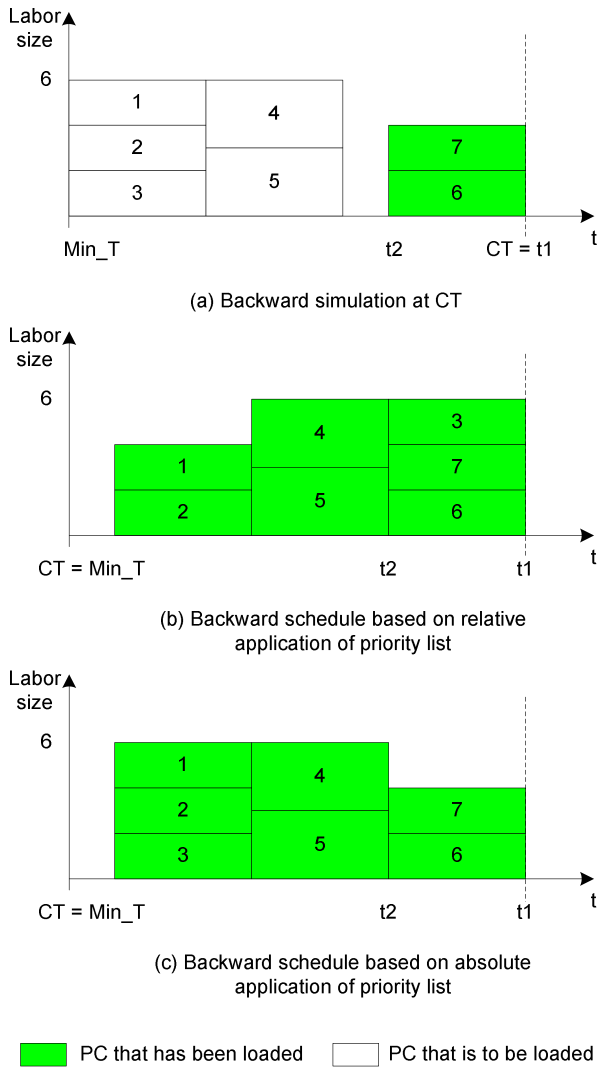
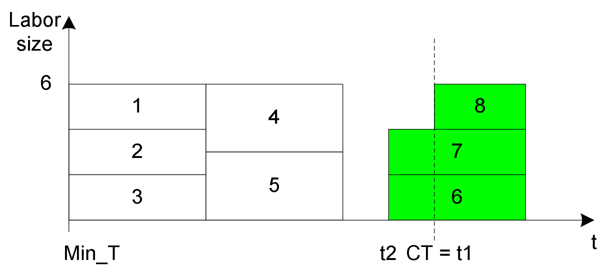


Figure 6.9: Example 1 of Relative and Absolute Applications of Priority List in Backward Simulation

Despite the above advantage, relative application might result in an infeasible schedule due to the possible difference between actual PC loading sequence and that in the priority list. During backward simulation, if a PC is loaded before any other PC with an earlier position in the priority list, there is a chance that the occupation of labour by the former impedes the latter from being loaded at a time later than or equal to its FT in the 1st forward simulation (i.e., $FT^{F1}_{g,p,i,2} \leq FT^{B}_{g,p,i,2}$), thus resulting in an infeasible schedule with unfinished PC. On the other hand, in absolute application, strict observance of PC loading sequence in the priority list can guarantee a feasible backward schedule, where the production time of every operation is later than or equal to that in the 1st forward schedule (e.g., $FT^{F1}_{g,p,i,2} \leq FT^{B}_{g,p,i,2}$ and $FT^{F1}_{g,p,i,3} \leq FT^{B}_{g,p,i,3}$).

Figure 6.10 illustrates the limitation of relative application compared with absolute application. As shown in Figure 6.10(a), Example 2 has the same input conditions as Example 1 in Figure 6.9, expect that one more PC, PC 8, has been loaded and t1 is moved to the end of PC 8. The focus of the backward simulation is still put on loading 5 PCs from t1 to Min_T. Both relative and absolute applications of the priority list are used to try to load PCs in a sequence from PC 5 to PC 1, resulting in two backward schedules, as shown in Figure 6.10(b) and 6.10(c) respectively. In Figure 6.10(b), the relative application leads to an infeasible schedule, where PC 1 cannot be loaded within the planning horizon. Production of PC 3 from t1 backward takes up labour that should be used for PC 4, moving ahead the production of PC 4 compared to the 1st forward schedule. Advanced PC 4 production, in turn, occupies labour that should be used for PC 1, so that PC 1 cannot be finished by Min_T. On the contrary, in Figure 6.10(c), the schedule based on absolute application is feasible. It is not unexpected since PC sequence in the priority list is strictly complied in PC loading.



(a) Backward simulation at CT

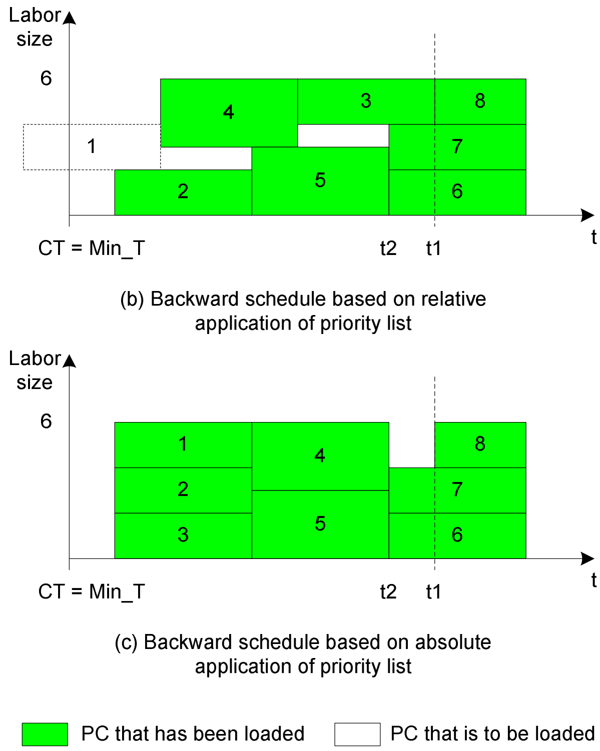


Figure 6.10: Example 2 of Relative and Absolute Applications of Priority List in Backward Simulation

For execution of operation 3 (curing) in the backward simulation, relative application is always superior to absolute application. First, like operation 2~0, relative application for operation 3 can fully utilize resource and pull back PC production as late as possible. In addition, operation 3 only uses mould as single resource and every PC has been allocated with a mould for exclusive use before the backward simulation starts. Therefore, the difference between actual PC loading sequence and PC sequence in the priority list would not cause any resource conflict between PCs using different moulds. In other words, unfinished operation 3 of any PC would not be caused by relative application of the priority list, as there is no mutual influence between executions of operation 3 with different moulds.

In conclusion, for execution of operation 3, relative application of the corresponding priority list can achieve a better performance than absolute application, while for execution of operation 2~0, the former is not necessarily superior to the latter. Therefore, in the backward simulation, only relative application of Priority List I is used for execution of operation 3, whereas Priority List II is applied both relatively and absolutely for execution of operation 2~0.

6.4.3 Simulation Procedure

The procedure of the backward simulation is given in Figure 6.11. At first, Event List is initialized. As in the 1st forward simulation, Min_T, Max_T, and PCs' due dates, and the time when availability of any mould changes are added into the Event List for the backward simulation. However, unlike the 1st forward simulation where the ST of NT zone on every working day is included in Event List, the backward simulation puts into Event List the FT of OT zone on every working day to update the profile of labour availability. This is because the FT of OT zone is a "start" point of time when labour become available on every working day in the backward simulation. Additionally, $FT^{F1}_{g,p,i,2}$ of every PC is added into Event List, as a signal of how to use labour working hours in NT and OT zones for operation 2~0, as previously mentioned. Priority List I and II are established for execution of operation 3 and operation 2~0 respectively. As discussed before, Priority List I includes PCs in a decreasing order of their $FT^{F1}_{g,p,i,3}$, whereas Priority List II includes PCs in a decreasing order of their $FT^{F1}_{g,p,i,2}$.

Next, advance the simulation clock, CT, to the next latest time in Event List, as the simulation is conducted backward in time. Initially, CT is equal to Max_T. At certain CT, if any event ends, i.e., operation 0 of any PC is finished, then labour or mould occupied by the PC is released. Besides, profile of resource availability is also updated if CT is equal to FT of OT zone of a working day or any time when mould quantity changes. Operation 3 of PCs in Priority List I and operation 2~0 of PCs in Priority List II are tried for execution at CT respectively. First, every PC in Priority List I is tried for loading sequentially, if Priority List I is not empty and the PC is ready for "curing". A PC is ready for "curing" only if the succeeding PC on the same mould has been loaded for "curing". The process of trying to execute operation 3 for a PC will be discussed below. If a PC in Priority List I is loadable, one mould of the corresponding exclusive mould type or the individual sharable mould is occupied and the profile of mould availability is updated. ST of operation

3 of the PC is inserted into Event List as the time when the PC is ready for execution of operation 2~0. The PC is then removed from Priority List I.

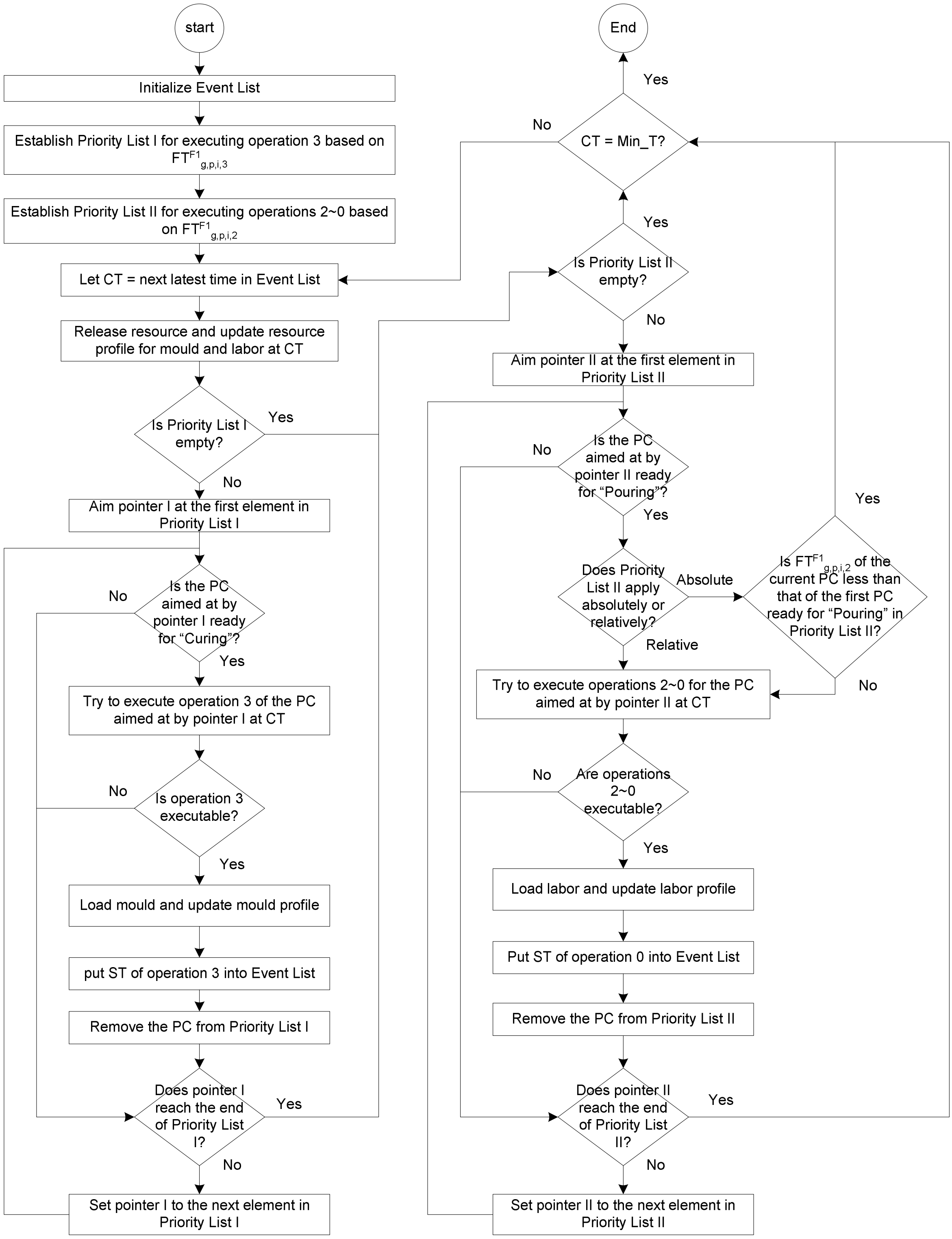


Figure 6.11: Procedure of the Backward Simulation

After operation 3 has been tried for execution for all PCs in Priority List I, operation 2~0 is tried for execution for PCs in Priority List II. Priority List II can be applied relatively or absolutely. As explained in the previous section, relative application tries to load every PC in Priority List II sequentially no matter whether PCs with earlier positions in the list is loadable or not. On the contrary, in absolute application, a PC is tried for loading only when its $FT^{F1}_{g,p,i,2}$ is no less than that of the 1st PC in Priority List II. If $FT^{F1}_{g,p,i,2}$ of the PC is less than that of the 1st PC in Priority List II, the PC loading at CT is stopped, and the system will start a new run of PC loading at the next latest time in Event List. Another condition for operation 2~0 of a PC to be tried for execution is that it is ready for "pouring", i.e., the "curing" (operation 3) of the PC has been finished by CT ($CT \le ST^{B}_{g,p,i,3}$). The process of trying to execute operation 2~0 for a PC will also be given below. If a PC in Priority List II is loadable, labour needed is occupied and the profiles of labour availability updated. ST of operation 0 of the PC is inserted into Event List as the time when the occupied mould and labour are released. The PC is then removed from Priority List II.

After execution of operation 2~0 has been done for PCs Priority List II, CT is advanced to the next latest time in Event List, and a new run of resource update and PC loading begins. The process continues until CT reaches Min_T, and the simulation stops.

It is straightforward to try to execute operation 3 of a PC in the backward simulation. Operation 3 is executable at CT if two conditions are satisfied, i.e., CT is no later than the PC's due date, and there is at least one mould available at CT for the PC loading.

The procedures of trying for execution of operation 2~0 in the backward simulation are presented in Figure 6.12 and the detailed algorithm given in Table E.5 of Appendix E. The procedure in Figure 6.12 involves arrangement of the 3 operations with proper hours in NT and OT zones, as explained step by step below:

1. If CT falls into holiday or BT zone, then $PC_{g,p,i}$ is unloadable;

2. Else if CT falls into OT zone and is greater than $FT^{F1}_{g,p,i,2}$, the PC is not loaded. The backward simulation aims to fully utilize NT available to reduce overused OT in the 1st forward schedule. Therefore, operation 2 should be loaded with NT instead of OT during any period of time after $FT^{F1}_{g,p,i,2}$;
3. Otherwise if CT falls into NT zone and is greater than $FT^{F1}_{g,p,i,2}$, then try to execute operation 2~0 with NT as much as possible while ensuring $ST^{B}_{g,p,i,a}$ is no earlier than $ST^{F1}_{g,p,i,a}$ ($a = 0,1,2$). At last, labour availability has to be examined to see if there is enough labour available at $ST^{B}_{g,p,i,0}$ for PC production. If yes, then the PC is loadable;
4. If all the above conditions cannot be met, then CT must be earlier than or equal to $FT^{F1}_{g,p,i,2}$. When Priority List II is applied absolutely, it is known that production time of every PC in the backward schedule is no earlier than that in the 1st forward schedule. Therefore, CT must be equal to $FT^{F1}_{g,p,i,2}$ in absolute application of Priority List II, and both NT and OT should be used to execute operation 2~0 in the backward simulation. In this case, the PC is loadable with STs of operation 2~0 being equal to those in the 1st forward schedule;
5. In the case that $CT \le FT^{F1}_{g,p,i,2}$ and relative application of Priority List II is used, both NT and OT are used for executing operation 2~0 to minimize any unfinished operation and PC. If any ST of the 3 operations is smaller than Min_T, it means the PC cannot be finished within the planning horizon. Otherwise, the final examination on resource availability at $ST^{B}_{g,p,i,0}$ is conducted. If both labour and mould available at $ST^{B}_{g,p,i,0}$ are enough for the PC production, then the PC is loadable.

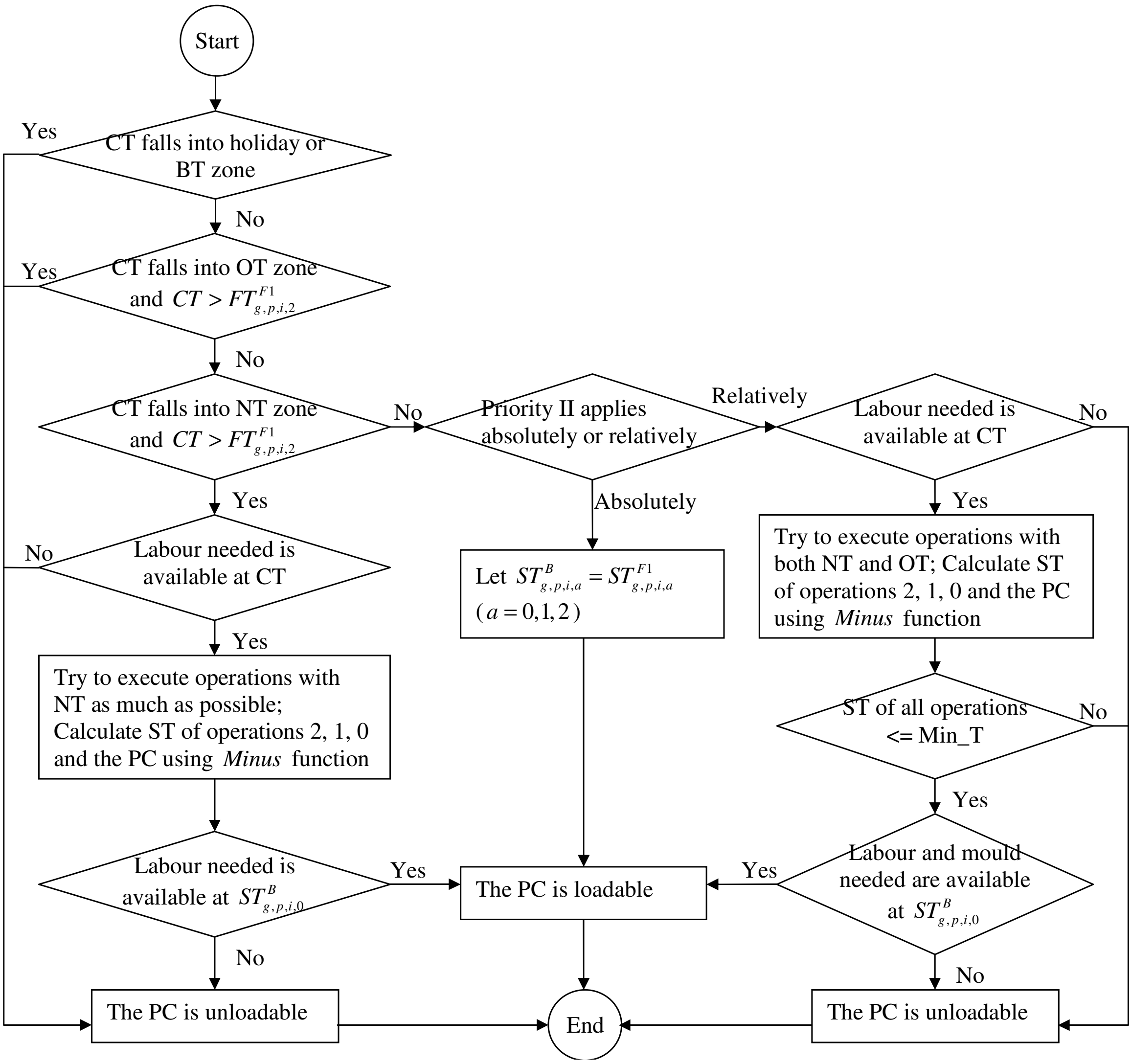


Figure 6.12: Procedure of Trying for Execution of Operation 2~0 in the Backward Simulation

6.5 The 2nd Forward Simulation

The purpose of the backward simulation is to improve the feasible schedule result from the 1st forward simulation. However, the generated backward schedule may not be ready for implementation in practice even if it is a feasible schedule without any unfinished PC. Firstly, the backward simulation would generate a time gap between operation 2 and 3 of a PC, if labour requirement cannot be satisfied at the time of $ST^{B}_{g,p,i,3}$ of the PC. By contrast, such gap does not exist as operation 2 (concrete pouring) is closely followed by operation 3 (curing) in practice. Secondly, the simulation is carried out backwards in time, from a day in future to the current day, and from OT zone to NT zone on each day. Therefore, it is possible that on a particular day in the backward schedule, labour are engaged in production in the evening and in the afternoon, but idle in the morning. This situation is also against practice. In daily shop-floor production, labour start working in the morning and are kept busy till they finish the job for the day. To "repair" the backward schedule and to make it consistent with practice and suitable for implementation, the 2nd forward simulation is performed.

6.5.1 Relationship between the 2nd Forward Simulation and the Backward Simulation

The 2nd forward simulation is closely related to the backward simulation. The main relationships between the 2nd forward simulation and the backward simulation are given below:

- The 2nd forward simulation aims to repair the schedule result from the backward simulation;
- The 2nd forward simulation is conducted after the backward simulation. Only when a feasible schedule is obtained from the backward simulation can the 2nd forward simulation proceed;
- The 2nd forward simulation keeps the same PC assignment to moulds and production sequence on every mould as those in the 1st forward schedule and the backward simulation;
- Production time of every PC in the feasible backward schedule forms a basis for operation execution in the 2nd forward simulation.

The last point can be discussed in more details. The backward schedule, if feasible, would have a good performance, though it may be inapplicable. Therefore, the purpose for the 2nd forward simulation is to repair the inapplicability of the backward schedule while maintaining its good performance. It is straightforward for a forward simulation to make a repair work, since it goes in a natural way consistent with reality, thus being capable of generating an applicable schedule. On the other hand, to achieve a good performance equivalent to the backward schedule, the production time from the backward schedule should be utilized as a basis for the 2nd forward simulation. The utilization of production time from the backward schedule is achieved in the following ways:

- Firstly, ST of every PC from the backward schedule is adopted as a basis to establish a priority list for dispatching PCs in the 2nd forward simulation. The smaller a PC's ST in the backward schedule is, the earlier the PC is tried for loading in the 2nd forward simulation. This attempts to achieve a resource utilization profile similar to that in the backward schedule, and thus to get a feasible 2nd forward schedule. To simplify the simulation process, only one priority list is used in the 2nd forward simulation for dispatching PCs, as opposed to two priority lists used in the 1st forward simulation. In this case, once a PC is selected for loading, the corresponding labour and mould, if any, is automatically allocated to the PC.
- Secondly, the 2nd forward simulation loads a PC on the same day as the backward simulation. This is to ensure that PCs would be produced as late as possible to avoid overstock;
- Thirdly, production of a PC in the 2nd forward simulation should fully utilize NT as long as its production time does not exceed that in the backward schedule. This is to avoid unnecessary OT usage while maintaining a feasible schedule without delay.

6.5.2 Simulation Procedure

The procedure of the 2nd forward simulation is given in Figure 6.13. At first, Event List is initialized, including the same elements as those for the 1st forward simulation. Priority List is established for PC dispatching based on ST of every PC from the backward schedule. All PCs in Priority List are arranged in an increasing order of their $ST^{B}_{g,p,i,0}$.

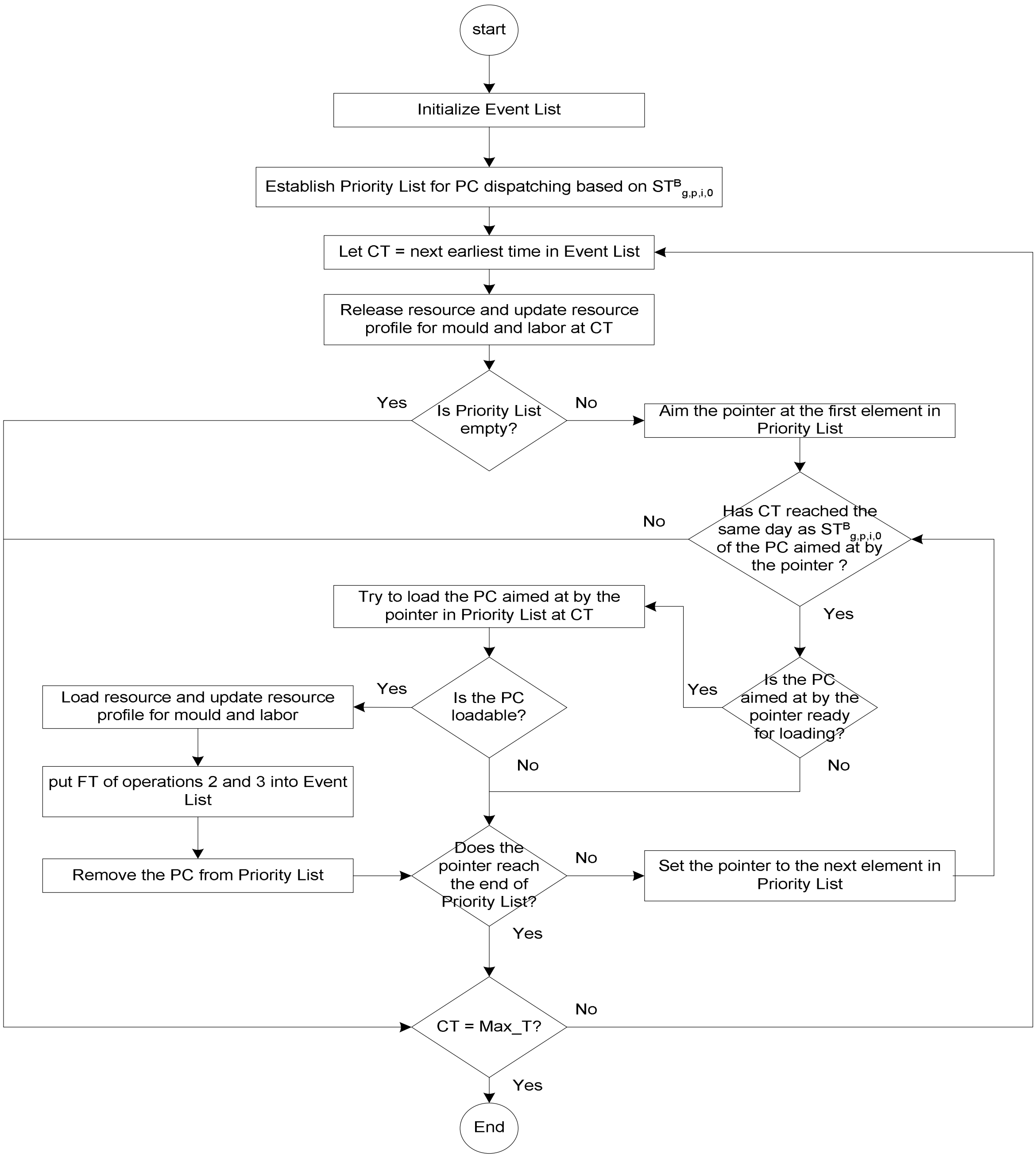


Figure 6.13: Procedure of the 2nd Forward Simulation

Next, advance the system clock, CT, to the next earliest time in Event List. At certain CT, profile of labour and mould availability is first updated, as in the 1st forward simulation. PCs in Priority List are then tried for loading sequentially if Priority List is not empty. For a particular PC, a judgement is made to see if CT has reached the same day as the PC's $ST^{B}_{g,p,i,0}$. If the answer is no, then the entire PC loading process at CT stops. Otherwise, the PC is tried for loading when it is ready, i.e., the preceding PC on the same mould has been loaded. The procedure of trying to loading a PC will be discussed in detail below. If a PC is loadable, mould and labour needed are occupied and the profiles of mould and labour availability updated. ST of operation 2 and 3 of the PC is inserted into Event List to indicate when to release resources. The PC is then removed from Priority List. After PC loading has been tried for all PCs in Priority List with their $ST^{B}_{g,p,i,0}$ being no later than the day of CT, CT is advanced to the next earliest time in Event List, and a new run of resource update and PC loading begins. The process continues until CT reaches Max_T, and the simulation stops.

The procedure of trying for PC loading in the 2nd forward simulation is presented in Figure 6.14 and the detailed algorithm given in Table E.6 of Appendix E. This procedure is similar to that in Figure 6.8 for the 1st forward simulation. The main difference lies in calculation of FT for operation 0~2. Operation 0, 1, or 2 is first executed with NT hours only to avoid unnecessary OT usage. If the resultant FT exceeds its counterpart from the backward simulation, the operation is executed again with both NT and OT.

6.6 Procedure of Bidirectional Simulation

A complete process of bidirectional Simulation(D) in Simulation-GA based approach for detailed scheduling is presented in Figure 6.15. First, the 1st forward simulation is conducted and the corresponding objective cost, C1, is calculated. If the 1st forward schedule is infeasible, then the bidirectional Simulation(D) stops and C1 is transferred to GA as the fitness value. However, if the 1st forward schedule is feasible, two backward simulations are performed with relative application and absolute application respectively of their Priority List II. For each backward simulation, if the resultant backward schedule is feasible, the 2nd forward simulation is conducted, and the objective cost, C2 or C3, is calculated. On the contrary, if the backward schedule is infeasible, the 2nd forward simulation is not done and C2 or C3 is set to be equal to C1. Finally, the minimum among C1, C2, and C3 is chosen as the fitness value and transferred to GA, and the corresponding 1st or 2nd forward schedule is regarded as the final schedule result from this run of bidirectional Simulation(D).

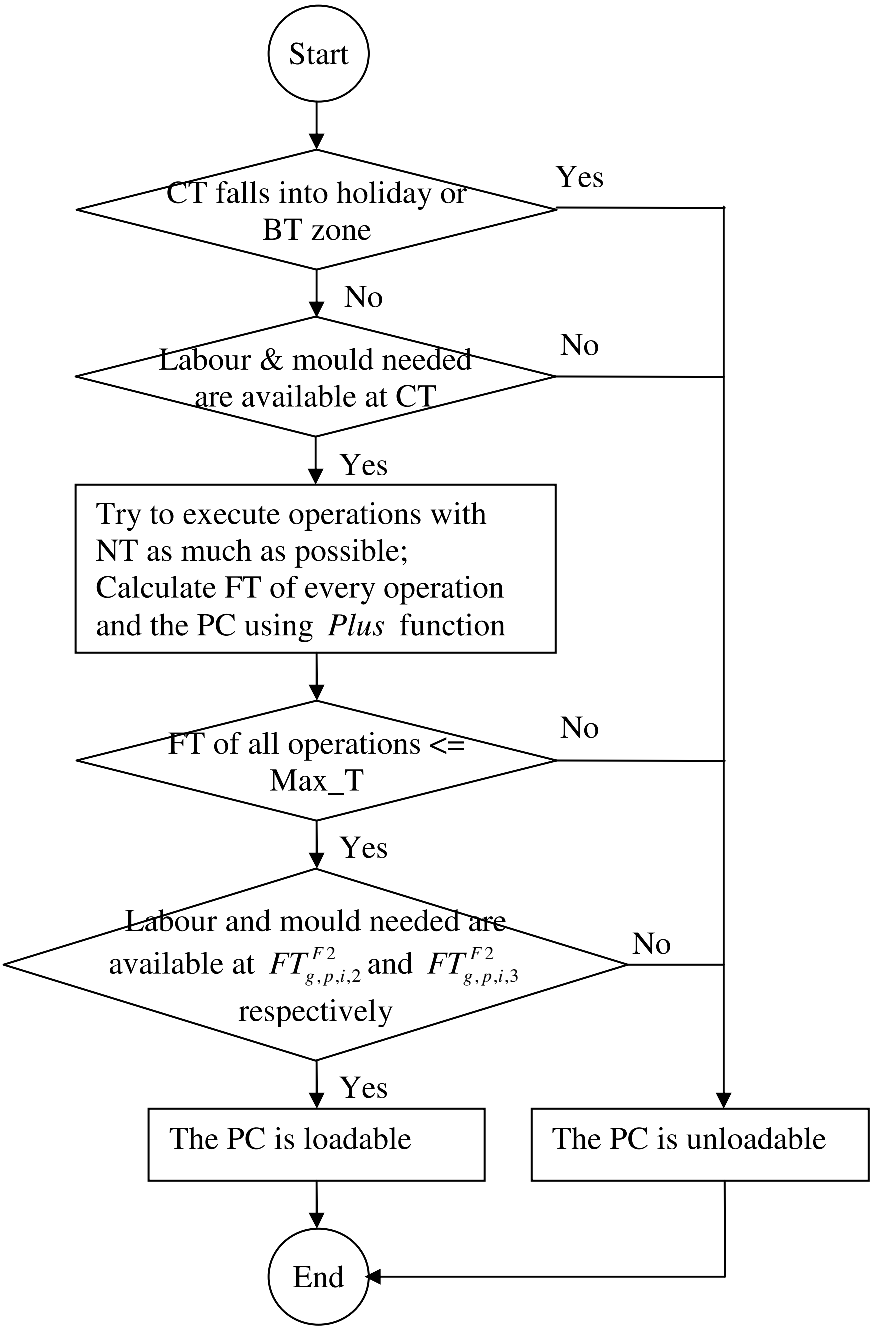


Figure 6.14: Procedure of Trying for PC Loading in the 2nd Forward Simulation

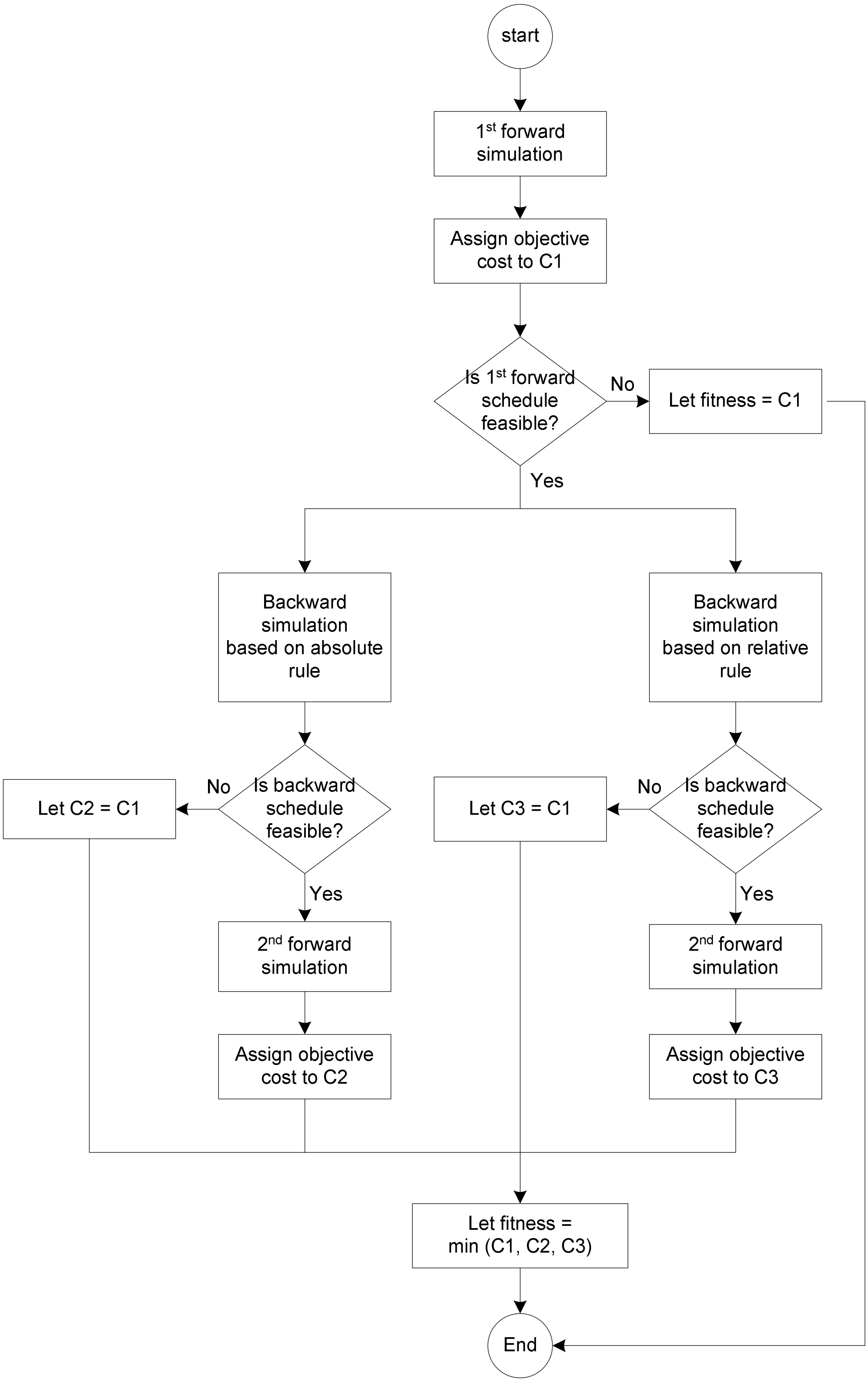


Figure 6.15: Bidirectional Simulation(D) in Simulation-GA Based Approach for Detailed Scheduling

6.7 Implementation of GA

Implementation of GA in *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring* at the operational level are described below.

6.7.1 Encoding and Decoding

The major distinction of GA for detailed scheduling lies in different encoding and decoding techniques used for the three modules at the operational level. Usually, the feasibility and legality of a chromosome has to be carefully handled during encoding and decoding between chromosomes and solutions. Feasibility refers to the phenomenon of whether a solution decoded from a chromosome lies in the feasible region of a given problem, whereas legality refers to the phenomenon of whether a chromosome represents a solution to a given problem (Gen and Cheng, 1997). Different strategies have been proposed to deal with infeasible or illegal chromosomes. As stated by Orvosh and Davis (1994), for many combinatorial optimization problems, the repairing strategy does indeed surpass other strategies such as rejecting strategy or penalizing strategy.

6.7.1.1 *Labour Grouping*

As mentioned above, labour size and max OT hour for every PC group in every planning period are the decision variables for *Labour Grouping*. Therefore, similar to chromosome representation in *Labour Sizing*, integer representation and real number representation are used for labour size and max OT hour respectively for *Labour Grouping*. Figure 6.16(a) shows an example of chromosome representation for *Labour Grouping* with 3 PC groups and 2 planning periods.

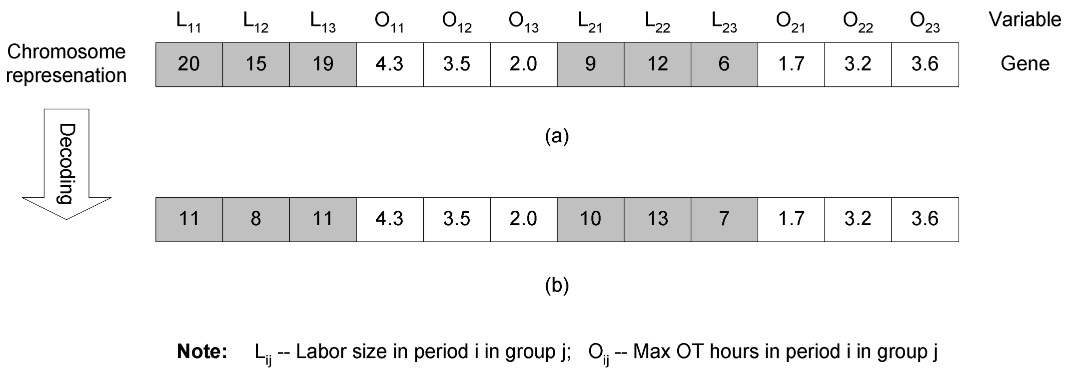


Figure 6.16: Example of Chromosome Representation and Decoding for *Labour Grouping*

With the above chromosome representation, however, infeasible chromosomes may be generated through two-cut-point crossover or uniform mutation. In *Labour Grouping*, the feasible region is represented by domain constraints (Equation 6.1 and 6.2) and equality constraints (Equation 6.3).

$$L_{ij} \in [L_{ij}^L, L_{ij}^U] \qquad \text{Equation (6.1)}$$

$$O_{ij} \in [O_{ij}^L, O_{ij}^U] \qquad \text{Equation (6.2)}$$

$$\sum_{j=1}^{n} L_{ij} = L_i^p \qquad \text{Equation (6.3)}$$

where L_{ij} and O_{ij} are decision variables of labour size and max OT hour in period i in PC group j, respectively. Domain constraints include the lower bounds (L_{ij}^L and O_{ij}^L) and upper bounds (L_{ij}^U and O_{ij}^U) on the variables (L_{ij} and O_{ij}), while equality constraints refer to the condition that the sum of labour sizes in all PC groups in a planning period is equal to the labour size available in the plant in the period (L_i^p). A feasible chromosome is one that can satisfy both domain constraints and equality constraints. However, after a two-cut-point crossover or uniform mutation, equality constraints (Equation 6.3) may not be satisfied by newly generated offspring. That is, the sum of labour sizes in all labour groups may be less or larger than the total labour size in the plant. Therefore, an infeasible offspring is yielded. To deal with this problem, a repairing approach is adopted in decoding procedure to transfer an infeasible chromosome to a feasible chromosome. If $\sum_{j=1}^{n} L_{ij} \neq L_i^p$ for any chromosome, then the decoding should be conducted with the following repairing approach.

$$L_{ij}^* = \text{int}\left(\frac{L_{ij}}{\sum_{j=1}^{n} L_{ij}} L_i^p \right), \quad j = 1, \ldots, n-1 \qquad \text{Equation (6.4)}$$

$$L_{i,n}^* = L_i^p - \sum_{j=1}^{n-1} L_{ij}^* \qquad \text{Equation (6.5)}$$

where L_{ij}^* represents the adjusted labour size in period i in PC group j.

In the example given in Figure 6.16, suppose the total labour sizes in the plant in both period 1 and 2 equal to 30. Obviously, the chromosome given in Figure 6.16(a) is infeasible since the sum of labour sizes in all three groups is 54 for period 1 and 27 for period 2. After the decoding based on Equation (6.4) and (6.5), a feasible chromosome is generated, as shown in Figure 6.16(b).

6.7.1.2 *PC Allocation & Sequencing*

PC Allocation & Sequencing and *Labour Transferring* actually belong to combinatorial optimization problems, which are characterized by a finite number of feasible solutions. Traditionally, chromosomes are represented by a simple binary string. This simple representation is not well suited for combinatorial problems (Gen and Cheng, 1997). Thus, various non-string representation schemes have been proposed during the past two decades. Random key representation is chosen in this research for *PC Allocation & Sequencing* and *Labour Transferring*. First introduced by Bean (1994), random key representation can eliminate the infeasibility and illegality of offspring that may be generated during genetic operations, thus is applicable to a wide variety of sequencing and optimization problems (Gen and Cheng, 1997, and Chan and Hu, 2002a). Random key representation encodes a solution with random numbers, which in turn are used as sort keys to decode the solution.

The module of *PC Allocation & Sequencing* only focuses on allocation of PCs (both B_PC and S_PC) among exclusive mould types and individual sharable moulds, and PC production sequence on every single sharable mould. When random key representation is applied to *PC Allocation & Sequencing* for a PC family with a certain sharable mould type and several exclusive mould types, each PC involved corresponds to a gene (a random key) in a chromosome. A random key consists of two parts: an integer and a fraction. The integer part is interpreted as the mould assignment for that PC, whereas sorting the fractional parts provides the PC sequence on each mould. This is similar to the application of random key generation in job shop scheduling (Norman and Bean, 1997). Consider a *PC Allocation & Sequencing* for a PC family, which consists of I ($I \geq 2$) PC types with N_i ($N_i \geq 1$) PCs in PC type i ($i = 1,...,I$). PCs in every PC type are sorted in an ascending order of their due dates, and let PC_{ij} stand for the j th ($j = 1,...,N_i$) PC of the i th ($i = 1,...,I$) type. Obviously, the quantity of PCs in the PC family is $\sum_{i=1}^{I} N_i$, equal to the length of the corresponding chromosome (the number of genes). Any PC_{ij} can be produced on a common sharable mould type with a quantity of S ($S \geq 1$). Besides, it may also be produced on a specific exclusive mould type with a quantity of E_i ($E_i \geq 0$). With the random key representation, a random key (gene value) for PC_{ij} in the chromosome is a real number randomly generated from $(1,\ 1+S+E_i)$. A random key less than $S+1$ means PC_{ij} is allocated to the common sharable mould type and the integer part indicate the specific mould PC_{ij} is allocated to. On the other hand, a random key greater than $S+1$ means PC_{ij} is allocated to its exclusive mould type.

An example of random key representation for *PC Allocation & Sequencing* is given in Figure 6.17(a). In the example, a PC family consists of two PC types, PC type 1 and 2, including 7 PCs and 5 PCs respectively. The two PC types share two moulds of a sharable mould type S(A). Besides, two moulds of exclusive mould type E(B) and one mould of exclusive mould type E(C) are also available for production for PC type 1 and 2 respectively. Therefore, the random keys are randomly generated from (1, 5) and (1, 4) for PC_{1j} and PC_{2j} respectively, and assigned to every gene in the chromosome accordingly, as shown in Figure 6.17(a).

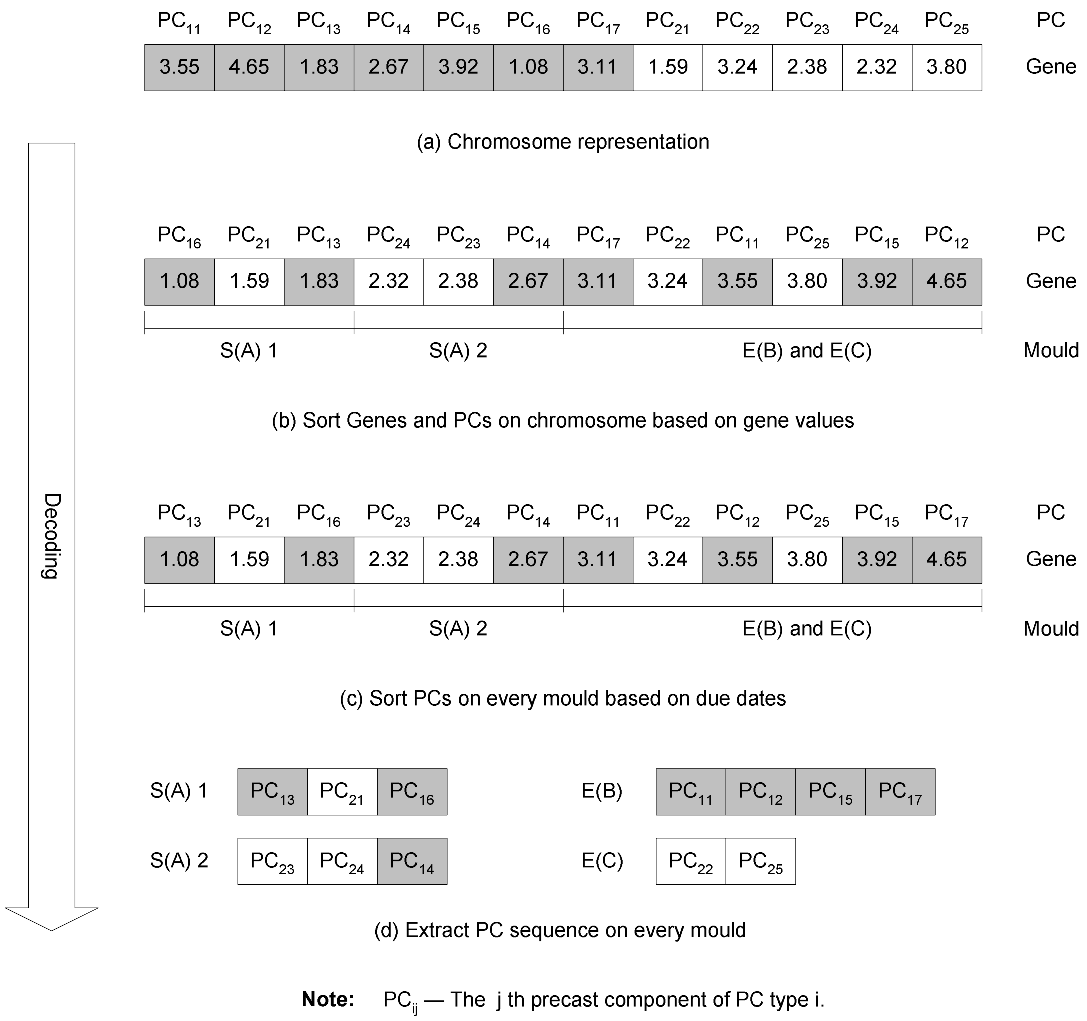


Figure 6.17: Example of Random Key Representation and Decoding for *PC Allocation & Sequencing*

Decoding the chromosome to a solution takes three steps, as shown by Figure 6.17(b), 6.17(c), and 6.17(d) respectively. First, genes and PCs in the chromosome are sorted in an ascending order of their random keys (gene values). The integer parts of the random keys specify the sharable mould to which the PC assigned, as given in Figure 6.17(b). If more than one PC of the same type is assigned to a particular mould, PCs with earlier due dates should be produced sooner. This is to achieve on-time delivery of PCs. To meet this requirement, for every mould, PCs from the same type are exchanged so that they are arranged in an ascending order of their due dates, while random key of every gene remains unchanged, as shown in Figure 13(c). At last, PC production sequence on every exclusive mould type and every single sharable mould can be extracted, as shown in Figure 6.17(d).

6.7.1.3 *Labour Transferring*

GA in the module of *Labour Transferring* aims to generate a reasonable sequence to transfer labour to PCs on exclusive mould types and individual sharable moulds in every PC group. Random key representation is also adopted in GA to encode labour transfer sequence into a chromosome. In this application, the length of a chromosome is equal to the number of PCs in the PC group for *Labour Transferring*, with each gene (a random key) corresponding to a PC. Every random key is a random number from (0, 1). Sorting the random keys in a chromosome provides the labour transfer sequence among PCs.

An example of random key representation for *Labour Transferring* is given in Figure 6.18(a). In the example, there are 3 moulds with 3, 3, and 4 PCs assigned to mould 1, 2 and 3 respectively. PC assignment and production sequence on every mould can be seen in the figure. For every PC, a random key are generated from (0, 1), and assigned to the corresponding gene in the chromosome.

Decoding the chromosome to a solution takes two steps, as shown by Figure 6.18(b) and 6.18(c) respectively. First, genes and PCs on the chromosome are sorted in an ascending order of their random keys (gene values), generating a preliminary sequence for transferring labour to PCs, as shown in Figure 6.18(b). However, this preliminary sequence may be infeasible as PCs from the same mould may not be arranged in the predetermined PC order on the mould. For example, in Figure 6.18(b), PC_{33} is placed ahead of PC_{31}. To repair the infeasible solution, PCs from the same mould are rearranged in the order consistent with their original position on the mould, and a final feasible sequence for transferring labour to PCs is created, as shown in Figure 6.18(c).

PC_{11}	PC_{12}	PC_{13}	PC_{21}	PC_{22}	PC_{23}	PC_{24}	PC_{31}	PC_{32}	PC_{33}	PC
0.32	0.83	0.59	0.55	0.08	0.11	0.67	0.38	0.92	0.24	Gene
Mould 1			Mould 2				Mould 3			

(a) Chromosome representation

PC_{22}	PC_{23}	PC_{33}	PC_{11}	PC_{31}	PC_{21}	PC_{13}	PC_{24}	PC_{12}	PC_{32}	PC
0.08	0.11	0.24	0.32	0.38	0.55	0.59	0.67	0.83	0.92	Gene

Decoding

(b) Sort genes and PCs on chromosome based on gene values

PC_{21}	PC_{22}	PC_{31}	PC_{11}	PC_{32}	PC_{23}	PC_{12}	PC_{24}	PC_{13}	PC_{33}	PC
0.08	0.11	0.24	0.32	0.38	0.55	0.59	0.67	0.83	0.92	Gene

(c) Sort PCs from every mould based on their positions on the mould

Note: PC_{ij} — The j th precast component on the i th mould.

Figure 6.18: Example of Random Key Representation and Decoding for *Labour Transferring*

6.7.2 Crossover, Mutation and Selection

GA that is applied for the three modules for detailed scheduling employs the same genetic operation subsystem and selection subsystem as those for aggregate planning. That is, two-cut-point crossover, uniform mutation, and $(\mu+\lambda)$ selection are adopted in GA for detailed scheduling, as explained in Section 5.4.2, 5.4.3 and 5.4.4 in Chapter 5. It should be noted that the crossover and mutation may yield infeasible offspring, which need to be repaired through the decoding subsystem, as described above.

Chapter 7

Validation and Testing of IPSMPP

7.1 Introduction

To test the validity of the proposed model, IPSMPP, a prototype system is established using the general object-oriented programming language, C#. Two tests are conducted where the prototype system is used to solve an aggregate planning problem and a detailed scheduling problem. The data used in the tests is based on the information collected from the field study in the two precast plants in Singapore, as mentioned in Chapter 3. Comparisons are then made among the results obtained from different approaches.

In IPSMPP, GA is used as an optimization technique in search of satisfying or optimal solutions. As mentioned in Chapter 2, a few parameters have direct impacts on the performance of GA and their values need to be determined. Based on the literature review on GA studies and preliminary tests, the values of these parameters used in the two tests are set as follows: (i) population size, 200, (ii) the number of generations, 200, (iii) crossover rate, 0.9, and (iv) mutation rate, 0.1.

7.2 Test I for Aggregate Planning

Test I aims to ascertain the validity of IPSMPP for aggregate planning. In particular, the following issues are examined in the test.

1. Planning method used in practice vs. IPSMPP;
2. Traditional rules vs. CP rule for PC dispatching;
3. Forward simulation vs. bidirectional simulation.

The actual method used in practice for intermediate planning usually takes three steps, namely mould planning, PC allocation, and labour planning. Forward scheduling method is adopted to develop the master production schedule, with the aim of fully utilizing resources and producing PCs as early as possible. During scheduling, EDD/LMC rule is used for PC dispatching. (Refer to Section 3.3.2 in Chapter 3 for a more detailed description of the actual method.)

In IPSMPP for aggregate planning, bidirectional simulation is established for schedule development with a novel CP rule for PC dispatching. For the purpose of comparison, two more approaches are designed. One approach uses single forward simulation based on CP rule to develop schedules. In the other approach, traditional PC dispatching rules is incorporated into single forward simulation for schedule development. As mentioned in Section 5.2.1 of Chapter 5, the traditional rules include EDD, LMC, and LSC. In the forward simulation, they are used consecutively, with EDD being the 1st rule, followed by LMC and LSC. Note that in the two planning approaches, GA is also used as an optimization engine to work together with simulation. The main distinction among the two approaches and IPSMPP lies in that they employ different priority rules or different scheduling directions. For simplicity, the following symbols are used to represent these approaches in this test.

- F_ACT: Actual method used in practice;
- F_TRD: Forward simulation based on traditional PC dispatching rules;
- F_CP: Forward simulation based on CP rule;
- BI_CP: IPSMPP employing bidirectional simulation based on CP rule.

For the model validation, the four approaches are applied respectively to solve the aggregate planning problem in the test. Then, the three issues mentioned above can be examined by comparing results from the four approaches.

7.2.1 Description of Test

Test I involves precast production for an existing project (A), a new project (B), and forecast demand (C) in a precast plant. The shop drawing design was just finished for Project B, and therefore it is time to do mould planning for the project, labour planning and master schedule development for the precast plant.

The planning horizon covers 8 planning periods (0~7), the duration of each being 1 month. Every planning period includes 4 loading buckets, with each being 1 week long and covering 6 working days. There are 32 (0~31) loading buckets in total. 24 workers are available in the current period, Period 0, and labour size can only be changed from Period 1 onwards. Daily NT and upper bound OT hours are 8 hours and 6 hours respectively. Hourly labour costs are S$5 (Singapore dollar) for NT working and S$7.5 for OT. Labour hiring and firing costs are estimated at S$400 and S$300 per labour respectively.

Table 7.1 shows relevant information in aggregate planning, including PC types in every project, mould type(s) that can be used for every PC type, man-hours needed per PC, stock cost per PC per day, unit volume per PC, minimum start week of every PC type, and PC demand to be met within the planning horizon. There are a total of 7 exclusive mould types (E0~E6) and 6 sharable mould types (S0~S5) available for PC production in the plant. Mould quantity of every mould type in Project A and sequence-dependent changeover hours on sharable moulds are given in Table 7.2 and 7.3 respectively. For Project B, there are 4 exclusive mould types (E3~E6) and 3 sharable mould types (S3~S5) involved in mould planning. For simplicity, assume that a PC production requires 24 mould hours of an exclusive or sharable mould. Therefore, one mould can produce at most 6 PCs in a week. The production capacity of a sharable mould decreases if there is any mould changeover incurred. “Minimum start week” in Table 7.1 refers to the earliest week where production of a PC type can start. It mainly depends on how long it takes for shop drawing design and mould fabrication. Forecast demand (C) is obtained based on market analysis and described in terms of “Typical PC for plant”, PC type 16.

Table 7.1: PC and Mould Information in Aggregate Planning

Project	PC Type	Mold type		Labor hours	Stock cost (S$)	PC volume (m3)	Min start week	PC demand at the end of every week																															
		E	S					0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A	0	E0	–	14	0.44	0.88	0	0	0	20	20	0	20	20	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	E1	S0	15	0.50	1.00	0	0	14	0	14	0	14	0	14	0	2	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	E2	S0	15	0.50	1.00	0	0	0	20	0	20	0	20	0	20	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	–	S1	12	0.38	0.76	0	0	16	16	16	16	0	0	0	0	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	–	S1	12	0.38	0.76	0	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
	5	–	S2	22	1.68	3.35	0	0	0	20	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	–	S2	22	1.68	3.35	0	0	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	–	S2	22	1.68	3.35	0	0	0	0	0	0	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B	8	E3	–	22	1.70	3.40	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	16	0	0	0	16	0
	9	E4	S3	24	1.80	3.60	8	0	0	0	0	0	0	0	0	18	18	18	18	5	5	5	5	5	5	18	18	18	18	5	5	5	5	5	5	18	18	18	18
	10	E5	S3	24	1.80	3.60	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	0	0	0	0	0	0	0	22	22	22	0	0	0	0
	11	–	S4	18	1.30	2.60	6	0	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
	12	–	S4	18	1.30	2.60	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	11	11	11	11	11	11	11	11	0	0	0
	13	E6	S5	19	1.40	2.80	6	0	0	0	0	0	0	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	14	–	S5	19	1.40	2.80	6	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	15	–	S5	19	1.40	2.80	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
C	16	–	–	18	0.98	1.95	8	0	0	0	0	0	0	0	0	0	0	0	0	28	28	28	28	32	32	32	32	40	40	40	40	43	43	43	43	51	51	51	51

Table 7.2: Mould Type and Quantity in Project A

Mould type	E0	E1	E2	S0	S1	S2
Quantity	3	1	1	1	3	4

Table 7.3: Mould Changeover Hours among PCs on Sharable Moulds

S0				S1				S2				
Change-over hour		To PC type		Change-over hour		To PC type		Change-over hour		To PC type		
		1	2			3	4			5	6	7
From PC Type	1	0	8	From PC Type	3	0	4	From PC type	5	0	4	2
	2	8	0		4	4	0		6	4	0	2
									7	2	2	0
S2				**S3**				**S4**				
Change-over hour		To PC type		Change-over hour		To PC type		Change-over hour		To PC type		
		9	10			11	12			13	14	15
From PC Type	9	0	8	From PC Type	11	0	4	From PC type	13	0	4	8
	10	8	0		12	4	0		14	4	0	2
									15	2	8	0

7.2.2 Analysis of Results

In the test, aggregate planning integrates mould planning, labour planning and master production schedule development, and resolves them together for a good solution to the problems as a whole, as explained in Chapter 5. First, aggregate planning is conducted using the actual planning method, F_ACT, to establish a base production plan (including mould and labour plans, and master production schedule). Then, three more production plans are generated with the Simulation-GA based approaches, F_TRD, F_CP and BI_CP, respectively. Some results obtained from Test I are given in Appendix B. A large delay penalty is set to ensure no delay is incurred in every resultant schedule. Performances of various production plans are evaluated based on the total variable cost, as shown in Table 7.4.

Table 7.4: Total Variable Costs (S$) in Various Plans

Cost category	F_ACT	F_TRD	F_CP	BI_CP
1. Mold cost (S$)	198,000	213,000	193,000	193,000
2. Labor cost (S$)	278,383	281,003	277,973	272,955
(1) Hiring & firing	*5,600*	*10,200*	*7,200*	*6,300*
(2) NT	*257,280*	*249,600*	*249,600*	*263,040*
(3) OT	*15,503*	*21,203*	*21,173*	*3,615*
3. Stock cost (S$)	17,948	23,416	14,142	11,916
Total cost (S$)	**494,331**	**517,419**	**485,114**	**477,871**
% of F_ACT	100.0%	104.7%	98.1%	96.7%

As expected, BI_CP plan achieves the best performance (lowest total variable cost) among all the plans developed by the four different approaches. It even attains the lowest cost in all the three major cost categories. Compared to F_ACT plan, BI_CP plan reduces overall cost by over 3%. F_CP plan ranks the second best, which may be attributed to its low mould investment and NT labour cost. F_TRD performs the worst in that it needs extra moulds, consumes more OT hours, as well as holds overstock. Explorations are made, as follows, into every cost category to see why these approaches behave differently in aggregate planning.

7.2.2.1 Mould Cost

Table 7.5 provides information on mould quantity and cost generated in the four production plans. It can be seen that F_CP and BI_CP use the smallest quantity of moulds or have the best combination of various mould types, resulting in the lowest total mould cost of S$193,000. On the other hand, F_TRD incurs the highest cost of S$213,000 in mould planning.

Table 7.5: Mould Quantity and Cost (S$) in Various Plans

Mould type	Unit cost (S$)	F_ACT		F_TRD		F_CP		BI_CP	
		No.	Cost	No.	Cost	No.	Cost	No.	Cost
E3	25,000	1	25,000	1	25,000	1	25,000	1	25,000
E4	27,000	0	0	0	0	1	27,000	1	27,000
E5	27,000	0	0	0	0	0	0	0	0
S3	32,000	3	96,000	3	96,000	2	64,000	2	64,000
S4	13,000	2	26,000	2	26,000	2	26,000	2	26,000
E6	12,000	3	36,000	3	36,000	3	36,000	3	36,000
S5	15,000	1	15,000	2	30,000	1	15,000	1	15,000
Total cost (S$)			198,000		213,000		193,000		193,000

In order to illustrate why this difference in mould planning takes place, consider the production of PC types 13, 14 and 15. PC type13 can be produced on both exclusive mould E6 and sharable mould S5, whereas PC types14 and 15 can only be made on S5. Through GA, F_CP generates the best mould combination – three E6 and one S5. Initial demand of PC types 13, 14 and 15 and their production on moulds E6 and S5 in F_CP plan are given in Table 7.6. Obviously, with this mould plan, F_CP approach can fully satisfy the PC demand without any delay. Since there is a fairly big demand for PC types 14 and 15, but only one S5 available, S5 becomes critical for PC types 14 and 15. It means production of PC types 14 and 15 should start early and take up S5 for a rather long time, otherwise some delays would be incurred.

Table 7.6: Initial Demand of PC Types 13, 14 & 15 and Their Production on E6 & S5 in F_CP Plan

Initial PC Demand														
Week		6	7		8	9	10	11	12		13	14	15	…
PC type	13	0	24		24	24	24	18	18		18	18	18	…
	14	0	0		0	0	0	9	9		9	0	0	…
	15	0	0		0	0	0	0	0		0	11	11	…
PC Production on E6 & S5														
Week		6	7		8	9	10	11	12		13	14	15	…
E6	PC type	13	13		13	13	13	13	13		13	13	13	…
	No.	18	18		18	18	18	18	18		18	18	18	…
S5	PC type	13	13	14	14	14	14	14	14	15	15	15	15	…
	No.	6	1	4	6	4	6	6	1	4	6	6	6	…

However, the mould combination of three E6 and one S5 does not work with F_TRD approach. F_TRD uses EDD as the first priority rule to dispatch PCs, and ignores the urgent mould requirement by PC types 14 and 15. Table 7.7 shows what F_TRD approach would do under this mould combination – PC demand and production at the end of Week 12. It can be seen that S5 has been occupied by PC type 13 from Week 6 to 9 since PC type 13 has the earliest due date during the simulation process of these weeks. PC type 14 only gets produced from Week 10 when its due date becomes immediate. Loading of PC types 14 and 15 apparently starts late considering their relatively large demand. Therefore one PC of PC type 14 is left unsatisfied at the end of Week 12, as shown in Table 7.7. From this week onwards, there would be more delays incurred for PC types 14 and 15. In order to generate a feasible master schedule with respect to due date, one more mould type S5 is added by F_TRD, at the price of extra mould investment.

Table 7.7: Demand of PC Types 13, 14 & 15 and Their Production at the End of Week 12 in F_TRD Plan

PC Demand												
Week		6	7	8	9	10	11	12	13	14	15	…
PC type	13	0	0	0	0	0	0	0	0	18	18	…
	14	0	0	0	0	0	0	1	9	0	0	…
	15	0	0	0	0	0	0	0	0	11	11	…
PC Production on E6 and S5												
Week		6	7	8	9	10	11	12	13	14	15	…
E6	PC type	13	13	13	13	13	13	13				…
	No.	18	18	18	18	18	18	18				…
S5	PC type	13	13	13	13	14	14	13				…
	No.	6	6	6	6	5	6	6				…

With CP rule based on the backward loading using mould as a single resource, BLWMO, F_CP approach can the solve problem with F_TRD. Table 7.8 gives the PC demand and result obtained from BLWMO at the beginning of Week 7 in F_CP plan. It can be seen there is no D_PC at Week 7 since all PCs are due for delivery on later weeks. Therefore, F_CP starts to identify M_PC and calculate its CV and/or MCA, using BLWMO. Since PC types 13, 14 and 15 can be produced on S5, they form a PC family and are identified for M_PC together. Initial BLWMO_E for PC type 13 on E6 results in 30 PCs to be loaded on the current week, Week 7. That is, PC_Gap@CB is equal to 30. Based on the algorithm for M_PC identification in Section 5.2.2.2, transferred demands of PC type 13 from E6 to S5 are calculated. As seen in Table 7.8, 6 PCs are transferred at Weeks 8, 9, 10, 20, and 30 respectively, so that the total amount of the transferred demands is equal to the PC_Gap@CB and the transferred demands are distributed as late as possible within the planning horizon. Then, BLWMO_S on S5 is conducted for the transferred demands of PC type 13 and the demands of PC types 14 and 15, leading to a CV of 23.9 for the PC family. It should be noted that, to account for the potential mould changeover on S5, the multiplier α_s in the algorithm in Table 5.3 is set to 1.1 in this test. Therefore, the weekly production capacity of S5 in BLWMO_S is equal to 5.45 ($=6/1.1$) PCs. At last, the maximum amount every PC type could contribute to the CV is calculated. PC types 13, 14 and 15 are all identified as M_PC with MCA of 18.5, 22.25 and 11.6 respectively, as shown in Table 7.8.

Table 7.8: Demand of PC Types 13, 14 & 15 and Result of BLWMO at the Beginning of Week 7 in F_CP Plan

Mould type	PC type for BLWMO	Demand, production & PC Gap		Week 7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
E6	PC 13	Demand		0	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	Initial	Produciton		0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	0
	BLWMO_E	PC Gap		30	24	18	12	12	12	12	12	12	30	24	18	12	6	6	6	6	6	6	24	18	12	6	0	0
E6	PC 13	Adjusted demand		0	18	18	18	18	18	18	18	18	0	24	24	24	18	18	18	18	18	18	0	24	24	24	18	0
	Adjusted	Adjusted produciton		0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	0
	BLWMO_E	Adjusted PC Gap		0	0	0	0	0	0	0	0	0	18	12	6	0	0	0	0	0	0	0	18	12	6	0	0	0
S5	PC 13	Transferred demand		0	6	6	6	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	6	0
	PC 14	Demand		0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	PC 15	Demand		0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
	BLWMO_S	Produciton		0	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	5.45	0	0	0	0.55	5.45	0
		PC Gap		23.9	23.35	22.8	22.25	18.7	15.15	11.6	6.05	0.5	5.95	11.4	16.85	22.3	21.75	18.2	14.65	11.1	5.55	0	0	0	0	0.55	0	0
	PC 13	Max contribution	18.5	0	6	6	6	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0
	PC 14		22.25	0	0	0	0	9	9	4.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	PC 15		11.6	0	0	0	0	0	0	0	11	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Next, PC loading is conducted for identified M_PC based on EDD/LMC rule. First, 19 PCs of PC type 13 with due date of Week 8 is loaded under the constraints of MCA and CV. Note that 19 is the minimum integer that is no less than $\min(18.5, 23.9)$. As shown in Table 7.6, 18 PCs have been loaded on E6 and 1 PC on S5. After this loading, PC type 13 runs out of its MCA and becomes N_PC, and the CV of the PC family is reduced to 5.4 ($=23.9-18.5$). Now it is the time to load PC types 14 and 15 as M_PC on S5 before any more PC type 13 can be loaded. 6 PCs of PC type 14 with due date of Week 11 are tried for loading, and only 4 PCs are loadable subject to the capacity of S5 and the mould changeover incurred from PC type 13 to PC type 14, as shown in Table 7.6. From Weeks 8 to 15, PC types 14 and 15 continue to be identified as M_PC or D_PC, and thus get the loading priority on S5. On the other hand, even if PC type 13 is identified as M_PC during this period, E6 alone is able to meet the production requirement set by its MCA. In this way, F_CP takes account of PC demand and mould requirement, avoiding the excessive occupation of S5 by PC 13 type.

With CP rule adopted in its forward simulation, BI_CP can generate the same mould plan as F_CP. Moreover, the best mould combination of E6 and S5 is also given by F_ACT. This is due to the fact that an experienced planner would load PCs onto exclusive moulds and sharable moulds along the planning horizon separately. At first, the exclusive mould E6 is employed to produce as many PCs of PC type 13 as possible in every week. Then, the sharable mould S5 is used for production of PC types 14 and 15, and the rest of PC type 13. In this way, the inordinate occupation of S5 by PC type 13, as would be incurred with the pure traditional priority rules, is avoided.

Planning for E4, E5 and S3 involves a situation similar to that of E6 and S5. F_CP and BI_CP give the best solution: 1 E4 and 2 S3, without E5 at all. This alternative does not work for F_TRD. Therefore 3 S3 is used by F_TRD instead, contributing to extra mould costs. Owing to its trial-and-error nature, the actual planning method, F_ACT, cannot guarantee an optimal solution, especially for a less experienced planner. It is possible that only sharable moulds, 3 S3, are used in practice for simplicity, instead of the combination of both exclusive and sharable moulds. Hereby, F_ACT gives the same answer as F_TRD to reflect this potential risk.

7.2.2.2 Labour Cost

It can be seen from Table 7.4 that of all the four planning approaches, BI_CP establishes a good balance among changes in labour size over periods (hiring/firing cost), labour size in every period (NT cost), and OT consumed in every period (OT cost), thus achieving the lowest overall labour cost. For more specific comparisons among the four approaches, Figure 7.1 presents the labour sizes over periods, and Figure 7.2 shows the OT hours consumed over periods.

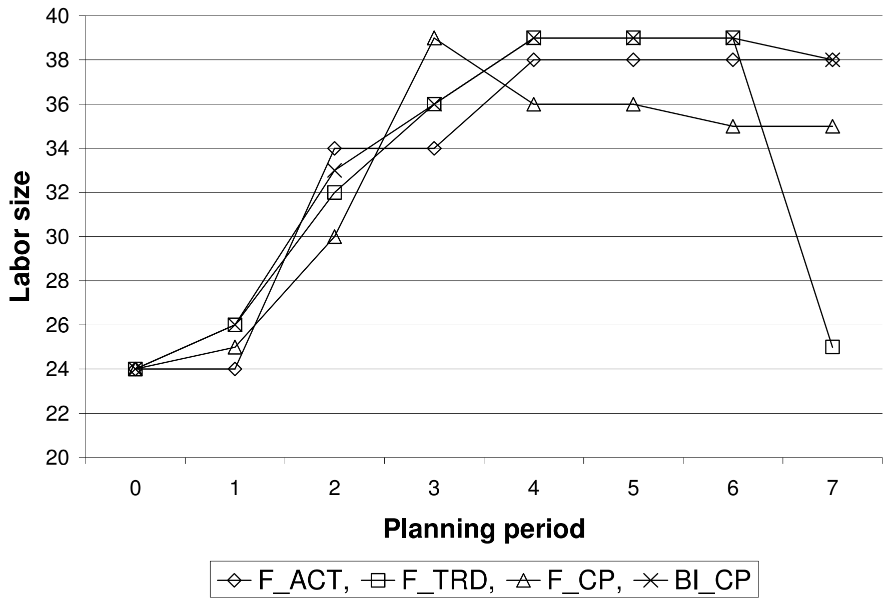


Figure 7.1: Labour Sizes over Periods in Various Plans

One main principle of F_ACT is to keep labour sizes over periods as stable as possible. This idea on labour planning is implemented in the test. As shown in Figure 7.1, F_ACT provides the minimum variation in labour size along the planning horizon. Therefore, it achieves the lowest cost for labour hiring and firing among the four approaches. Nevertheless, the stable labour sizes come with a price – relatively high NT cost and OT cost, as shown in Table 7.4 and Figure 7.2.

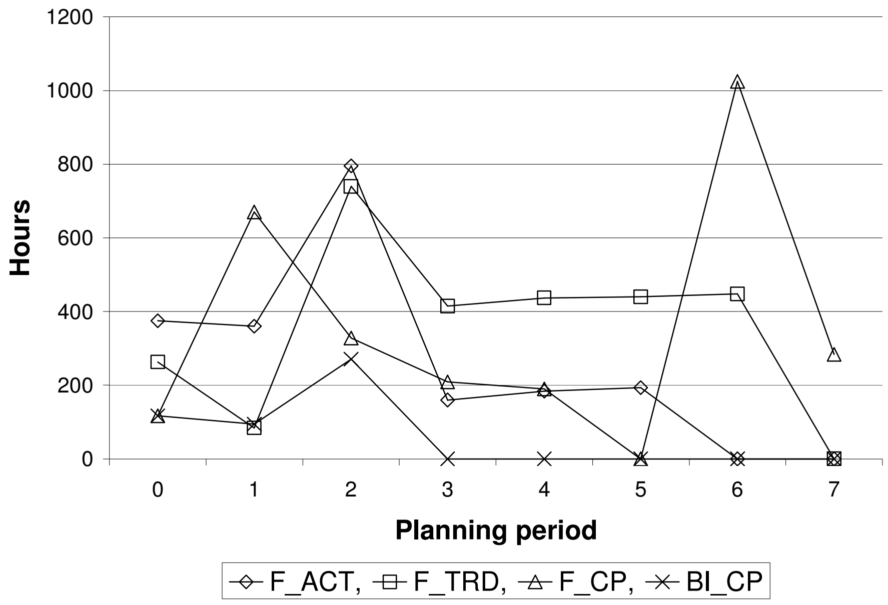


Figure 7.2: OT hours Consumed over Periods in Various Plans

Table 7.4 shows that F_TRD and F_CP have quite smaller NT costs than F_ACT and BI_CP. To achieve this, however, they have to dramatically change labour sizes over periods, leading to large costs for labour hiring and firing. Furthermore, additional OT has to be consumed to offset the shortage of man-hours in every period.

Among the four production plans, BI_CP consumes the most NT hours, as shown in Table 7.4. However, it does make sense. Figure 7.1 and Figure 7.2 reveal that the high NT used in BI_CP effectively avoids both dramatic changes in labour size and unnecessary OT usage. As a result, it accomplishes the best performance in terms of overall labour cost. The excellent performance of BI_CP is completely attributed to backward simulation conducted based on the proceeding forward simulation. Figure 7.3 shows the man-hours consumed in the forward simulation and the succeeding backward simulation separately in BI_CP. Apparently, the backward simulation pulls back PC production as late as possible and reduces excessive OT usage by utilizing NT available in the forward schedule.

Compared to F_TRD and F_CP where only forward simulation is adopted, BI_CP tends to keep a minor surge in labour size over time, which is more consistent with labour planning principles in F_ACT. This is one attractive feature of BI_CP that should make it an acceptable approach by practitioners. In Figure 7.3, both forward and backward simulations in BI_CP keep the same labour sizes over the planning periods, thus having the same profile of labour size changes. However, despite the low cost for labour hiring and firing (S$6,300), the forward schedule is associated with excessive OT cost (S$31,800) and stock cost (S$36,468), and thus a high total variable cost (S$530,608). In a GA based F_CP planning process, this forward schedule would get little chance to be selected to propagate to the final solutions due to its poor performance. On the contrary, the poor forward schedule could be greatly improved by the subsequent backward simulation in BI_CP, as shown in Figure 7.3, thus having more chance to survive in GA. It is known from Table 7.4 that the OT cost, stock cost and total variable cost are largely reduced to S$3,615, S$11,916 and S$ 477,871 respectively. In this way, BI_CP effectively protects the potential for a production schedule with slight surge of labour size to contribute to or even become the final solution.

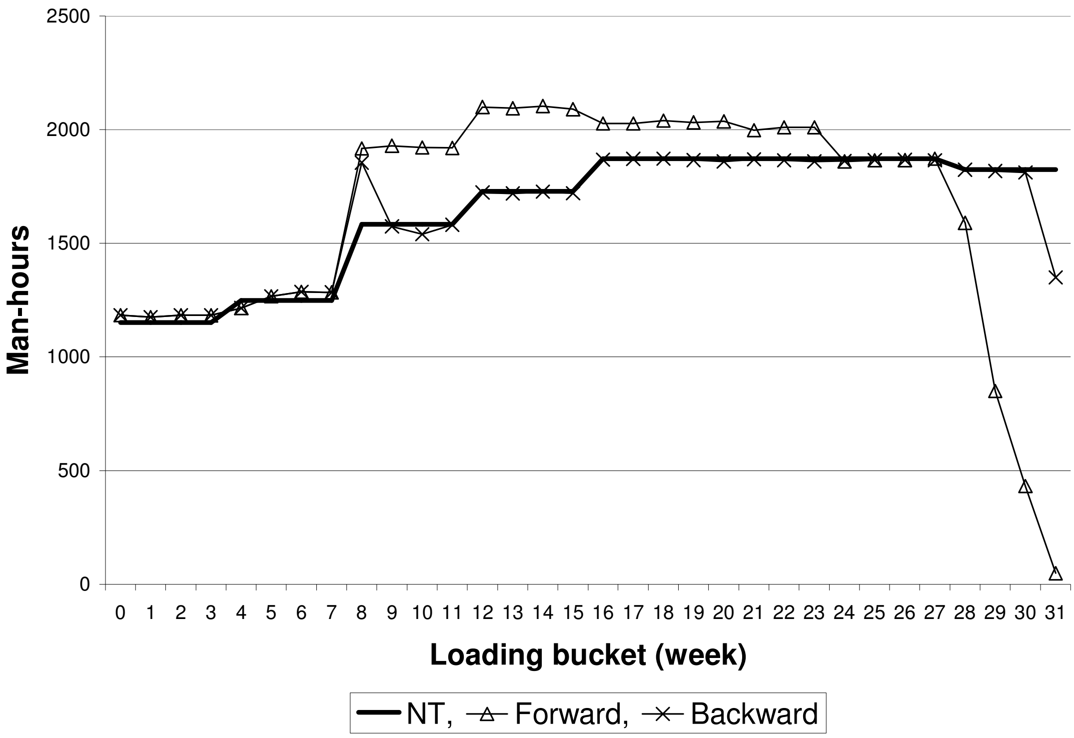


Figure 7.3: Man-Hours Consumed in Forward and Backward Simulations in BI_CP Plan

7.2.2.3 Stock Cost

The overall stock costs established by the four approaches are given in Table 7.4. As the backward simulation in BI_CP tends to pull back production of PCs as close to their due dates as possible, there is no doubt that BI_CP gives the lowest stock cost out of the four approaches. This advantage has been discussed in the above section and illustrated in Figure 7.3.

More specifically, Figure 7.4 presents PC stock volume over weeks in every production plan. BI_CP keeps the minimum PC stocks in nearly all the planning periods. The poor performance of F_ACT, F_TRD, and F_CP is mainly attributable to their underlying forward simulation, which tends to produce as early as possible. F_TRD behaves the worst in the second half of the planning horizon. This could result from the fact that it uses extra moulds, as well as a large labour size and excess OT so as to expedite the production of PCs that are not needed until a later stage.

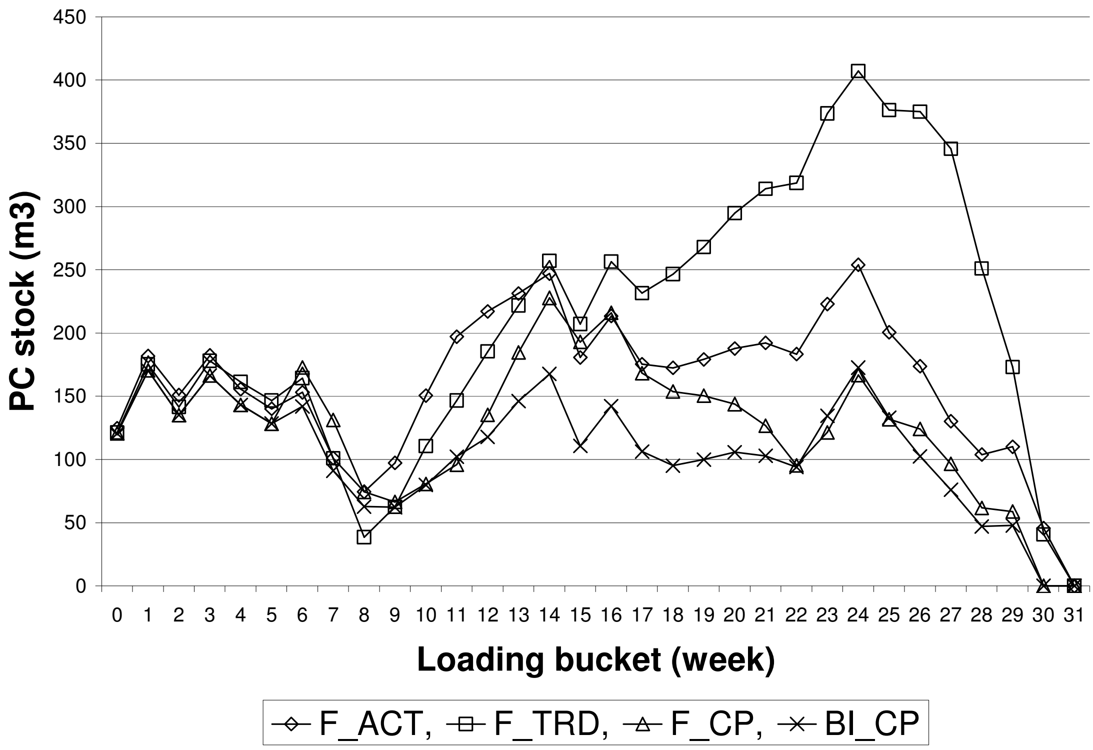


Figure 7.4: PC Stock over Weeks in Various Plans

7.3 Test II for Detailed Scheduling

Test II is designed to ascertain the validity of IPSMPP for detailed scheduling. In particular, the following issues are examined in the test.

1. Traditional rules vs. CM rule for labour transfer;
2. Forward simulation vs. bidirectional simulation;
3. Capability of GA to improve PC assignment and sequencing on moulds;
4. Capability of GA to improve labour transfer to PCs on every mould.

For this purpose, the test is performed with the prototype system for detailed scheduling. That is, the three scheduling modules, *Labour Grouping*, *PC Allocation & Sequencing,* and *Labour Transferring*, are implemented in sequence based on the approach of integrated Simulation(D) and GA. Besides, *Labour Grouping* is also conducted using traditional labour transfer rules and proposed CM rule separately, combined with forward simulation as a single scheduling pass in Simulation(D). In the test, the following symbols are used to represent specific Simulation-GA based approaches to *Labour Grouping*, where the underlying Simulation(D) is performed with different labour transfer rules or in different scheduling directions.

- F_EDD: Forward simulation based on EDD labour transfer rule;
- F_LQ: Forward simulation based on LQ labour transfer rule;
- F_CM: Forward simulation based on CM labour transfer rule;
- BI_CM: IPSMPP employing bidirectional simulation based on CM labour transfer rule.

It should be noted that EDD/LMC PC dispatching rule is adopted in all these approaches to *Labour Grouping*. Besides, EDD and LQ are regarded as traditional rules for labour transfer, based on the literature reviews on DRC scheduling in Chapter 2. Result from F_CM can be compared with those from F_EDD and F_LQ to test the superiority of CM rule over traditional labour transfer rules. It can be further compared with that from BI_CM to justify the adoption of bidirectional simulation instead of single forward simulation in IPSMPP. As for the above-mentioned last two issues, obviously, they can be examined through execution of *PC Allocation & Sequencing* and *Labour Transferring* modules respectively.

7.3.1 Description of Test

Test II involves precast production for a 28-day planning horizon, including 4 planning periods (0~3). Every planning period is 1 week long, covering 6 working days and 1-day public holiday. 21 workers are available in the plant during the planning horizon. Daily NT and upper bound OT hours are 8 hours and 6 hours respectively. Hourly labour costs are S$5 (Singapore dollar) for NT working and S$7.5 for OT. There are 13 PC types involved in the production, which are divided into two PC groups. For simplicity, some symbols are used in the test to represent various PCs and moulds. $PC[i][j]$ is used to stand for the jth PC type in PC group i, and $PC[i][j][k]$ for the kth PC of $PC[i][j]$ with the due date of $PC[i][j][k]$ earlier than or equal to that of $PC[i][j][k+1]$. In addition, $E[i][j]$ and $S[i][j]$ represent the jth exclusive mould type and sharable mould type, respectively, in PC group i. $S[i][j][k]$ stands for the kth mould of $S[i][j]$. Table 7.9 shows relevant information of various PCs in detailed scheduling, including PC types in PC group 1 and 2, mould type(s) that can be used for every PC type, labour needed per PC, stock cost per PC per day, unit volume per PC, durations of operation 1, 2 and 3 involved in every PC production, and PC demand to be met within the planning horizon. Besides, various mould types and their quantity, and mould changeover hours among PCs on sharable moulds are given in Table 7.10 and 7.11 respectively. Table 7.12 also provides the scheme of PC allocation on every exclusive mould type and individual sharable mould. It is one of the constraints transferred from aggregate planning at the tactical level. For E_PC types (e.g., $PC[0][5]$), their allocation on moulds is not given in the table, since they can only be produced on an exclusive mould type.

Table 7.9: PC Information in Detailed Scheduling

PC Group	PC Type	Mould type		Labors per PC	Stock cost (S$)	PC Volume (m3)	Operation duration						Total
		E	S				1		2		3		
							Hr	Min	Hr	Min	Hr	Min	
0	[0][0]	[0][0]	[0][0]	2	0.53	1.00	4	10	0	40	10	0	52
	[0][1]	-	[0][0]	2	0.53	1.00	4	10	0	40	10	0	4
	[0][2]	-	[0][0]	2	0.53	1.00	4	10	0	40	10	0	5
	[0][3]	[0][1]	[0][1]	2	0.40	0.76	3	40	0	30	9	0	24
	[0][4]	[0][2]	[0][1]	2	0.40	0.76	3	40	0	30	9	0	27
	[0][5]	[0][3]	-	3	0.84	1.60	3	20	0	40	11	0	10
1	[1][0]	-	[1][0]	3	1.76	3.35	6	0	0	50	12	0	20
	[1][1]	-	[1][0]	3	1.76	3.35	6	0	0	50	12	0	13
	[1][2]	-	[1][0]	3	1.76	3.35	6	0	0	50	12	0	11
	[1][3]	[1][0]	-	3	1.84	3.50	6	30	1	0	12	0	40
	[1][4]	[1][1]	-	3	1.68	3.20	5	40	1	0	11	20	4
	[1][5]	[1][2]	-	3	1.47	2.80	5	20	0	50	11	0	9
	[1][6]	[1][3]	-	3	1.74	3.30	5	50	0	50	11	20	30

PC Type	PC demand at the end of every day																				
	Week 0							Week 1							Week 2						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
[0][0]	0	0	0	6	6	0	0	0	0	0	6	6	0	0	0	0	0	6	6	0	0
[0][1]	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
[0][2]	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
[0][3]	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	4	4	0	0	0	0
[0][4]	0	0	0	0	0	0	0	4	0	0	5	0	0	0	4	0	0	5	0	0	0
[0][5]	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0
[1][0]	0	0	0	5	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
[1][1]	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	5	0	0	0
[1][2]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
[1][3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[1][4]	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[1][5]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0
[1][6]	0	0	0	6	0	0	0	0	0	0	6	0	0	0	0	0	0	6	0	0	0

PC Type	PC demand at the end of every day (cont.)										
	Week 3							…			
	21	22	23	24	25	26	27	…	31	…	38
[0][0]	0	0	0	6	6	0	0	0	4	0	0
[0][1]	0	0	0	1	0	0	0	0	1	0	0
[0][2]	0	0	0	0	1	0	0	0	1	0	0
[0][3]	0	4	4	0	0	0	0	0	0	0	0
[0][4]	4	0	0	5	0	0	0	0	0	0	0
[0][5]	0	0	0	2	0	0	0	0	2	0	0
[1][0]	0	0	0	5	0	0	0	0	5	0	0
[1][1]	0	0	0	0	0	0	0	0	3	0	0
[1][2]	0	0	0	5	0	0	0	0	0	0	1
[1][3]	0	0	0	20	20	0	0	0	0	0	0
[1][4]	0	0	0	0	0	0	0	0	0	0	0
[1][5]	0	0	0	0	0	0	0	0	0	0	0
[1][6]	0	0	0	6	0	0	0	0	6	0	0

Table 7.10: Mould Type and Quantity

PC group	0					
Mould type	E[0][0]	E[0][1]	E[0][2]	E[0][3]	S[0][0]	S[0][1]
Quantity	2	1	1	1	1	1
PC group	1					
Mould type	E[1][0]	E[1][1]	E[1][2]	E[1][3]	S[1][0]	
Quantity	2	1	1	3	2	

Table 7.11: Mould Changeover Hours among PCs on Sharable Moulds

S[0][0]				
Change-over hour		To		
		PC[0][0]	PC[0][1]	PC[0][2]
From	PC[0][0]	0	4	8
	PC[0][1]	4	0	4
	PC[0][2]	8	4	0

S[0][1]			
Change-over hour		To	
		PC[0][3]	PC[0][4]
From	PC[0][3]	0	4
	PC[0][4]	4	0

S[1][0]				
Change-over hour		To		
		PC[1][0]	PC[1][1]	PC[1][2]
From	PC[1][0]	0	4	2
	PC[1][1]	4	0	2
	PC[1][2]	2	2	0

Table 7.12: Scheme of PC Allocation on Every Mould

<table>
<tr><th>PC group</th><th>Mould</th><th>PC quantity</th><th colspan="22">PCs allocated</th></tr>
<tr><td rowspan="11">0</td><td rowspan="2">S[0][0][0]</td><td rowspan="2">20</td><td colspan="11">PC[0][0]</td><td colspan="4">PC[0][1]</td><td colspan="5">PC[0][2]</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>2</td><td>5</td><td>8</td><td>11</td><td>24</td><td>27</td><td>30</td><td>39</td><td>40</td><td>45</td><td>46</td><td>0</td><td>1</td><td>2</td><td>3</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td rowspan="3">E[0][0]</td><td rowspan="3">41</td><td colspan="22">PC[0][0]</td></tr>
<tr><td>0</td><td>1</td><td>3</td><td>4</td><td>6</td><td>7</td><td>9</td><td>10</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>25</td><td>26</td></tr>
<tr><td>28</td><td>29</td><td>31</td><td>32</td><td>33</td><td>34</td><td>35</td><td>36</td><td>37</td><td>38</td><td>41</td><td>42</td><td>43</td><td>44</td><td>47</td><td>48</td><td>49</td><td>50</td><td>51</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">S[0][1][0]</td><td rowspan="2">15</td><td colspan="6">PC[0][3]</td><td colspan="9">PC[0][4]</td><td colspan="7" rowspan="2"></td></tr>
<tr><td>3</td><td>6</td><td>12</td><td>14</td><td>19</td><td>21</td><td>1</td><td>7</td><td>9</td><td>11</td><td>13</td><td>17</td><td>20</td><td>24</td><td>26</td></tr>
<tr><td rowspan="2">E[0][1]</td><td rowspan="2">18</td><td colspan="18">PC[0][3]</td><td colspan="4" rowspan="2"></td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>4</td><td>5</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>13</td><td>15</td><td>16</td><td>17</td><td>18</td><td>20</td><td>22</td><td>23</td></tr>
<tr><td rowspan="2">E[0][2]</td><td rowspan="2">18</td><td colspan="18">PC[0][4]</td><td colspan="4" rowspan="2"></td></tr>
<tr><td>0</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>8</td><td>10</td><td>12</td><td>14</td><td>15</td><td>16</td><td>18</td><td>19</td><td>21</td><td>22</td><td>23</td><td>25</td></tr>
<tr><td rowspan="4">1</td><td rowspan="2">S[1][0][0]</td><td rowspan="2">22</td><td colspan="8">PC[1][0]</td><td colspan="3">PC[1][1]</td><td colspan="11">PC[1][2]</td></tr>
<tr><td>0</td><td>2</td><td>4</td><td>7</td><td>8</td><td>9</td><td>13</td><td>15</td><td>10</td><td>11</td><td>12</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">S[1][0][1]</td><td rowspan="2">22</td><td colspan="12">PC[1][0]</td><td colspan="10">PC[1][1]</td></tr>
<tr><td>1</td><td>3</td><td>5</td><td>6</td><td>10</td><td>11</td><td>12</td><td>14</td><td>16</td><td>17</td><td>18</td><td>19</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
</table>

7.3.2 Analysis of Results

As mentioned above, in the test, *Labour Grouping* is conducted using four approaches based on different labour transfer rules or in different simulation directions. In addition, *PC Allocation & Sequencing* and *Labour Transferring* are conducted using IPSMPP. Some results obtained from Test II are given in Appendix C. A large delay penalty is set in the test to ensure there is no delay incurred in every resulting schedule. Therefore, performances of various production schedules are evaluated based on the total variable cost, as shown in Table 7.13.

As expected, BI_CM schedule achieves the best performance (lowest total variable cost) among all the schedules developed by the four different approaches to *Labour Grouping*. Compared to F_EDD schedule, BI_CM schedule reduces overall cost by nearly one third, from S$6455.4 to S$4460.5. F_CM does a better job than the other two traditional approaches, F_EDD and F_LQ, owing to its CM rule for labour transfer. Schedule derived from BI_CM is further improved through *PC Allocation & Sequencing* and *Labour Transferring*. The total variable cost for the proposed model is successfully reduced from S$S4460.5 to S$3894.2 and finally to S$3769.5. Explorations are made, as follows, into every module to see why these approaches behave differently in *Labour Grouping* and how *PC Allocation & Sequencing* and *Labour Transferring* make improvement in detailed scheduling for precast production.

Table 7.13: Total Variable Costs (S$) in Various Detailed Production Schedules

PC group	Cost category	Compared approach			IPSMPP			
		Labor Grouping			*Labor Grouping*	*PC Allocation & Sequencing*		*Labor Transferring*
		F_EDD	F_LQ	F_CM	BI_CM	1	2	
0	*1. OT cost (S$)*	*1180.0*	*1616.3*	*706.3*	*597.5*	*322.5*	*167.5*	*122.5*
	2. Stock cost (S$)	*222.9*	*243.9*	*244.7*	*249.3*	*229.4*	*218.0*	*203.8*
	Subtotal (S$)	1402.9	1860.1	951.0	846.8	551.9	385.5	326.3
	Final schedule		-		F2("re")	F2("re")	F2("re")	F2("re")
1	*1. OT cost (S$)*	*3003.8*	*1848.8*	*1946.3*	*1923.8*	*1818.8*	-	*1755.0*
	2. Stock cost (S$)	*2048.8*	*1883.6*	*1674.3*	*1689.9*	*1690.0*		*1688.2*
	Subtotal (S$)	5052.6	3732.3	3620.5	3613.6	3508.7		3443.2
	Final schedule		-		F1	F2("ab")		F2("ab")
Total (S$)		6455.4	5592.5	4571.5	4460.5	3894.2		3769.5
% of BI_CM		144.7	125.4	102.5	100.0	87.3		84.5

Note: "Final schedule" indicates how bi-directional Simulation(D) is conducted to get the final schedule.
F1: Only the 1st forward simulaiton is conducted to get the final schedule;
F2("re"): Bi-directional simulation is conducted with relative application of Priority List II in the backward simulation; The 2nd forward schedule is used as the final schedule;
F2("ab"): Bi-directional simulation is conducted with absolute application of Priority List II in the backward simulation; The 2nd forward schedule is used as the final schedule.

7.3.2.1 *Labour Grouping*

Two major issues in the test are to examine the superiority of CM rule over traditional labour transfer rules, and to justify the adoption of bidirectional simulation instead of single forward simulation in Simulation(D). For this purpose, comparisons are made among the four approaches to *Labour Grouping*. Labour sizes and max OT minutes result from these approaches are listed in Table 7.14.

Table 7.14: Labour Sizes and Max OT Minutes in Various Schedules

Period	PC group	Labor size				Maximum OT (min)			
		F_EDD	F_LQ	F_CM	BI_CM	F_EDD	F_LQ	F_CM	BI_CM
0	0	6	6	9	9	100	200	60	190
	1	15	15	12	12	320	270	140	130
1	0	6	6	6	6	60	140	50	60
	1	15	15	15	15	290	30	40	100
2	0	9	6	6	6	300	90	60	190
	1	12	15	15	15	0	80	190	70
3	0	9	9	9	9	300	60	70	250
	1	12	12	12	12	50	50	180	210

7.3.2.1.1 F_CM vs. F_EDD and F_LQ

F_CM, F_EDD and F_LQ are different from one another in terms of labour transfer rules used in the forward simulation. Therefore, the better overall performance of

F_CM (S$4571.5) over F_EDD (S$6455.4) and F_LQ (S$5592.5) demonstrates that CM rule is superior to EDD and LQ rules in labour transfer. Take PC production in PC group 1 for example. From Table 7.9, it can be known that demand of PC[1][5] is not urgent since 3 weeks (18 working days) are long enough to produce 9 PCs on one mould. Similarly, demand of PC[1][6] is not urgent either, as there are 3 moulds available for production of 30 PCs with their due dates evenly distributing in 5 weeks. Therefore, production of PC[1][5] and PC[1][6] can, to a certain degree, be postponed without incurring any delay. By contrast, PC[1][4] is critical since 4 PCs have to be produced on one mould in week 0 (6 working days). It means production of PC[1][4] must start immediately, otherwise some delays may be incurred. Compared to PC[1][5] and PC[1][6], PC[1][3] is also rather imperative because only 2 moulds are available to produce 40 PCs within 22 working days, almost 1 PC per mould per day.

(1) Labour Allocation

However, F_EDD improperly puts urgency on PC [1][5] and PC[1][6]. In fact, with EDD rule, E[1][2] for PC[1][5] and E[1][3] for PC[1][6] obtain priority over E[1][0] for PC[1][3] in labour transfer for most of time in the planning horizon, since the 40 PCs of PC[1][3] are not required till relatively late dates of day 24 and 25. Therefore, some PCs from PC [1][5] and PC[1][6] are unnecessarily produced in Period 0 consuming extra man-hours, while their production can actually be scheduled at a later stage. Figure 7.5 shows STs of some PCs in PC group 1 of various schedules for *Labour Grouping*. It can be seen that, production of PC [1][5] and PC[1][6] in F_EDD schedule is much earlier than that in the other three schedules. In order to meet the urgent demand of PC[1][3], F_EDD has to allocate, for Period 0, 15 labour to Group 1, leaving only 6 labour to Group 0, as shown in Table 7.14.

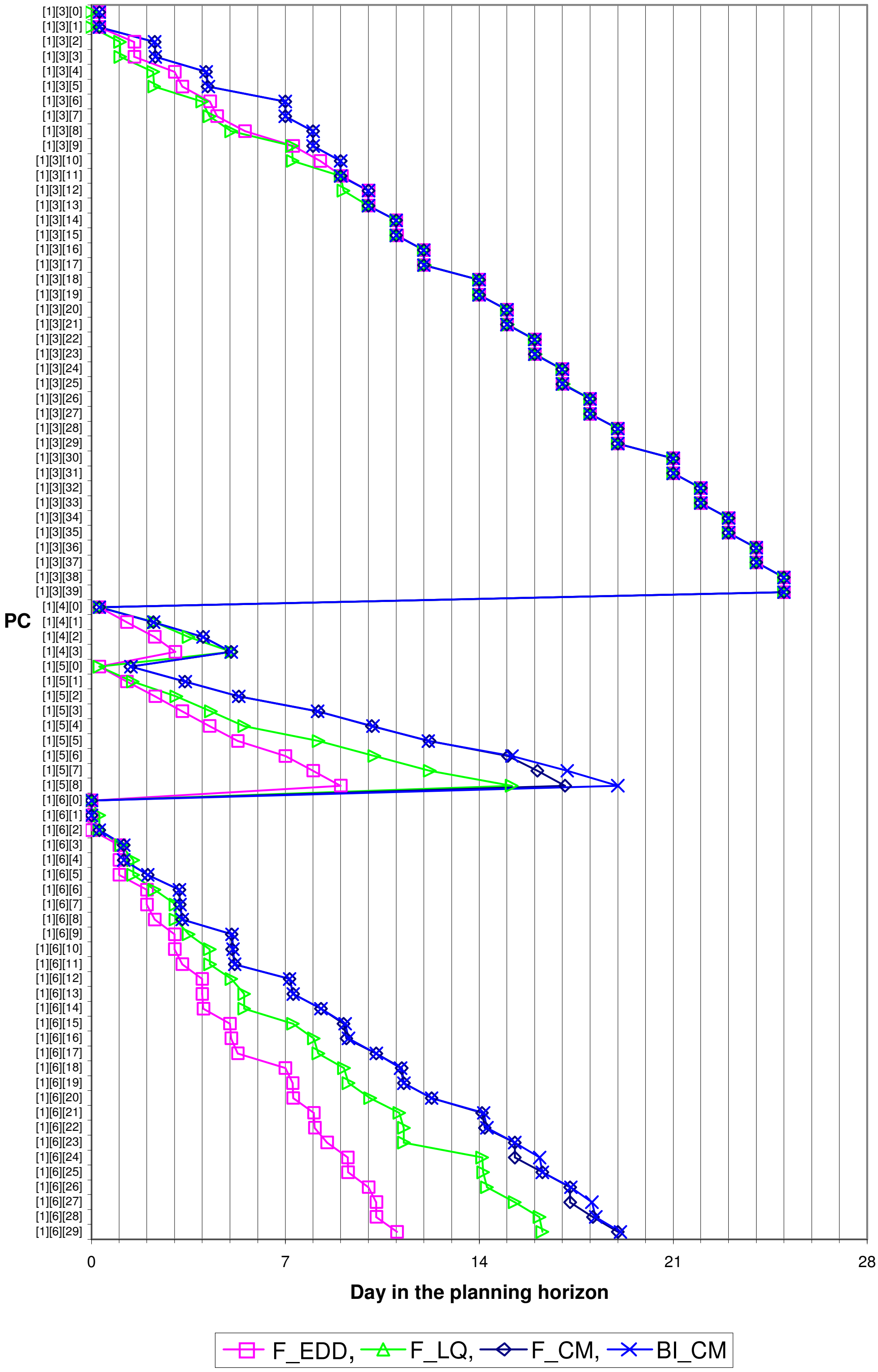


Figure 7.5: STs of Some PCs in PC Group 1 of Various Schedules for *Labour Grouping*

In addition, with LQ rule, F_LQ neglects the urgency of PC[1][4], since it forms a the shortest queue (only 4 PCs to be produced) before E[1][1] out of all moulds involved in Group 1. During scheduling, the moulds for non-critical PCs, such as PC[1][5] and PC[1][6], get priority over E[1][1] for PC[1][4] in labour transfer. It increases the production in Group 1 in Period 0. Compared to F_CM, F_LQ clearly schedules more PC production in Period 0, as shown in Figure 7.5. Therefore, to meet the increased production requirement and to satisfy the urgent due date of PC[1][4], 15 labour has to be assigned by F_LQ to Group 1 in Period 0, as listed in Table 7.14. The 15 labour are also kept in Group 1 for Period 1 and 2 to speed up production of both urgent and ordinary PCs. On the other hand, F_CM can tackle the above problems with F_EDD and F_LQ. With the special backward loading — BLWMO embedded, CM rule can accurately capture the above criticality of various PC demands and mould requirements. Thus, F_CM achieves a reasonable scheme for labour allocation into PC groups, as shown in Table 7.14. Since PC[1][5] and PC[1][6] are not urgent, 12 labour is enough for PC production of Group 1 in Period 0. This leaves more labour (9 labour) to perform the production in Group 0 for other urgent demands.

(2) OT Cost

With F_EDD, large labour size (15 labour) for Period 0 and 1 is not enough for production in Group 1. Extra OT hours are used for the production, as shown in Figure 7.6. Therefore, F_EDD gives the highest OT cost for Group 1 among the four approaches, as seen in Table 7.13. F_LQ maintains 15 labour for the first 3 periods, especially Period 2 and 3, cutting the need for OT in Group 1. This contributes to the lowest OT cost of F_LQ schedule. However, the lowest OT usage in PC group 1 may not be worth it. Since only 6 labour are available in Group 0 for the first 3 periods, F_LQ has to employ excessive OT to meet the demand in Group 0, leading to the max OT hours and cost in Group 0 among the four schedules, as illustrated in Figure 7.7 and Table 7.13 respectively. The similar situation happens with F_EDD schedule in PC group 0. Allocation of 6 labour for Period 0 and 1 results in a relatively high OT usage, compared to F_CM.

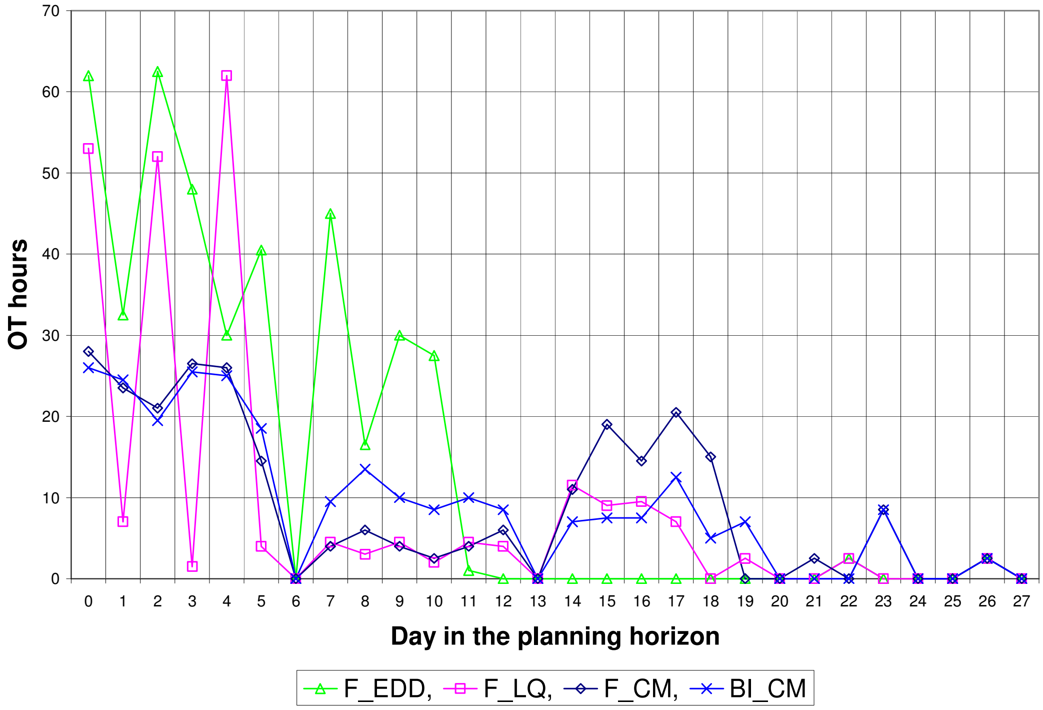


Figure 7.6: OT Hours Consumed in PC Group 1 in Various Schedules for *Labour Grouping*

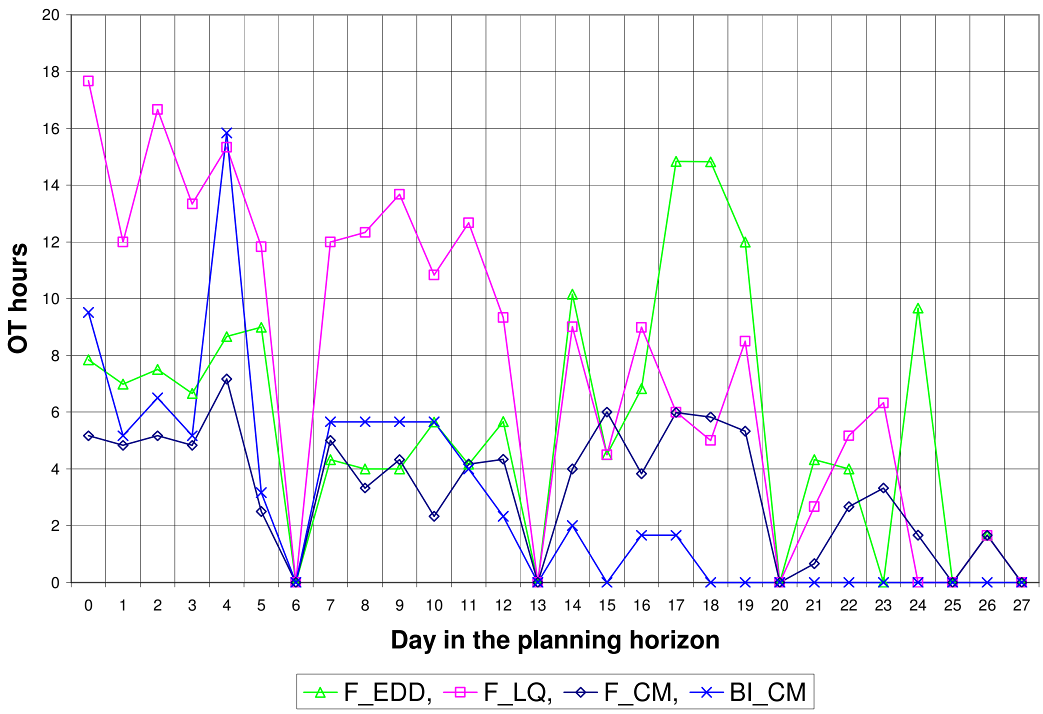


Figure 7.7: OT Hours Consumed in PC Group 0 in Various Schedules for *Labour Grouping*

On the contrary, F_CM makes a good balance between labour allocation and OT usage in every group. By putting off production of some non-critical PCs, it reduces, in Period 0, the need for labour size in Group 1, leaving more labour (9 labour) to Group 0. Thus, as demonstrated by Figure 7.6 and 7.7, and Table 7.13, F_CM successfully avoids the excessive OT usage in Group 0, with a small OT cost in Group 1, which is only marginally higher than that of F_LQ.

(3) Stock Cost

Figure 7.8 presents PC stock in Group 1 in the four schedules for *Labour Grouping*. It can be seen that PC stocks in F_EDD, F_LQ and F_CM schedules have similar profiles over time, except that F_EDD keeps the highest stock every day and F_LQ ranks the second highest. Finally, F_EDD and F_LQ reach the top two PC stock costs in Group 1, as shown in Table 7.13. This is not unexpected due to the fact that production of some non-critical PCs has been improperly expedited. The lowest stock cost in Group 1 is achieved by F_CM, owing to the accurate identification of mould criticality by CM rule.

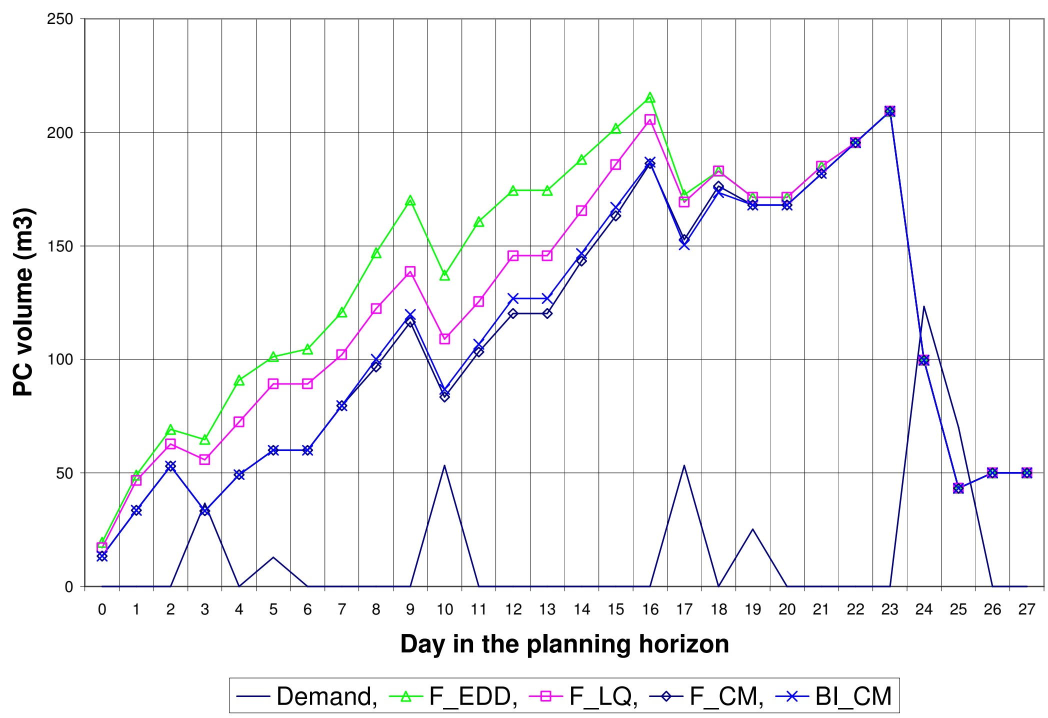


Figure 7.8: PC Stock in PC Group 1 in Various Schedules for *Labour Grouping*

PC stock in Group 0 in the four schedules for *Labour Grouping* is given in Figure 7.9. In contrast to Group 1, F_EDD, F_LQ and F_CM present diverse distributions of PC stock over time in Group 0, where apparently no one is much better than the others. This may come from the specific arrangements of labour allocation and OT usage in the three approaches. Table 7.13 shows that the three approaches generate comparable PC stock costs in Group 0, with F_CM being a little higher than other two. Nevertheless, F_CM achieves the best performance in terms of the overall PC stock cost in all groups.

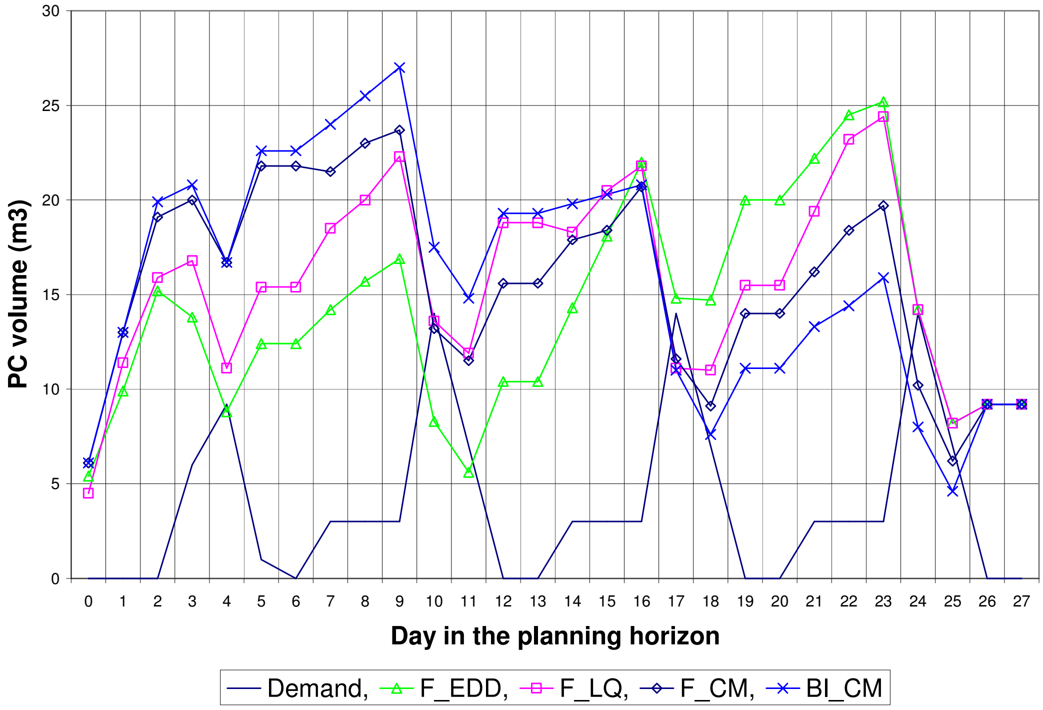


Figure 7.9: PC Stock in PC Group 0 in Various Schedules for *Labour Grouping*

7.3.2.1.2 F_CM vs. BI_CM

From Table 7.13, it is seen that BI_CM gets a lower total variable cost than F_CM. The result shows that the proposed bidirectional simulation does a better job than traditional single forward simulation in PC production scheduling. Nevertheless, F_CM and BI_CM generate the same labour allocation plan, as shown in Table 7.14. This comes from the fact that both of the approaches incorporate forward simulation with CM labour transfer rule in schedule development.

The good performance of BI_CM is attributed to its excellent work in PC group 0, as shown in Table 7.13. Bidirectional simulation is used to generate the final schedule. The backward simulation and the 2nd forward simulation reduce the OT overused by the 1st forward simulation by utilizing NT available in 1st forward schedule. Therefore, the lowest OT hours are consumed by BI_CM among the four approaches. Although BI_CM gives a little higher stock than the other 3 approaches, it finally achieves a minimum total variable cost owing to the lowest OT cost, as illustrated in Figure 7.7, Figure 7.9 and Table 7.13.

In Group 1, BI_CM gets a result equivalent to F_CM, as shown in Table 7.13, Figure 7.6 and Figure 7.8. This is due to the fact that in the bidirectional simulation, no feasible schedule can be generated by the backward simulation and the 2nd forward simulation. Therefore, like F_CM, BI_CM only uses one forward simulation to establish the final schedule. The reason behind this is that there is much PC demand to be met in Group 1 under the current labour allocation plan. In the 1st forward schedule of BI_CM, PC production consumes nearly 100% of NT hours available, and some OT hours have to be used to meet the demand, as shown in Figure 7.10. Therefore, there is little space left for subsequent backward and forward simulations to improve the 1st forward schedule.

7.3.2.1.3 Three Simulations in Simulation(D)

Simulation(D) in IPSMPP takes three scheduling passes, including 2 forward simulation and 1 backward simulation, for schedule development in every module at the operational level. As explained in Chapter 6, in one iteration of bidirectional Simulation(D), the 1st forward simulation is used to generate a feasible production schedule. Then, the backward simulation tries to improve the feasible schedule. The 2nd forward simulation thus repairs the improved schedule and makes it executable in practice. In the test, these functions of the three simulations in Simulation(D) are illustrated with BI_CM for *Labour Grouping* in Group 0.

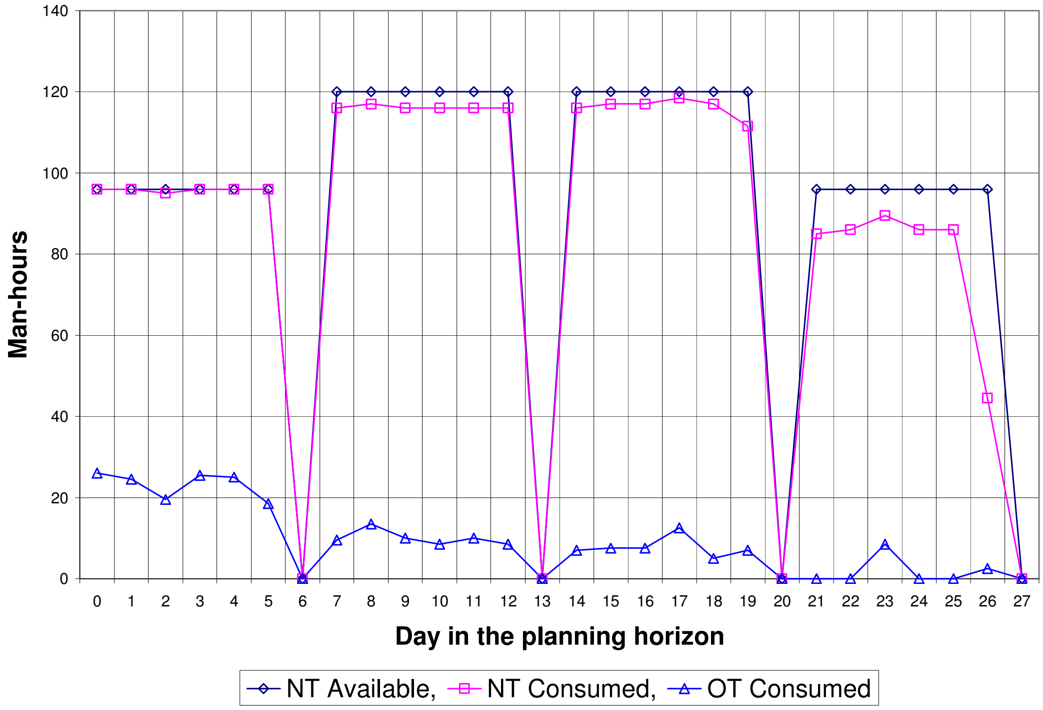


Figure 7.10: NT and OT Hours Consumed in PC Group 1 in BI_CM Schedule for *Labour Grouping*

(1) Improvement of Overall Performance

Table 7.15 presents the total variable costs of Group 0 generated by the three simulations in BI_CM. The 1st forward simulation does creates a feasible schedule, but with a poor performance. A great improvement is made through the backward simulation by pulling back PC production and reducing OT usage. Thus, the total variable cost is reduced by almost 50%, from S$1648.7 to S$798.8. The 2nd forward simulation also gives a much lower overall cost (S$846.8) than the 1st forward simulation, since its repairing work is performed on the basis of the backward schedule.

Table 7.15: Total Variable Costs (S$) of PC Group 0 in Three Schedules of BI_CM

Cost	1st Forward	Backward	2nd Forward
OT (S$)	1352.5	607.5	597.5
Stock (S$)	296.2	191.3	249.3
Total (S$)	1648.7	798.8	846.8

(2) Reduction of PC stock

Figure 7.11 shows the PC stock levels of Group 0 in the three schedules of BI_CM. Obviously, PC production in the 1st forward schedule has been considerably dragged close to due dates through the backward simulation, leading to a minimum PC stock level. Although the 2nd forward simulation does not achieve a level of PC stock as good as the backward simulation, it comes out with an implementable schedule.

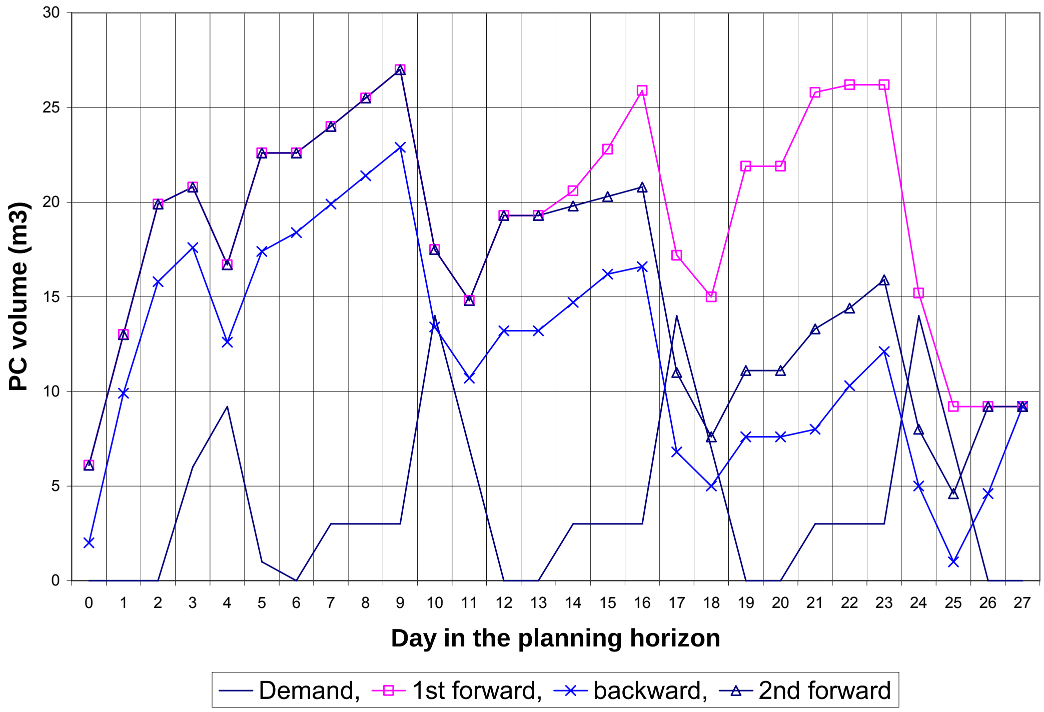


Figure 7.11: PC Stock of PC Group 0 in Three Schedules of BI_CM

The capability of the bidirectional simulation to reduce PC stock can be further demonstrated with production of PC[0][5] on E[0][3], as shown in Figure 7.12. Compared to the 1st forward schedule, the backward schedule and the 2nd forward schedule pull back the production of PC [0][5][6], [0][5][7], [0][5][8] and [0][5][9] 6, 6, 6 and 5 days separately without any delay, resulting in lower stock costs.

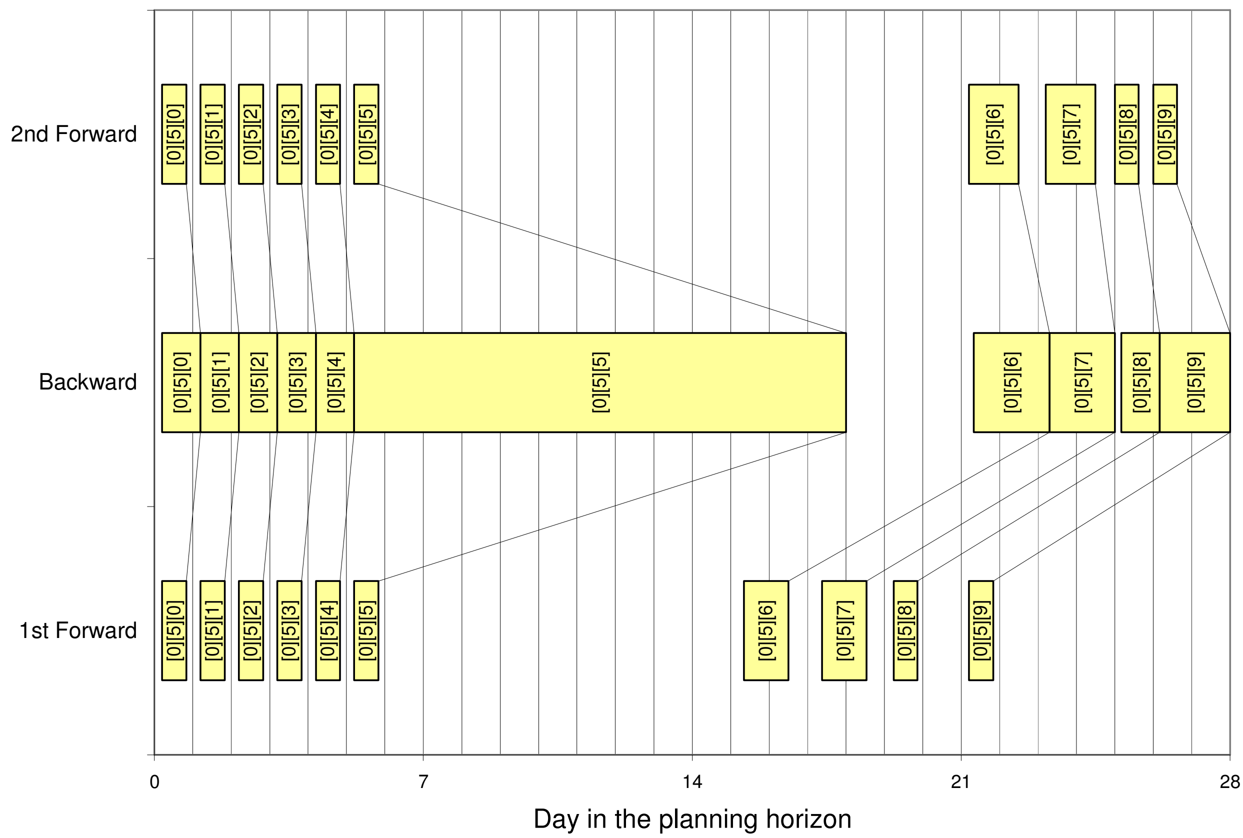
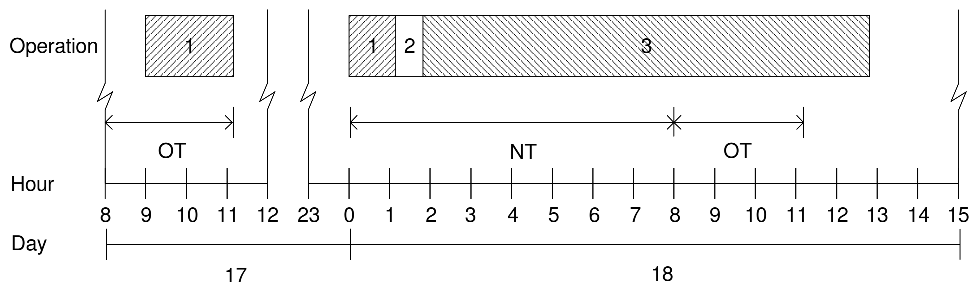


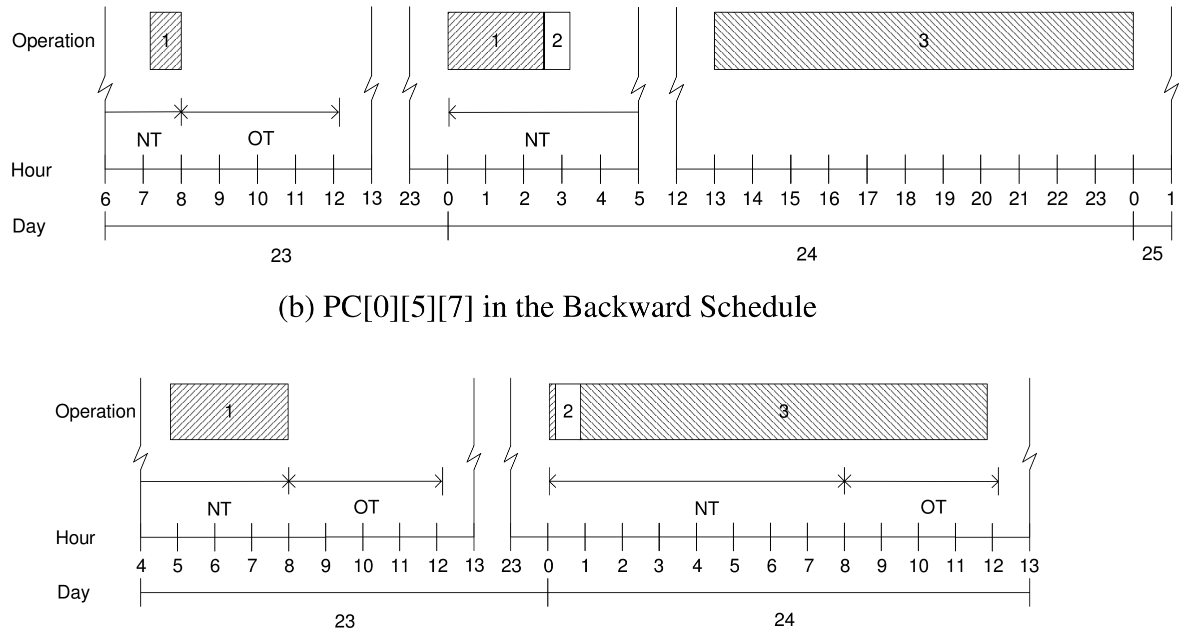
Figure 7.12: Three Schedules of PC[0][5] on E[0][3] in BI_CM

(3) Reduction of OT Usage

Bidirectional simulation can also reduce OT use by utilizing unused NT hours in the 1st forward schedule. Figure 7.13 gives the detailed operation schedules of PC[0][5][7] in BI_CM.



(a) PC[0][5][7] in the 1st Forward Schedule



(b) PC[0][5][7] in the Backward Schedule

(c) PC[0][5][7] in the 2nd Forward Schedule

Figure 7.13: Operation Schedules of PC[0][5][7] in BI_CM

The 1st forward simulation tries to utilize both NT and OT available. Thus, when there are resources (both labour and mould) available at 9 o'clock on day 17, the production of PC[0][5][7] is launched, even if OT is used for operation 1. Three labour are needed for production of PC[0][5][7] and each works for 2.17 hours of OT. Therefore, 6.5 hours of OT are consumed in total. The OT consumption by operation 1 is successfully avoided in the backward and the 2nd forward simulations by executing the operation at a later time using NT available. In the backward schedule, when operation 1 has not been finished on day 24, there is no need to use OT on day 23 to produce the remaining part since the NT available on day 23 is sufficient for its production. Likewise in the 2nd forward schedule, when NT on day 23 is not enough for PC[0][5][7], part of operation 1 and the entire operation 2 can be moved to day 24 and executed with NT, thus avoiding the unnecessary use of OT on day 23.

(4) Necessity of the 2nd Forward Simulation

In the bidirectional simulation, the 2nd forward simulation is necessary, though the backward simulation can efficiently reduce both PC stock and OT usage. This is because the backward simulation has two deficiencies, and thus unable to generate a reasonable schedule for execution in practice. These deficiencies are: firstly, in practice precast production is carried out forward in time, starting from hour 0 on every working day. Production of a PC is launched whenever labour and mould needed become available. On the contrary, in backward simulation, production of PCs and thus resource consumption proceed backwards, starting from the end of the working time zone (NT or OT) everyday. Therefore, it sometimes keeps labour busy in the evening or afternoon while making them idle early in the morning. This phenomenon is against what really happens in daily production. For example, this unreal situation shows up in production of PC[0][5][7] in Figure 7.13(b). On day 23, operation 1 is finished at 7:10, releasing labour and leaving them idle for the early hours of the day.

Secondly, the backward simulation may create an unreasonable gap between operation 3 and 2 of a PC production. Take the backward schedule in Figure 7.13(b) for example. At 13:00 when operation 3 is finished, operation 2 cannot be executed immediately since it falls within the non-working time zone (BT zone). Execution of operation 2 is finally launched at 3:10 when labour become available. Clearly, there is an unreasonable gap between operation 2 and 3. In actual production, operation 3 starts whenever operation 2 finishes, and therefore there is no time gap between the two operations. In Figure 7.12, the long durations of PC[0][5][5], PC[0][5][6] and PC[0][5][9] in the backward schedule also result from the unnecessary gaps between operation 2 and 3.

The defective backward schedule can be repaired by the succeeding 2nd forward simulation. In the 2nd forward schedule in Figure 7.13(c), production of PC[0][5][7] starts at hour 4:50 on day 23 once labour needed are released from other PCs, and it keeps the labour busy till the end of the NT zone. On the other hand, operation 3 is executed immediately after the finish of operation 2 on day 24 since the mould needed by operation 3 has already been occupied by operation 2, thus making the schedule consistent with practice.

(5) Advantage over Single Forward Simulation

Compared to the total variable cost result from F_CM in Group 0 (S$951.0), the 2nd forward simulation of BI_CM gives a better outcome (S$846.8). However, the 1st forward simulation of BI_CM does generate a poor schedule with a much worse performance (S$1648.7). The poor 1st forward schedule has a big potential for improvement, which is finally realized through the backward simulation in BI_CM. On the other hand, if the same schedule is created by F_CM with single forward simulation, no improvement can be made. There would be good chances that the schedule is removed by GA at an early generation due to the bad performance, and loses its opportunity to evolve into the final schedule. Thus, it can be said that the advantage of bidirectional simulation over pure forward simulation lies in that bidirectional simulation can effectively exploit the space for improvement to a forward schedule.

7.3.2.2 ***PC Allocation & Sequencing***

In *Labour Grouping*, PC allocation on moulds is received as constraint from aggregate planning, and PC sequence on every mould is determined based on common PC dispatching rules, with EDD as the 1st priority rule and LMC as the 2nd priority rule. It is likely that this arrangement may not produce an optimal schedule. The module of *PC Allocation & Sequencing* is thus designed to improve PC allocation and sequence on moulds, and thus the schedule performance, with the aid of GA. The validity of the module is also examined in Test II. Table 7.13 shows that through *PC Allocation & Sequencing*, the total variable cost is successfully reduced by about 13%, from S$4460.5 to S$3894.2.

The focus is placed on Group 0 with two types of sharable mould, S[0][0] and S[0][1]. From Table 7.11, it is known that the largest mould changeover that could happen on S[0][0] and S[0][1] are 8 hours and 4 hours respectively. Therefore, *PC Allocation & Sequencing* is conducted in two steps, first for those PC types that can be produced on S[0][0], namely PC[0][0], PC[0][1] and PC[0][2], and then for PC types that can be produced on S[0][1], including PC [0][3] and PC[0][4].

Figures 7.14 and 7.15 show the PC production schedules on S[0][0][0] and E[0][0] respectively, obtained from *Labour Grouping* (BI_CM) and *PC Allocation & Sequencing*.

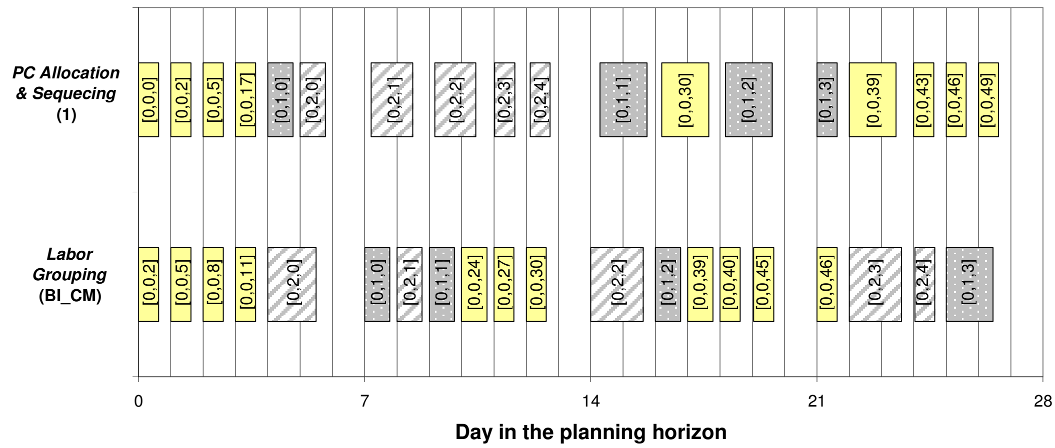


Figure 7.14: PC Production on S[0][0][0] Result from *Labour Grouping* (BI_CM) and *PC Allocation & Sequencing* (1)

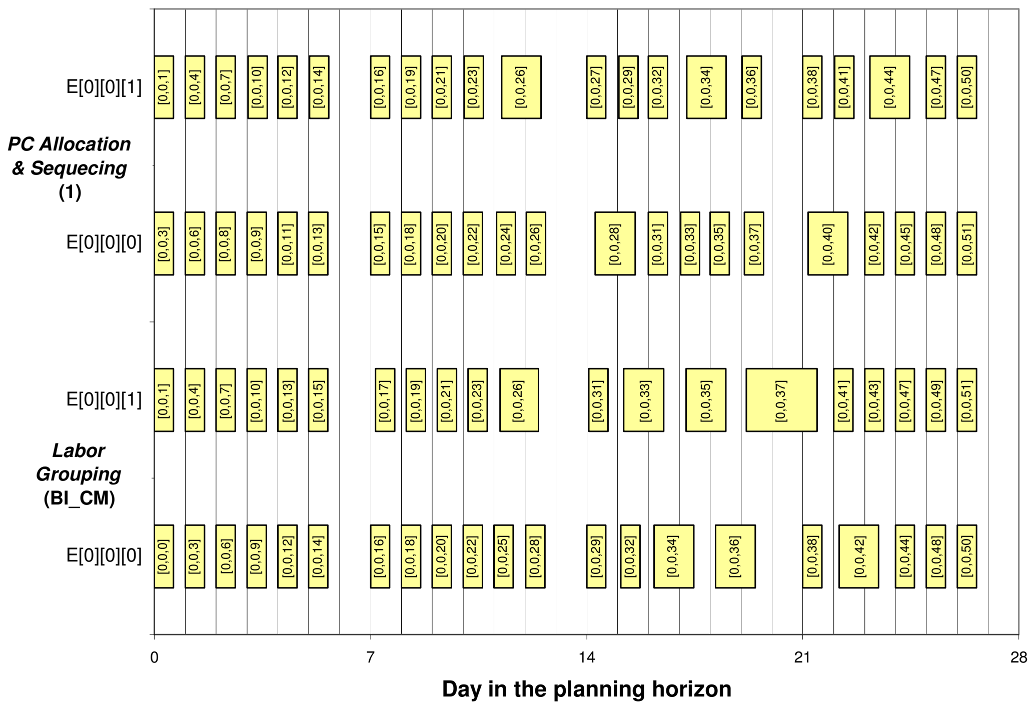
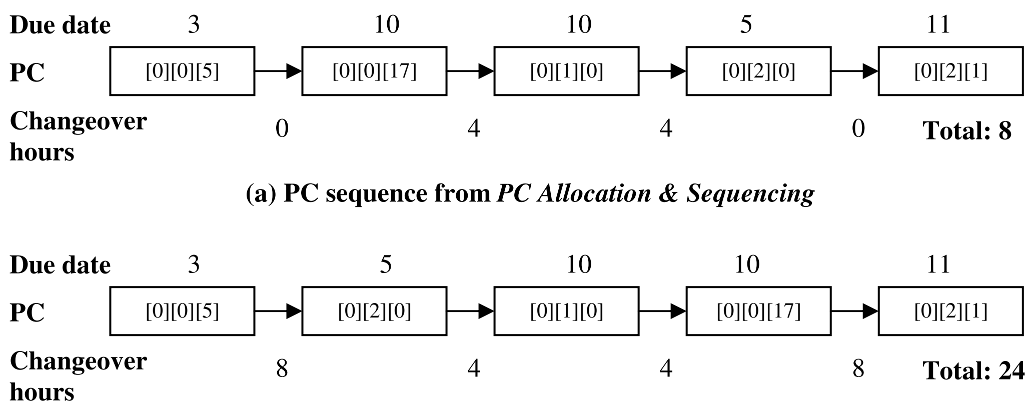


Figure 7.15: PC Production on E[0][0] Result from *Labour Grouping* (BI_CM) and *PC Allocation & Sequencing* (1)

It can be seen that through *PC Allocation & Sequencing*, PC[0][0], PC[0][1] and PC[0][2] are reallocated among S[0][0][0] and E[0][0], and PC quantity on

S[0][0][0] has been cut from 20 to 18. At the same time, PC sequence on S[0][0][0] is adjusted so that more PCs of the same type are produced continuously. The mould changeover times has been reduced by 4, from 10 to 6. As a result, the total variable cost in Group 0 is lowered from S$846.8 to S$551.9.

Note that in PC schedule from *Labour Grouping* (BI_CM) of Figure 7.14, all PCs on S[0][0][0] are arranged in an increasing order of their due dates since BI_CM is conducted based on EDD/LMC rule. This is not the case in the counterpart PC schedule from *PC Allocation & Sequencing*. For example, PC[0][0][17] and PC[0][1][0] with due date of day 10 is put ahead of PC[0][2][0] with due date of day 5. This arrangement is not unreasonable, as only 8 hours are needed in total for mould changeovers, as shown in Figure 7.16(a). If the three PCs are sequenced according to EDD/LMC rule as in Figure 7.16(b), there would be 24 changeover hours incurred. It would be not worth it to reduce stock of a PC by a couple of days at the price of extra 32 man-hours ($(24-8)hours \times 2labor$). Therefore, *PC Allocation & Sequencing* provides a better PC production sequence than EDD/LMC rule.



(a) PC sequence from *PC Allocation & Sequencing*

(b) PC sequence based on EDD/LMC rule

Figure 7.16: Changeover Hours Needed for Different PC Sequence on S[0][0][0]

Similarly, *PC Allocation & Sequencing* is conducted for PC[0][3] and PC[0][4] on S[0][1], E[0][1] and E[0][2] subsequently. Again, performance of the schedule in Group 0 is improved from S$551.9 to S$385.5. It should be noted that the improvements made by *PC Allocation & Sequencing* are mainly attributed to OT reductions. As shown in Table 7.13, the original OT cost, S$597. 5, is reduced to S$322.5 by the 1st step of *PC Allocation & Sequencing* and further to S$167.5 by the 2nd step. There may be two reasons for the considerable decreases in OT usage. Firstly, reduction of mould changeover times cuts down the overall hours required in production, and further mitigates the need for extra OT hours to meet the production. Secondly, the bidirectional simulation tends to reduce OT usage by flexibly arranging production in available NT hours. By providing numerous alternatives of PC assignment and sequencing plans, GA enables the bidirectional simulation to deploy its capability of OT reduction in a vast space, therefore increasing the possibility of getting a satisfying or optimal solution.

7.3.2.3 *Labour Transferring*

The strength of CM rule for labour transfer has been demonstrated in Section 7.3.2.1.1. However, CM rule may not guarantee an optimal sequence of transferring labour among moulds. The module of *Labour Transferring* is thus established to search for a better labour transfer sequence with GA to further improve the schedule performance.

Table 7.13 shows that *Labour Transferring* in the test does make an improvement in schedule performance, reducing the total variable cost from S$3894.2 to S$3769.5. Table 7.16 provides the sequences of transferring labour among moulds of Group 0 in modules of *PC Allocation & Sequencing* and *Labour Transferring*. Obviously, the sequence generated by GA in *Labour Transferring* is rather different from that created based on CM rule in *PC Allocation & Sequencing*. The difference in labour transfer sequence finally leads to the discrepancy in total variable costs of the two schedules.

Table 7.16: Labour Transfer Sequences of PC Group 0 in Modules of *PC Allocation & Sequencing* and *Labour Transferring*

***PC Allocation & Sequencing* (2)**						***Labor Transferring***					
S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould
1	E[0][0]	1	62	E[0][0]	20	1	S[0][0][0]	1	62	E[0][0]	23
2	E[0][0]	2	63	S[0][0][0]	9	2	S[0][1][0]	1	63	E[0][0]	24
3	S[0][0][0]	1	64	E[0][1]	9	3	E[0][0]	1	64	E[0][0]	25
4	S[0][1][0]	1	65	E[0][2]	10	4	E[0][0]	2	65	E[0][0]	26
5	E[0][1]	1	66	S[0][1][0]	11	5	E[0][0]	3	66	S[0][1][0]	13
6	E[0][2]	1	67	E[0][0]	21	6	E[0][1]	1	67	S[0][0][0]	9
7	E[0][3]	1	68	E[0][0]	22	7	S[0][0][0]	2	68	E[0][1]	7
8	E[0][0]	3	69	S[0][0][0]	10	8	E[0][0]	4	69	S[0][0][0]	10
9	E[0][0]	4	70	E[0][3]	8	9	E[0][0]	5	70	E[0][0]	27
10	S[0][0][0]	2	71	S[0][1][0]	12	10	E[0][0]	6	71	E[0][0]	28
11	S[0][1][0]	2	72	E[0][0]	23	11	E[0][0]	7	72	E[0][0]	29
12	E[0][1]	2	73	E[0][0]	24	12	E[0][1]	2	73	E[0][1]	8
13	E[0][2]	2	74	S[0][0][0]	11	13	E[0][1]	3	74	E[0][1]	9
14	E[0][3]	2	75	E[0][1]	10	14	S[0][1][0]	2	75	S[0][1][0]	14
15	E[0][0]	5	76	E[0][2]	11	15	E[0][0]	8	76	E[0][3]	7
16	E[0][0]	6	77	E[0][0]	25	16	E[0][2]	1	77	E[0][0]	30
17	S[0][0][0]	3	78	S[0][1][0]	13	17	E[0][2]	2	78	S[0][0][0]	11
18	S[0][1][0]	3	79	E[0][0]	26	18	S[0][0][0]	3	79	E[0][0]	31
19	E[0][1]	3	80	E[0][3]	9	19	S[0][0][0]	4	80	E[0][0]	32
20	E[0][2]	3	81	S[0][1][0]	14	20	E[0][0]	9	81	E[0][0]	33
21	E[0][3]	3	82	E[0][0]	27	21	E[0][0]	10	82	E[0][0]	34
22	E[0][0]	7	83	E[0][0]	28	22	E[0][2]	3	83	E[0][2]	8
23	E[0][0]	8	84	S[0][0][0]	12	23	E[0][2]	4	84	S[0][0][0]	12
24	S[0][0][0]	4	85	E[0][1]	11	24	E[0][0]	11	85	S[0][0][0]	13
25	S[0][1][0]	4	86	E[0][2]	12	25	S[0][0][0]	5	86	E[0][2]	9
26	E[0][1]	4	87	E[0][0]	29	26	E[0][3]	1	87	S[0][0][0]	14
27	E[0][2]	4	88	S[0][1][0]	15	27	S[0][1][0]	3	88	E[0][2]	10
28	E[0][3]	4	89	E[0][0]	30	28	S[0][1][0]	4	89	E[0][1]	10
29	E[0][0]	9	90	E[0][2]	13	29	E[0][3]	2	90	E[0][1]	11
30	E[0][0]	10	91	E[0][1]	12	30	E[0][3]	3	91	E[0][0]	35
31	S[0][0][0]	5	92	E[0][3]	10	31	E[0][2]	5	92	E[0][0]	36
32	S[0][1][0]	5	93	S[0][1][0]	16	32	E[0][0]	12	93	S[0][1][0]	15
33	E[0][1]	5	94	E[0][0]	31	33	S[0][1][0]	5	94	E[0][0]	37
34	E[0][2]	5	95	S[0][0][0]	13	34	E[0][1]	4	95	S[0][1][0]	16
35	E[0][3]	5	96	E[0][0]	32	35	S[0][0][0]	6	96	S[0][1][0]	17
36	E[0][0]	11	97	E[0][2]	14	36	E[0][3]	4	97	S[0][0][0]	15
37	E[0][0]	12	98	E[0][0]	33	37	E[0][3]	5	98	S[0][1][0]	18
38	S[0][0][0]	6	99	E[0][0]	34	38	E[0][2]	6	99	S[0][1][0]	19
39	S[0][1][0]	6	100	S[0][1][0]	17	39	E[0][1]	5	100	E[0][3]	8
40	E[0][1]	6	101	S[0][0][0]	14	40	S[0][1][0]	6	101	E[0][1]	12
41	E[0][2]	6	102	E[0][2]	15	41	E[0][1]	6	102	E[0][0]	38
42	E[0][3]	6	103	E[0][0]	35	42	E[0][3]	6	103	E[0][0]	39
43	E[0][0]	13	104	S[0][0][0]	15	43	E[0][2]	7	104	E[0][0]	40
44	E[0][0]	14	105	S[0][1][0]	18	44	S[0][1][0]	7	105	S[0][0][0]	16
45	S[0][1][0]	7	106	E[0][0]	36	45	E[0][0]	13	106	E[0][2]	11
46	S[0][0][0]	7	107	E[0][2]	16	46	S[0][1][0]	8	107	E[0][2]	12
47	E[0][1]	7	108	E[0][0]	37	47	E[0][0]	14	108	E[0][3]	9
48	E[0][2]	7	109	E[0][0]	38	48	E[0][0]	15	109	E[0][0]	41
49	E[0][0]	15	110	S[0][0][0]	16	49	E[0][0]	16	110	S[0][0][0]	17
50	E[0][0]	16	111	S[0][1][0]	19	50	E[0][0]	17	111	S[0][1][0]	20
51	S[0][1][0]	8	112	E[0][2]	17	51	S[0][1][0]	9	112	S[0][1][0]	21
52	E[0][2]	8	113	E[0][0]	39	52	E[0][0]	18	113	S[0][1][0]	22
53	S[0][0][0]	8	114	E[0][0]	40	53	S[0][0][0]	7	114	E[0][2]	13
54	E[0][1]	8	115	S[0][0][0]	17	54	S[0][0][0]	8	115	E[0][2]	14
55	S[0][1][0]	9	116	S[0][1][0]	20	55	S[0][1][0]	10	116	E[0][3]	10
56	E[0][0]	17	117	E[0][0]	41	56	S[0][1][0]	11	117	E[0][2]	15
57	E[0][0]	18	118	E[0][0]	42	57	S[0][1][0]	12	118	S[0][0][0]	18
58	E[0][2]	9	119	S[0][0][0]	18	58	E[0][0]	19	119	E[0][2]	16
59	E[0][3]	7	120	S[0][1][0]	21	59	E[0][0]	20	120	E[0][0]	42
60	S[0][1][0]	10	121	E[0][0]	43	60	E[0][0]	21	121	E[0][2]	17
61	E[0][0]	19	122	S[0][1][0]	22	61	E[0][0]	22	122	E[0][0]	43

The OT hours consumed and PC Stock in PC Group 0 of schedules established by the three modules for detailed scheduling are given in Figure 7.17 and 7.18 respectively. It can be seen that, *Labour Transferring* has made improvements, in both OT usage and PC stock level, to the schedule from *PC Allocation & Sequencing*. These improvements, however, are less significant, compared to those made by *PC Allocation & Sequencing* to the schedule from *Labour Grouping*. The reasons may lies in two aspects. Firstly, CM rule is already very effective in labour transfer. It may be difficult to propose an alternative sequence of labour transfer with better performance. Secondly, before *Labour Transferring* starts, *Labour Grouping* and *PC Allocation & Sequencing* are performed first to determine satisfying labour allocation plan and max OT allowance, and PC assignment and production sequence on moulds, respectively. With these constraints from the previous modules and improvements made beforehand, there is a very limited space left to further enhance the schedule performance.

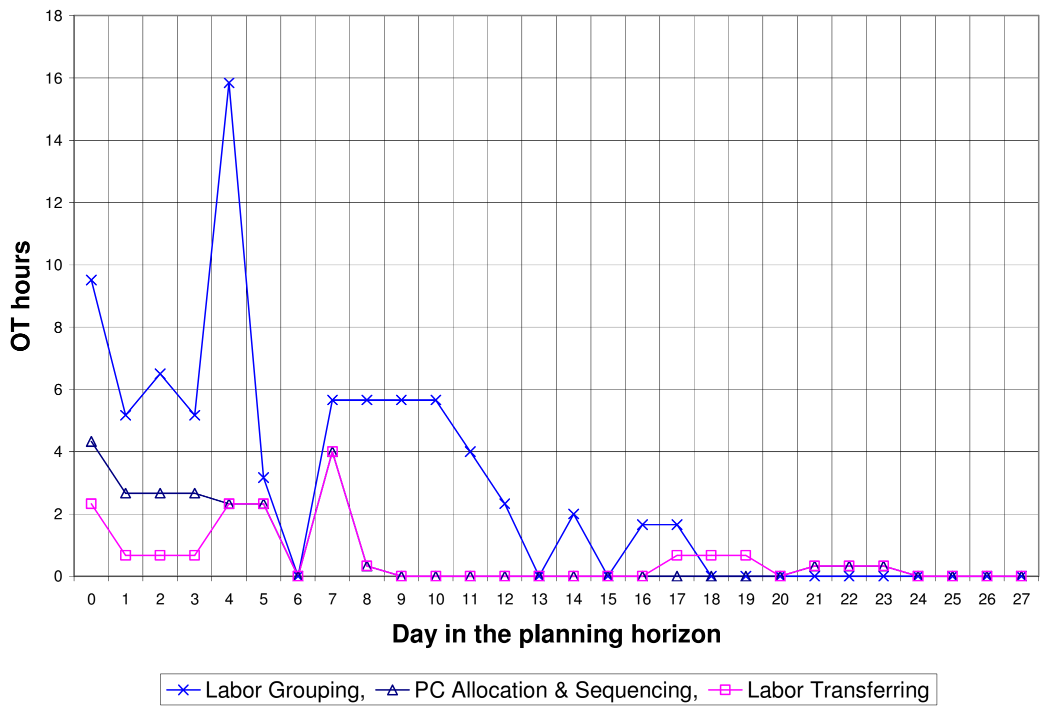


Figure 7.17: OT Hours Consumed in PC Group 0 of Schedules Generated by the Three Modules for Detailed Scheduling

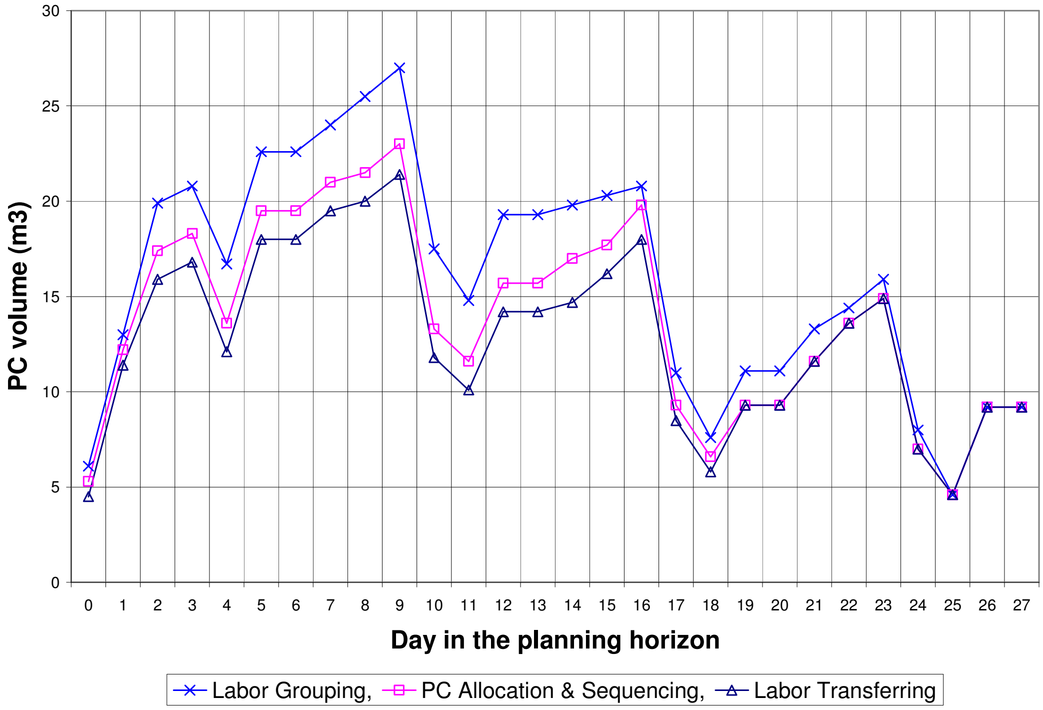


Figure 7.18: PC Stock of PC Group 0 in Schedules Generated by the Three Modules for Detailed Scheduling

Chapter 8

Conclusion and Recommendations

8.1 Conclusion

Precast technology has been increasingly applied in the construction industry, and it will be more and more extensively utilized in Singapore and many other countries. There is a need for a special-purpose planning and scheduling model to aid precasters in effective production management in precast plants. The model should effectively capture distinctive features of precast production, and help generate production schedules and resource plans to fully meet PC demand with minimum production-related cost. Based on these requirements, an integrated planning and scheduling model, IPSMPP, is presented for make-to-order precast production using a comprehensive casting organization. IPSMPP covers both aggregate planning at the tactical level and detailed scheduling at the operational level. Five modules at the two levels are designed for different planning purposes. A Simulation-GA based approach is proposed to solve specific problems in every module. Specialized priority rules and bidirectional simulation passes are further formulated in order to improve the schedule performance. Based on the model and its inner workings, a prototype system has been developed for model validation. Finally, two tests are conducted for aggregate planning and detailed scheduling respectively. The validity of IPSMPP has been demonstrated by comparison of the results from the prototype system, planning methods used in practice, and other traditional approaches. IPSMPP can considerably reduce not only the total variable cost, but also cost in nearly every cost category, thus leading to feasible schedules with best performance. In conclusion, the main contributions made in this research lies in the following aspects.

(1) Identification of Distinctive Features of Precast Production, and Establishment of Objectives and Performance Measurement Scheme for Planning and Scheduling

Compared to the production processes in other manufacturing industries, prefabrication has its own distinctive features, which should be taken into specific account in model development for precast production planning and scheduling. Through field study, questionnaire survey, and follow-up interviews, relevant information of current production practices in Singapore's precast plants are collected and summarized. Then, eight characteristics of precast construction are identified.

Based on the literature review and precast production analysis, objectives of precast production planning and scheduling are established, including zero tardiness, improvement of mould planning, enhancement of labour planning, and minimization of PC inventory. As accomplishments of these objectives may conflict with each other, a performance measurement scheme is further proposed. Under this scheme, performance of a feasible schedule is evaluated in terms of total variable cost incurred during production, including labour cost, mould cost, and stock holding cost.

(2) Development of Integrated Planning and Scheduling Model for Precast Production

To achieve the above objectives, an integrated planning and scheduling model for precast production, IPSMPP, is developed based on the philosophy of hierarchical production planning. In this model, the overall planning and scheduling process is structured into two levels, a tactical level and an operational level. During planning, mid-range aggregate planning at the tactical level is carried out at first. Then, subject to the constraints imposed by the aggregate plan, short-term detailed scheduling is done at the operational level. Besides, a feedback mechanism is incorporated to guarantee the transferring feasibility from aggregate planning to detailed scheduling.

For different planning purposes, five modules are developed for both levels: *Labour Sizing* and *Mould Planning* at the tactical level, and *Labour grouping*, *PC*

Allocation & Sequencing and *Labour Transferring* at the operation level. *Labour Sizing* is used to calculate proper labour sizes and max OT hours to consume for the whole plant in every planning period. Similarly, *Mould Planning* produces quantities for various moulds involved in a new precast project. Provided with the labour size for the whole plant, *Labour Grouping* aims to determine suitable labour sizes in different PC groups. On this basis, an optimal PC allocation and production sequence on every mould is resolved using *PC Allocation & Sequencing*. Finally, *Labour Transferring* generates a reasonable sequence to transfer labour among all moulds in every PC group.

At the tactical level, *Mould Planning* is project-based and *Labour Sizing* is plant-based, they can be integrated and conducted together to achieve a satisfying solution to the problems as a whole. At the operational level, PC production is modelled as a dual-resource constrained (DRC) system, with mould and labour as critical resources. In such a system, *Labour Grouping*, *PC Allocation & Sequencing*, and *Labour Transferring* are established to deal with labour flexibility, PC dispatching, and labour transfer, respectively.

(3) Establishment of Simulation-GA Based Approach for Each Module

To solve specific problems in every module, a Simulation-GA based approach is established. While simulation and GA are different techniques used for modelling and optimization respectively, they are integrated together to form a viable approach for precast production planning and scheduling. The scheduling process of each module is an iterative procedure of progressive improvement. During one scheduling iteration, simulation produces production schedules with given values of decision variables, while GA evaluates the schedule performance, adjusts values of the decision variables for the simulation, and selects the better ones for the next iteration.

Simulation can accurately capture constraints and dynamics in precast production. In the Simulation-GA based approach, two discrete-event simulation engines, Simulation(A) and Simulation(D), are designed to meet different requirements of modelling detail in aggregate planning and detailed scheduling respectively. At the tactical level, Simulation(A) adopts fixed-increment algorithm (FIA) for simulation clock advancing and produces master production schedules for individual PCs. On the other hand, at the operational level, Simulation(D) uses next-event algorithm (NEA) for simulation clock advancing and develops detailed production schedules for every operation.

As a generic optimization technique, GA is able to obtain satisfying or optimal solutions to complex problems efficiently. Moreover, it can give a family of final solutions, which are very useful to decision-making, especially when there are other planning considerations involved. In the Simulation-GA based approach, GA contains three consecutively executed subsystems, namely, selection, genetic operation, and decoding. Different configurations are proposed for these subsystems based on the nature of decision variables involved in each module.

(4) Design of Specialized Rules for Precast Production Planning and Scheduling

Proper priority rules are needed to run a discrete-event simulation. As precast production scheduling is modelled as a DRC problem, two sets of priority rules are used in Simulation(D) for transferring labour to moulds and dispatching PCs on every mould respectively. On the other hand, for simplicity of the model, only a single priority rule is used in Simulation(A) to assign PCs to every mould together with labour.

At the tactical level, a novel priority rule, CP rule, is established for PC dispatching in Simulation(A). With CP rule, all PCs to be loaded are divided into 3 categories according to their criticality, and mould-related critical PCs are identified using BLWMO — a special backward loading using mould as a single resource. In this way, CP rule takes mould requirement and availability into consideration. Furthermore, at the operational level, a new rule, CM rule, is created for labour transfer in Simulation(D). Similar to CP rule, CM rule focuses on mould requirement by overall PC demands, and also uses BLWMO to identify the criticality of every mould. The advantages of CP rule and CM rule over traditional rules for PC dispatching (EDD/LMC rule) and labour transfer (EDD and LQ rules) are demonstrated with the two tests in Chapter 7.

(5) Introduction of Bidirectional Simulation for Schedule Development at Both Tactical and Operational Levels

Instead of a traditional forward simulation, both Simulation(A) and Simulation(D) use a bidirectional simulation for schedule development. Simulation(A) takes two scheduling passes, including a forward simulation and a backward simulation. During one simulation process, the 1st forward simulation tries to generate a feasible production schedule by producing as early as possible with both NT and OT available. Then the backward simulation is conducted to improve the schedule by pulling back the production of PCs close to their due dates and utilizing NT available to reduce OT usage.

On the other hand, Simulation(D) adopts three scheduling passes, including two forward simulations and one backward simulation. The algorithms for operation time calculation are created for both forward and backward simulations based on characteristics of various casting operations. During schedule development, the 1st forward simulation and the backward simulation are conducted sequentially, with the same functions as those in Simulation(A). Finally, the 2nd forward simulation is performed to repair the backward schedule and make it applicable in practice. The adoption of the bidirectional simulation is also justified in the tests for both aggregate planning and detailed scheduling. Compared to the single forward simulation, the bidirectional simulation can reduce excessive OT usage and PC stock, thus leading to a better performance.

8.2 Limitations and Recommendations

8.2.1 Limitations of the Research

As described in the previous section, the research has basically fulfilled its goal for integrated planning and scheduling of precast production. However, it is not without limitations, which may lie in the following aspects.

8.2.1.1 Limited Scope

In order to attend to the main planning and scheduling issues and to not complicate the modelling work, the research is confined to a certain scope.

(1) Focus on Casting Process with Two Critical Resources

First, the research simplifies the planning problem by concentrating on developing and refining the schedules for the bottleneck activities and resources only. Among several types of activities involved in precast production, only casting process is taken into consideration in the proposed model, as it is the most critical activity in the entire production process. Similarly, production scheduling is modelled as a DRC problem, because labour and moulds are identified as the bottleneck resources in casting process. Planning of other production activities (such as materials preparation, PC finishing and PC storage) and resources (such as crane) still need to be done for precast production, though they are not the focus of the research.

(2) Focus on Comprehensive Labour Organization

Labour organizations used in casting process in precast plants can be classified into comprehensive organization and specialization organization. Based on the investigation on Singapore's precast industry, comprehensive organization is adopted by most precasters as it is more suited for heterogeneous production. Therefore, the model is developed mainly for precast production under a comprehensive organization. Specialization organization is not a focus in this research, though a couple of precasters do prefer it due to its high efficiency in terms of labour and equipment utilization.

(3) Assumption of One Sharable Mould Type for a PC

In the model development, it is assumed that if a PC can be produced with sharable moulds, then there is only one type of sharable mould available for its production. This assumption is made to simplify the PC allocation procedure in Simulation(A) for aggregate planning. In addition, CP rule in aggregate planning is designed based on the assumption. It is not completely unreasonable to make such assumption, as the assumption is applicable for most of PC types in daily precast production. Nevertheless, it might be possible that some PC types can be produced with more than one type of sharable mould. In this case, one could designate a most suitable sharable mould type for a PC type to use, thus keeping the assumption effective.

8.2.1.2 Increased Computation Time

In the tests in Chapter 7, while the proposed model does generate a better solution than those approaches using traditional rules or based on single forward simulation, it needs more computation time to obtain the solution. For example, the test for aggregate planning was performed on a personal computer of AMD Athlon(TM) XP 1800+. The times taken for F_TRD, F_CP and BI_CP to generate their final master production schedules are 77 s, 177 s, and 223 s separately. Apparently, in comparison with F_TRD, BI_CP used nearly three times the time, while F_CP consumed more than twice the time. The increased computation time of the model (BI_CP) is result from the way it works in the following aspects:

(1) Use of CP or CM Rule with BLWMO

CP rule is used in Simulation(A) for aggregate planning and CM rule used in Simulation(D) for detailed scheduling. Compared to traditional rules, such as EDD/LMC rule for PC dispatching and EDD and LQ rules for labour transfer, CP rule and CM rule are more complicated. To measure the level of PC demands and mould requirements, BLWMO needs to be conducted in both of the rules before and during the formal simulations for schedule development. This procedure inevitably increases the overall computation time.

(2) Adoption of Bidirectional Simulation

Instead of a traditional forward simulation, the model adopts a bidirectional simulation in both Simulation(A) and Simulation(D). In an iteration of schedule development, the multiple-pass directional simulation clearly consumes more time than the single-pass forward simulation.

Nevertheless, the increased computation time of the proposed model may be worth the while for precasters to get a schedule with much better performance. Furthermore, when the model is implemented on a high performance computer or GA applied in the model is improved (as discussed in the following section), the overall computation time could be reduced.

8.2.2 Recommendations for Future Study

There are many possible research and development works based on the current research. First, in order to draw a more definite conclusion on the validity of the model, further tests could be conducted with different data inputs. In addition to those aspects that have been examined in the two tests in Chapter 7, the future tests can explore some new issues. Two examples of such issues are given below:

1. Transferring feasibility between two levels. A feedback mechanism has been established in the proposed model to guarantee the transferring feasibility from aggregate planning at the tactical level to detailed scheduling at the operation level. The validity of the feedback mechanism could be examined;
2. Impact of forecast demand consideration. Forecast demand of PCs may not be considered in an actual planning work, while it is explicitly represented in terms of "Typical PC for plant" in the proposed model. In the future tests, the impact of forecast demand on schedule performance can be investigated by comparing the schedules with and without consideration of the forecast demand.

Besides, follow-up interviews with professionals in precast production planning and scheduling could be made. During the interviews, the proposed model and results from the tests could be presented. Comments and advice from the professionals could then be collected for further model validation and modification.

Last but not least, some improvements and extensions can be made to the current model, as follows.

(1) Improvement of GA

In the proposed model, GA plays a critical role in developing a satisfying or optimal production schedule. However, it is only applied in the current research to demonstrate its capability to work well with simulation for precast production planning and scheduling. It is shown in literature that refinement of GA can make an efficient implementation for a specific problem. In this research, improvement of GA would reduce the computation time for schedule development or result in schedules with lower total variable costs. Some possible areas where GA could be improved for the proposed model are given below:

- Comparing random key representation with other encoding techniques, and choosing appropriate chromosome representations for *PC Allocation & Sequencing* and *Labour Transferring*;
- Comparing repairing strategy with penalizing strategy in treatment of infeasible or illegal chromosomes, and deciding the best strategies to be used in every module;
- Designing new problem-specific genetic operators to replace the simple conventional operators (two-cut-point crossover and uniform mutation);
- Testing different selection methods based on deterministic or stochastic sampling mechanisms in the proposed model;
- Incorporating conventional heuristics into GA to obtain a more competitive hybrid GA.

(2) Planning for Non-Critical Activities and Resources

As an extension to the current model, an add-on model could be developed for planning for non-critical activities (e.g., rebar preparation and PC finishing) and non-critical resources (e.g., cranes and casting space used for casting process, and labour used for non-critical activities). The planning work should be conducted based on the "master schedule" of casting process. For example, at the tactical level, PC type and volume to be produced in every week can be obtained from the weekly PC casting schedule. On this basis, the total man-hours needed for rebar preparation and PC finishing can be derived with the given man-hours per PC volume. GA could also be used to determine the labour sizes for these activities by making a tradeoff between cost of labour hiring/firing and cost of NT and OT. At the operational level, after the detailed schedule for PC casting is established, production schedules for rebar preparation and PC finishing can be derived within the labour constraints.

(3) Adjustment for Specialization Labour Organization

As mentioned in the previous section, both comprehensive and specialization labour organizations are used by precasters in Singapore, though the latter is not very popular for MTO precast production. For this reason, it may be worth future study to adjust the model for precast production under a specialization organization. In this case, the focus should be placed on how to efficiently utilize labour at the operation level.

(4) Modelling of Labour Flexibility and Labour Transfer Delay

Labour flexibility has a major impact on job shop performance. In this research, labour flexibility is mainly modelled as labour allocation into different PC groups. It is assumed that labour with multiple skills can perform each skill equally well and are interchangeable with one another. While the assumption is used to simplify the problem, there are some other ways to model labour flexibility in DRC literature. For example, the efficiency of labour that are transferred and the specific machines to which a labour can be transferred can be used as control parameters in DRC systems. Future work could try to model labour flexibility in different ways. In addition, labour transfer delay is not taken into account in the current model, although it has been acknowledged by a few researchers in their DRC studies. In future study, labour transfer delay could be introduced in the model to account for the time needed to orientate the transferred labour on the new moulds.

(5) Consideration of Uncertainties

There are various uncertain and risk factors involved in precast production, such as adverse weather and changes in PC demand. These uncertainties can have a large impact on production system, and should be carefully considered in production planning and scheduling. Two potential methods could be adopted to handle the uncertainties in the proposed model. One is to incorporate a certain level of slack (PC stock) during schedule development, while the other is to use stochastic simulation to measure the effect of the uncertainties on production schedules.

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APPENDICES

Appendix A: Questionnaire for Survey on Current Production Practices in Singapore's precast plants

Company Information

[1] Types of **precast components (PCs)** produced in your company:

____

____

____

[2] Number of direct labour employed in your company: ____________

[3] Monthly precast production volume in your company: ____________ (m^3)

Note:

[1] The following questions (from Part I to IV) are only for Make-To-Order precast production. If such a system is not adopted in your company, please answer the questions based on your experiences.

[2] For most of the questions, please select the proper answer(s) by checking in the corresponding box(es). For the rest, please answer as prompted.

Part I. Production Practice

[1] Select the production system(s) adopted in your company.

Production system	System adopted
1. Make-To-Order where outline design is supplied by the client, customized moulds are required, and PCs are produced according to order.	☐

2. Make-To-Stock where standardized PCs are produced in batches and kept in stock for use of different orders.	☐

[2] Among different types of activities involved in precast production, which one is the critical process?

- ☐ Preparation of materials (such as concrete and reinforcement).
- ☐ Casting of PCs (including demoulding and mould preparation, rebar and cast-in-item fixing, concrete pouring, and curing)
- ☐ PC finishing
- ☐ Others (please specify):

[3] What is/are critical resource(s) in **precast component (PC)** production?

- ☐ Mould
- ☐ Labour
- ☐ Crane
- ☐ Curing facility
- ☐ Others (please specify): ____________________

[4] Usually how many months does production for a precast project take?

____________________ months.

[5] Usually after receipt of an order from a precast project, how many weeks does it take to make preparation (including shop drawing preparation, mould fabrication, etc) before production?

____________________ weeks.

[6] Usually for how many days is a PC kept in stock before delivery to site?

____________________ days.

[7] Delivery due dates of PCs in a precast project are

- ☐ Prescribed by the contractor and must be met by precaster.
- ☐ Provided by the contractor and negotiable between each other.
- ☐ Assigned by precaster and approved by contractor.

[8] Which curing method is adopted in PC production?

- ☐ PCs are cured through a natural process in the open air.
- ☐ PCs are cured with artificial curing facilities.

[9] Is JIT production applied by precaster? Why?

Part II. Mould Arrangement

[1] What type of mould system is adopted in your plant?

☐ Stationary moulds ☐ Movable moulds

[2] For a precast project, is it reasonable to assume that a mould can be used through the entire project duration?

☐ Yes ☐ No

[3] Usually how many weeks does it take for mould fabrication?

____________________ weeks.

[4] Usually what percentage of moulds used for a precast project are sharable moulds, which can be used to produce different PCs?

____________________ %.

[5] Mould changeover on sharable mould is

☐ Sequence-dependent. It depends on both the PC to be produced and the immediately proceeding finished PC.

☐ Sequence-independent. It depends only on the PC to be produced.

[6] Are identical or similar PCs often produced continuously to reduce mould changeovers even it is not consistent with delivery sequence?

☐ Yes ☐ No

[7] How do you conduct mould planning for a new precast project?

Part III. Labour Utilization

[1] How do you conduct labour planning?

[2] In labour planning, do you tend to keep labour size in plant stable within the planning horizon?

☐ Yes ☐ No

[3] During production, do you divide PCs into several groups, with each assigned with a group of labour for its production?

☐ Yes ☐ No

[4] If the answer to question [1] is "yes", how to divide PCs into groups?

☐ PCs from one project are grouped together.

☐ PCs of similar types are grouped together.

[5] Do labour sizes in different PC groups need to be adjusted periodically (say weekly) to meet requirement of PC production? (This is to make Labour dedicated to a specific job in a short time for ease of management and working efficiency improvement.)

☐ Yes ☐ No

[6] How many working shifts per day do you use in precast production?

☐ One ☐ Two

☐ Three

[7] How often do labour work overtime to meet the demand?

☐ Always ☐ Frequently ☐ Sometimes ☐ Seldom

[8] Do labour in plant have to work at least 8 hours per day even if there is no urgent demand?

☐ Yes ☐ No

[9] There are two alternatives of labour organization in precast casting process, as follows.

- ***Specialization organization***. The casting process is broken into several operations (namely, demoulding & mould preparation, rebar & cast-in-item fixing, concrete pouring, and curing), which are performed by different teams with specialized tools and work methods.
- ***Comprehensive organization***. The same team performs all the operations in the casting process. After one PC is cast, the team moves to the next mould and start to work from the beginning.

[9.1] Which form of labour organization is adopted in your plant?

☐ Comprehensive organization ☐ Specialization organization

[9.2] For each labour organization, please choose the proper conditions where it is most applicable.

Labour organization	**Production system**		**Daily working shift(s)**		**Mould system**	
	MTO	MTS	single	multiple	stationary	movable
Comprehensive	☐	☐	☐	☐	☐	☐
Specialization	☐	☐	☐	☐	☐	☐

[9.3] What are advantages and disadvantages of comprehensive and specialization organization respectively?

Part IV. Planning and Scheduling

[1] What planning and scheduling method is used for precast production?

- ☐ Material requirements planning (MRP) / Manufacturing resource planning (MRPII)
- ☐ Just-in-time (JIT)
- ☐ Optimized production technology (OPT)
- ☐ Mathematical programming based on HPP (hierarchical production planning)
- ☐ Trial-and-error method based on experiences
- ☐ Others (please specify): ____________________

[2] By comparison, which one is more significant in precast production planning and scheduling?

- ☐ Capacity (mould, labour, etc.) planning
- ☐ Material (rebar, concrete, etc.) planning

[3] For every possible planning objective listed below, please rate their importance in precast production by checking in a proper box. The scale of importance is set as follows.

4: Most Important; 3: Very Important; 2: Moderately Important; 1: Slightly Important; 0: Irrelevant.

Possible production objectives	**Importance**				
	4	**3**	**2**	**1**	**0**
Meet the delivery schedule / site demand	☐	☐	☐	☐	☐
Ensure production schedules feasible in terms of capacity (within resource constraints)	☐	☐	☐	☐	☐
Reduce mould quantity / investment	☐	☐	☐	☐	☐
Reduce labour cost (for hiring/firing, NT, and OT working)	☐	☐	☐	☐	☐
Fully utilize labour in plant	☐	☐	☐	☐	☐
Minimize mould changeovers	☐	☐	☐	☐	☐
Minimize PC inventory	☐	☐	☐	☐	☐
Others (please specify)					
	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐

[4] Accomplishment of the above objectives may conflict with each other. Therefore, is it reasonable to say that final production schedules are satisfying or optimal if all precast demands are fulfilled with a minimum production-related cost?

☐ Yes ☐ No

[5] Please explain the planning and scheduling method used in your company for precast production, and indicate the procedure of production schedule development step by step.

____

[6] Generally how many man-hours does it need to develop all the production plans and schedules for a particular precast project?

______________________ man-hours.

[7] When an order from a precast project is received, what is the precedence relationship between calculating mould quantity for the project and labour size needed in plant?

☐ Mould quantity and labour size are determined at the same time.

☐ Mould quantity is determined at first. Then, labour size is determined.

☐ Labour size is determined at first. Then, mould quantity is determined.

[8] Please specify the computer software used in precast production planning and scheduling and their functions?

Software used: ______________________

Functions: ☐ Data storage and retrieval ☐ Planning or scheduling tool

☐ Others (please specify): ______________________

____

[9] Do you make monthly forecasting of unknown demand in order to prepare target production plan and to make labour arrangement in future?

☐ Yes ☐ No

[10] If the answer to question [9] is "yes", forecasting of unknown demand can be made

☐ For every typical PC type.

☐ In terms of precast volume (m3) in plant.

[11] If the answer to question [9] is "yes", how many months do you make such forecasting for?

________________ months.

[12] What are the criteria used to determine PC production sequence?

- ☐ PC with least mould changeover is produced first.
- ☐ PC with earliest due date is produced first.
- ☐ PC with shortest processing time is produced first.
- ☐ PC with lowest stock cost is produced first.
- ☐ PC with least demand volume is produced first.
- ☐ Others (please specify): ________________

[13] Please specify the problems/limitations in the planning and scheduling method used in practice, and recommend any improvements that should be made in future?

Respondent's Particulars

Name: ________________

Designation: ________________ Years of Experience: ________

Company: ________________

Address: ________________

____

Tel: ________________ Fax: ________________

Email: ________________

Do you wish to have a copy of the findings of this survey?

☐ Yes ☐ No

Thank you very much for your time and effort!

Appendix B: Results from Test I for Aggregate Planning

Some results obtained from Test I for aggregate planning in Chapter 7 are given in Appendix B, including

Table **Page**

Table B.1: Master Production Schedule on Moulds and PC Stock Obtained from F_ACT

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 0	Demand		0	0	20	20	0	20	20	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	E[0]	18	18	17	18	18	17	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	36	33	31	49	46	26	26	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 1	Demand		0	14	0	14	0	14	0	14	0	2	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	6	10	6	8	6	6	2	0	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[1]	6	6	6	6	6	6	6	2	0	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	6	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	4	14	6	14	6	12	0	0	2	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 2	Demand		0	0	20	0	20	0	20	0	20	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	6	11	7	11	9	11	5	9	11	8	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[2]	6	6	6	6	6	6	5	6	6	6	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	0	5	1	5	3	5	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		6	17	4	15	4	15	0	9	0	8	4	8	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 3	Demand		0	16	16	16	16	0	0	0	0	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	18	18	18	10	0	0	0	0	0	3	16	18	18	18	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	6	6	6	6	0	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	6	6	6	4	0	0	0	0	0	0	5	6	6	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	6	6	6	0	0	0	0	0	0	3	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	20	22	16	0	0	0	0	0	3	3	5	7	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 4	Demand		0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	6	17	18	11	2	17	14	0	0	0	0	9	17	18	18	18	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	0	0	0	0	5	6	6	2	6	6	0	0	0	0	0	5	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	0	0	0	1	6	6	5	0	6	6	0	0	0	0	4	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	0	0	0	5	6	6	0	0	5	2	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	6	23	24	18	3	3	0	0	0	0	0	9	9	10	11	12	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 5	Demand		0	0	20	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	11	9	6	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	5	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		11	20	6	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B.1 <Continued>

PC type	Demand, production & stock	Mould	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 6	Demand		0	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	14	18	7	3	6	16	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	2	6	4	0	0	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	6	6	6	3	3	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	14	20	15	6	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 7	Demand		0	0	0	0	0	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	17	18	3	13	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	0	0	0	5	6	0	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	0	5	6	3	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	0	2	0	0	4	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	17	18	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 8	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	16	0	0	0	16	0
	Production	E[3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	6	0	4	6	6	0	4	6	6	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	0	0	4	10	0	0	4	10	0	0
PC 9	Demand		0	0	0	0	0	0	0	0	18	18	18	18	5	5	5	5	5	5	18	18	18	18	5	5	5	5	5	5	18	18	18	18
	Production	Total	0	0	0	0	0	0	0	0	18	18	18	18	18	2	0	4	6	7	17	18	18	17	15	0	0	6	4	6	17	17	18	14
		E[4]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	6	6	6	6	6	2	0	0	0	0	5	6	6	6	6	0	0	0	0	0	5	6	6	6
		S[3][1]	0	0	0	0	0	0	0	0	6	6	6	6	6	0	0	0	0	1	6	6	6	6	6	0	0	1	4	1	6	6	6	6
		S[3][2]	0	0	0	0	0	0	0	0	6	6	6	6	6	0	0	4	6	6	6	6	6	5	3	0	0	5	0	5	6	5	6	2
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	13	10	5	4	5	7	6	6	6	5	15	10	5	6	5	6	5	4	4	0
PC 10	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	0	0	0	0	0	0	0	22	22	22	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	13	18	13	12	10	0	0	0	0	1	16	17	10	12	10	0	0	0	0
		E[5]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	6	6	0	0	0	0	0	5	6	6	6	6	0	0	0	0
		S[3][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	4	0	0	0	0	0	5	6	4	1	4	0	0	0	0
		S[3][2]	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	1	0	0	0	0	0	0	1	6	5	0	5	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	13	31	22	12	0	0	0	0	0	1	17	34	22	12	0	0	0	0	0

Columns 0–31 are weeks (header "Week").

Table B.1 <Continued>

PC type	Demand, production & stock	Mould	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
			Week																															
PC 11	Demand		0	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	4	9	11	12	12	12	12	12	12	8	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][0]	0	0	0	0	0	0	4	6	6	6	6	6	6	6	6	6	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][1]	0	0	0	0	0	0	0	3	5	6	6	6	6	6	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	4	2	2	3	4	5	6	7	8	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
PC 12	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	11	11	11	11	11	11	11	11	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	6	6	11	12	12	12	11	11	11	11	0	0	0	0
		S[4][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	6	6	6	6	0	0	0	0
		S[4][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	6	6	6	6	6	6	5	5	5	5	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	8	9	10	11	11	11	11	11	0	0	0	0
PC 13	Demand		0	0	0	0	0	0	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	Production	Total	0	0	0	0	0	0	24	19	18	18	18	18	18	18	18	18	23	18	18	18	18	18	18	18	18	18	23	24	24	23	2	0
		E[6]	0	0	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	2	0
		S[5][0]	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	5	6	6	5	0	0
	Stock		0	0	0	0	0	0	24	19	13	7	1	1	1	1	1	1	24	18	12	6	0	0	0	0	0	0	23	23	23	22	0	0
PC 14	Demand		0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	3	6	6	6	6	0	0	0	0	0	5	6	6	5	5	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	3	9	15	21	18	9	0	0	0	0	5	11	17	22	18	9	0	0	0	0	0	0	0	0	0
PC 15	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	5	0	0	0	0	0	0	5	6	6	5	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	5	11	6	0	0	0	0	0	0	0	5	11	6	0	0	0	0	0	0	0
PC 16	Demand		0	0	0	0	0	0	0	0	0	0	0	0	28	28	28	28	32	32	32	32	40	40	40	40	43	43	43	43	51	51	51	51
	Production		0	0	0	0	0	0	0	0	0	8	27	25	20	20	20	21	32	32	32	40	39	38	37	43	37	34	34	41	47	47	67	35
	Stock		0	0	0	0	0	0	0	0	0	8	35	60	52	44	36	29	29	29	29	37	36	34	31	34	28	19	10	8	4	0	16	0

Table B.2: Master Production Schedule on Moulds and PC Stock Obtained from F_TRD

PC type	Demand, production & stock	Mould	Week																														
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 0	Demand		0	0	20	20	0	20	20	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	E[0]	18	18	14	16	18	18	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	36	30	26	44	42	22	22	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 1	Demand		0	14	0	14	0	14	0	14	0	2	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	6	10	6	8	6	6	2	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[1]	6	6	6	6	6	6	6	2	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	6	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	4	14	6	14	6	12	0	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 2	Demand		0	0	20	0	20	0	20	0	20	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	6	11	7	11	9	11	5	12	8	8	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[2]	6	6	6	6	6	6	5	6	6	6	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	0	5	1	5	3	5	0	6	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		6	17	4	15	4	15	0	12	0	8	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 3	Demand		0	16	16	16	16	0	0	0	0	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	18	18	18	10	0	0	0	0	0	15	18	18	18	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	6	6	6	6	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	6	6	6	4	0	0	0	0	0	5	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	6	6	6	0	0	0	0	0	0	5	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	20	22	16	0	0	0	0	0	15	17	19	21	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 4	Demand		0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	6	17	18	11	16	18	0	0	0	0	5	15	18	18	18	10	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	0	0	0	0	5	6	6	6	6	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	0	0	0	1	6	6	5	6	6	0	0	0	0	0	4	6	6	6	4	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	0	0	0	5	6	6	0	4	6	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	6	23	24	18	17	18	1	1	1	1	6	21	22	23	24	17	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 5	Demand		0	0	20	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	10	10	12	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	4	4	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		10	20	12	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B.2 <Continued>

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 6	Demand		0	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	12	12	12	12	12	7	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	6	6	6	6	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	6	6	6	6	6	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	12	12	12	12	12	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 7	Demand		0	0	0	0	0	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	3	11	12	8	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	0	0	3	6	6	2	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	3	14	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 8	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	16	0	0	0	16	0
	Production	E[3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	4	0	6	6	4	0	4	6	6	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	0	0	6	12	0	0	4	10	0	0
PC 9	Demand		0	0	0	0	0	0	0	0	18	18	18	18	5	5	5	5	5	5	18	18	18	18	5	5	5	5	5	5	18	18	18	18
	Production	Total	0	0	0	0	0	0	0	0	18	18	18	18	15	5	5	0	0	7	17	18	18	18	14	5	5	0	0	7	17	18	18	17
		E[4]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	6	6	6	6	6	5	5	0	0	0	5	6	6	6	6	5	5	0	0	0	5	6	6	6
		S[3][1]	0	0	0	0	0	0	0	0	6	6	6	6	6	0	0	0	0	2	6	6	6	6	6	0	0	0	0	2	6	6	6	6
		S[3][2]	0	0	0	0	0	0	0	0	6	6	6	6	3	0	0	0	0	5	6	6	6	6	2	0	0	0	0	5	6	6	6	5
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	10	10	10	5	0	2	1	1	1	1	10	10	10	5	0	2	1	1	1	0
PC 10	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	0	0	0	0	0	0	0	22	22	22	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	10	12	17	18	9	0	0	0	0	0	10	12	17	18	9	0	0	0	0
		E[5]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	0	0	0	0	0	0	0	5	6	6	0	0	0	0
		S[3][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	3	0	0	0	0	0	5	6	6	6	3	0	0	0	0
		S[3][2]	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	0	0	0	0	0	0	5	6	6	6	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	10	22	17	13	0	0	0	0	0	0	10	22	17	13	0	0	0	0	0

Table B.2 <Continued>

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 11	Demand		0	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	11	11	2	12	12	12	12	12	12	8	6	4	3	6	1	0	0	0	0	0	0	0	0	0	0	0
		S[4][0]	0	0	0	0	0	0	6	6	2	6	6	6	6	6	6	6	6	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][1]	0	0	0	0	0	0	5	5	0	6	6	6	6	6	6	2	0	0	3	6	1	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	11	11	2	3	4	5	6	7	8	5	6	5	3	4	0	0	0	0	0	0	0	0	0	0	0	0
PC 12	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	11	11	11	11	11	11	11	11	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	7	8	6	10	12	12	12	12	12	12	6	0	0	0	0
		S[4][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	6	6	6	6	6	6	6	6	6	0	0	0	0
		S[4][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	2	0	4	6	6	6	6	6	6	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	4	6	6	10	11	12	13	14	15	16	11	0	0	0	0
PC 13	Demand		0	0	0	0	0	0	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	Production	Total	0	0	0	0	0	0	24	10	14	30	30	19	18	18	18	15	28	29	29	18	18	18	18	18	0	24	24	24	24	0	0	0
		E[6]	0	0	0	0	0	0	18	10	14	18	18	18	18	18	18	15	18	18	18	18	18	18	18	18	0	18	18	18	18	0	0	0
		S[5][0]	0	0	0	0	0	0	6	0	0	6	6	0	0	0	0	0	5	6	6	0	0	0	0	0	0	5	6	6	6	0	0	0
		S[5][1]	0	0	0	0	0	0	0	0	0	6	6	1	0	0	0	0	5	5	5	0	0	0	0	0	0	1	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	24	10	0	6	12	13	13	13	13	10	38	43	48	42	36	36	36	36	18	24	48	48	48	24	0	0
PC 14	Demand		0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	9	12	6	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0	0
		S[5][0]	0	0	0	0	0	0	0	0	0	0	0	5	6	6	0	0	0	0	0	5	6	6	0	0	0	0	0	0	0	0	0	0
		S[5][1]	0	0	0	0	0	0	0	0	0	0	0	4	6	0	0	0	0	0	0	4	3	3	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	9	18	18	9	0	0	0	0	0	0	0	0	0
PC 15	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	6	0	0	0	0	0	0	10	12	0	0	0	0	0	0	0	0
		S[5][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0
		S[5][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	10	22	11	0	0	0	0	0	0	0
PC 16	Demand		0	0	0	0	0	0	0	0	0	0	0	0	28	28	28	28	32	32	32	32	40	40	40	40	43	43	43	43	51	51	51	51
	Production		0	0	0	0	0	0	0	0	0	8	16	15	23	25	25	32	32	32	37	44	39	38	44	44	68	41	44	55	12	35	35	32
	Stock		0	0	0	0	0	0	0	0	0	8	24	39	34	31	28	32	32	32	37	49	48	46	50	54	79	77	78	90	51	35	19	0

Table B.3: Master Production Schedule on Moulds and PC Stock Obtained from F_CP

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 0	Demand		0	0	20	20	0	20	20	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	E[0]	18	18	12	14	18	18	0	2	2	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	36	28	22	40	38	18	20	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 1	Demand		0	14	0	14	0	14	0	14	0	2	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	2	10	6	8	6	6	6	0	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[1]	6	2	6	6	6	6	6	6	0	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	6	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	0	10	2	10	2	8	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 2	Demand		0	0	20	0	20	0	20	0	20	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	2	11	7	11	9	11	9	12	8	0	8	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[2]	2	6	6	6	6	6	6	6	6	0	6	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	0	5	1	5	3	5	3	6	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		2	13	0	11	0	11	0	12	0	0	4	4	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 3	Demand		0	16	16	16	16	0	0	0	0	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	18	18	18	10	0	0	0	0	0	3	16	18	18	18	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	6	6	6	6	0	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	6	6	6	4	0	0	0	0	0	0	5	6	6	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	6	6	6	0	0	0	0	0	0	3	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	20	22	16	0	0	0	0	0	3	3	5	7	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 4	Demand		0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	6	17	18	10	18	3	13	0	0	0	0	9	17	18	18	18	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	0	0	0	0	5	6	6	6	3	6	0	0	0	0	0	5	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	0	0	0	1	6	6	4	6	0	6	0	0	0	0	4	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	0	0	0	5	6	6	0	6	0	1	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	6	23	24	17	18	4	0	0	0	0	0	9	9	10	11	12	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 5	Demand		0	0	20	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	11	9	6	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		11	20	6	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B.3 <Continued>

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 6	Demand		0	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	13	18	8	6	6	10	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	0	0	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	1	6	6	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	6	6	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	13	19	15	9	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 7	Demand		0	0	0	0	0	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	15	18	12	6	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	5	6	1	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	0	5	6	5	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	15	16	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 8	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	16	0	0	0	16	0
	Production	E[3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	6	0	4	6	6	0	4	6	6	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	0	0	4	10	0	0	4	10	0	0
PC 9	Demand		0	0	0	0	0	0	0	0	18	18	18	18	5	5	5	5	5	5	18	18	18	18	5	5	5	5	5	5	18	18	18	18
	Production	Total	0	0	0	0	0	0	0	0	18	18	18	18	6	6	6	6	6	9	17	18	18	15	0	6	6	6	6	7	16	17	15	18
		E[4]	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6	6	6	6	6	6	6	6	0	6	6	6	6	6	6	6	6	6
		S[3][0]	0	0	0	0	0	0	0	0	6	6	6	6	0	0	0	0	0	0	5	6	6	4	0	0	0	0	0	0	4	6	6	6
		S[3][1]	0	0	0	0	0	0	0	0	6	6	6	6	0	0	0	0	0	3	6	6	6	5	0	0	0	0	0	1	6	5	3	6
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	5	9	8	8	8	5	0	1	2	3	4	6	4	3	0	0
PC 10	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	0	0	0	0	0	0	0	22	22	22	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	10	12	12	12	12	8	0	0	0	1	11	10	11	11	12	10	0	0	0	0
		E[5]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	6	6	0	0	0	1	6	6	6	6	6	6	0	0	0	0
		S[3][1]	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	6	2	0	0	0	0	5	4	5	5	6	4	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	10	22	34	24	14	0	0	0	0	1	12	22	33	22	12	0	0	0	0	0

Table B.3 <Continued>

PC type	Demand, production & stock	Mould	Week 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 11	Demand		0	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	11	9	4	11	12	12	12	12	12	9	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][0]	0	0	0	0	0	0	6	6	4	6	6	6	6	6	6	6	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][1]	0	0	0	0	0	0	5	3	0	5	6	6	6	6	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	11	9	2	2	3	4	5	6	7	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0
PC 12	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	11	11	11	11	11	11	11	11	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	6	6	6	11	12	8	9	12	10	12	12	6	0	0	0
		S[4][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	6	6	6	6	6	0	0	0
		S[4][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	6	6	6	6	6	2	3	6	4	6	6	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	7	8	5	3	4	3	4	5	0	0	0	0
PC 13	Demand		0	0	0	0	0	0	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	Production	Total	0	0	0	0	0	0	24	19	18	18	18	18	18	18	18	18	23	18	18	18	18	18	18	18	18	18	20	24	16	17	19	0
		E[6]	0	0	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	16	17	18	0
		S[5][0]	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	2	6	0	0	1	0
	Stock		0	0	0	0	0	0	24	19	13	7	1	1	1	1	1	1	24	18	12	6	0	0	0	0	0	0	20	20	12	5	0	0
PC 14	Demand		0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	4	6	4	6	6	1	0	0	0	0	5	6	6	5	5	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	4	10	14	20	17	9	0	0	0	0	5	11	17	22	18	9	0	0	0	0	0	0	0	0	0
PC 15	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	0	0	0	0	0	4	6	6	6	0	0	0	0	0	0	5	6	6	5	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	4	10	5	0	0	0	0	0	0	0	5	11	6	0	0	0	0	0	0	0
PC 16	Demand		0	0	0	0	0	0	0	0	0	0	0	0	28	28	28	28	32	32	32	32	40	40	40	40	43	43	43	43	51	51	51	51
	Production		0	0	0	0	0	0	0	0	0	0	3	11	32	31	34	34	27	27	26	35	31	29	40	40	43	43	43	46	48	51	51	51
	Stock		0	0	0	0	0	0	0	0	0	0	3	14	18	21	27	33	28	23	17	20	11	0	0	0	0	0	0	3	0	0	0	0

Table B.4: Master Production Schedule on Moulds and PC Stock Obtained from BI_CP

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 0	Demand		0	0	20	20	0	20	20	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	E[0]	18	18	12	14	18	18	0	0	4	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	36	28	22	40	38	18	18	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 1	Demand		0	14	0	14	0	14	0	14	0	2	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	2	10	6	8	6	6	6	0	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[1]	6	2	6	6	6	6	6	6	0	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	6	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	0	10	2	10	2	8	0	0	0	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 2	Demand		0	0	20	0	20	0	20	0	20	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	2	11	7	11	9	11	9	9	11	0	8	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		E[2]	2	6	6	6	6	6	6	6	6	0	6	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[0][0]	0	5	1	5	3	5	3	3	5	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		2	13	0	11	0	11	0	9	0	0	4	4	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 3	Demand		0	16	16	16	16	0	0	0	0	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	18	18	18	10	0	0	0	0	0	1	15	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	6	6	6	6	0	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	6	6	6	4	0	0	0	0	0	0	5	6	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	6	6	6	0	0	0	0	0	0	1	5	4	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		18	20	22	16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 4	Demand		0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	6	17	18	11	2	17	14	0	0	0	0	1	16	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][0]	0	0	0	0	5	6	6	2	6	6	0	0	0	0	0	5	6	6	5	5	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][1]	0	0	0	1	6	6	5	0	6	6	0	0	0	0	1	6	5	5	6	6	0	0	0	0	0	0	0	0	0	0	0	0
		S[1][2]	0	0	0	5	6	6	0	0	5	2	0	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	6	23	24	18	3	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 5	Demand		0	0	20	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	11	9	6	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		11	20	6	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B.4 <Continued>

PC type	Demand, production & stock	Mould	Week																															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 6	Demand		0	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	12	13	18	8	6	6	10	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	0	0	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	1	6	6	6	6	6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	6	6	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		12	13	19	15	9	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 7	Demand		0	0	0	0	0	17	17	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	15	18	8	10	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][0]	0	0	0	0	5	6	1	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][2]	0	0	0	0	5	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[2][3]	0	0	0	0	5	6	1	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	15	16	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 8	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	16	0	0	0	16	0
	Production	E[3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	4	6	0	5	6	6	6	0	3	6	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	10	0	0	5	11	1	7	7	10	0	0
PC 9	Demand		0	0	0	0	0	0	0	0	18	18	18	18	5	5	5	5	5	5	18	18	18	18	5	5	5	5	5	5	18	18	18	18
	Production	Total	0	0	0	0	0	0	0	0	18	18	18	18	6	6	6	6	6	6	14	18	18	16	8	6	6	6	6	6	11	17	18	18
		E[4]	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6	6	6	6	6	6	6	6	2	6	6	6	6	6	6	6	6	6
		S[3][0]	0	0	0	0	0	0	0	0	6	6	6	6	0	0	0	0	0	0	5	6	6	4	0	0	0	0	0	0	0	5	6	6
		S[3][1]	0	0	0	0	0	0	0	0	6	6	6	6	0	0	0	0	0	0	3	6	6	6	6	0	0	0	0	0	5	6	6	6
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	5	6	2	2	2	0	3	4	5	6	7	8	1	0	0	0
PC 10	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	0	0	0	0	0	0	0	22	22	22	0	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	6	12	12	12	12	12	0	0	0	1	6	11	12	12	12	12	0	0	0	0
		E[5]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[3][0]	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	6	6	6	0	0	0	1	6	6	6	6	6	6	0	0	0	0
		S[3][1]	0	0	0	0	0	0	0	0	0	0	0	0	1	6	6	6	6	6	0	0	0	0	0	5	6	6	6	6	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	6	18	30	20	10	0	0	0	0	1	7	18	30	20	10	0	0	0	0	0

Table B.4 <Continued>

PC type	Demand, production & stock	Mould	Week 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
PC 11	Demand		0	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0
	Production	Total	0	0	0	0	0	0	4	9	9	12	12	12	12	12	12	10	6	4	0	5	5	0	0	0	0	0	0	0	0	0	0	0
		S[4][0]	0	0	0	0	0	0	4	6	6	6	6	6	6	6	6	6	6	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S[4][1]	0	0	0	0	0	0	0	3	3	6	6	6	6	6	6	4	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	4	2	0	1	2	3	4	5	6	5	6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC 12	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	11	11	11	11	11	11	11	11	0	0	0
	Production	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	6	7	6	6	10	11	11	11	11	11	11	11	0	0	0
		S[4][0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	6	6	6	5	6	6	6	6	6	6	0	0	0
		S[4][1]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	5	6	0	0	4	6	5	5	5	5	5	5	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
PC 13	Demand		0	0	0	0	0	0	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	18	18	18	18	18	0	24	24	24	24	0
	Production	Total	0	0	0	0	0	0	24	19	18	18	18	18	18	18	18	18	20	21	18	18	18	18	18	18	18	18	1	23	24	24	24	0
		E[6]	0	0	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	0	18	18	18	18	0
		S[5][0]	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	1	5	6	6	6	0
	Stock		0	0	0	0	0	0	24	19	13	7	1	1	1	1	1	1	21	18	12	6	0	0	0	0	0	0	1	0	0	0	0	0
PC 14	Demand		0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	2	6	6	6	6	1	0	0	0	0	2	6	6	6	6	1	0	0	0	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	2	8	14	20	17	9	0	0	0	0	2	8	14	20	17	9	0	0	0	0	0	0	0	0	0
PC 15	Demand		0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0	0	0	11	11	0	0	0	0	0	0
	Production	S[5][0]	0	0	0	0	0	0	0	0	0	0	0	0	4	6	6	6	0	0	0	0	0	0	4	6	6	6	0	0	0	0	0	0
	Stock		0	0	0	0	0	0	0	0	0	0	0	0	4	10	5	0	0	0	0	0	0	0	4	10	5	0	0	0	0	0	0	0
PC 16	Demand		0	0	0	0	0	0	0	0	0	0	0	0	28	28	28	28	32	32	32	32	40	40	40	40	43	43	43	43	51	51	51	51
	Production		0	0	0	0	0	0	0	0	0	0	5	15	29	21	22	23	36	33	39	24	43	39	42	43	37	36	60	37	49	48	44	51
	Stock		0	0	0	0	0	0	0	0	0	0	5	20	21	14	8	3	7	8	15	7	10	9	11	14	8	1	18	12	10	7	0	0

Table B.5: NT Working Hours Available and Man-Hours Consumed over Weeks in Various Plans

Week	F_ACT		F_TRD		F_CP		BI_CP	
	NT available	Consumed	NT available	Consumed	NT available	Consumed	NT available	Consumed
0	1152	1244	1152	1222	1152	1184	1152	1184
1	1152	1257	1152	1223	1152	1175	1152	1175
2	1152	1253	1152	1211	1152	1183	1152	1183
3	1152	1229	1152	1215	1152	1183	1152	1183
4	1152	1205	1248	1247	1200	1215	1248	1215
5	1152	1253	1248	1267	1200	1267	1248	1267
6	1152	1255	1248	1281	1200	1489	1248	1287
7	1152	1255	1248	1280	1200	1499	1248	1284
8	1632	1829	1536	1726	1440	1524	1584	1855
9	1632	1836	1536	1716	1440	1530	1584	1574
10	1632	1828	1536	1722	1440	1516	1584	1540
11	1632	1830	1536	1720	1440	1518	1584	1581
12	1632	1667	1728	1836	1872	1928	1728	1724
13	1632	1680	1728	1831	1872	1923	1728	1719
14	1632	1672	1728	1827	1872	1924	1728	1727
15	1632	1669	1728	1833	1872	1922	1728	1720
16	1824	1865	1872	1984	1728	1775	1872	1868
17	1824	1871	1872	1985	1728	1781	1872	1871
18	1824	1878	1872	1979	1728	1770	1872	1872
19	1824	1866	1872	1977	1728	1776	1872	1866
20	1824	1869	1872	1989	1728	1725	1872	1860
21	1824	1877	1872	1977	1728	1715	1872	1870
22	1824	1865	1872	1976	1728	1727	1872	1865
23	1824	1878	1872	1986	1728	1722	1872	1860
24	1824	1816	1872	1980	1680	1942	1872	1862
25	1824	1811	1872	1986	1680	1931	1872	1866
26	1824	1817	1872	1984	1680	1940	1872	1867
27	1824	1824	1872	1986	1680	1932	1872	1865
28	1824	1822	1200	1192	1680	1772	1824	1824
29	1824	1823	1200	1194	1680	1781	1824	1818
30	1824	1808	1200	1194	1680	1771	1824	1812
31	1824	966	1200	984	1680	1350	1824	1350

Appendix C: Results from Test II for Detailed Scheduling

Some results obtained from Test II for detailed scheduling in Chapter 7 are given in Appendix C, including

Table C.1: Detailed Production Schedule Obtained from F_EDD for *Labour Grouping*

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	0	0	0	0	0	0	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][3]	1	0	0	1	14	50	4	-	-	-	-	-	-	1	0	0	1	4	10	1	4	10	1	4	50	1	4	50	1	14	50
[0][0][4]	1	3	20	1	18	10	4	-	-	-	-	-	-	1	3	20	1	7	30	1	7	30	1	8	10	1	8	10	1	18	10
[0][0][5]	1	4	50	1	19	40	4	1	4	50	1	4	50	1	4	50	1	9	0	1	9	0	1	9	40	1	9	40	1	19	40
[0][0][6]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][8]	2	1	50	2	16	40	5	2	1	50	2	1	50	2	1	50	2	6	0	2	6	0	2	6	40	2	6	40	2	16	40
[0][0][9]	3	0	0	3	14	50	5	-	-	-	-	-	-	3	0	0	3	4	10	3	4	10	3	4	50	3	4	50	3	14	50
[0][0][10]	3	1	10	3	16	0	5	-	-	-	-	-	-	3	1	10	3	5	20	3	5	20	3	6	0	3	6	0	3	16	0
[0][0][11]	3	4	50	3	19	40	5	3	4	50	3	4	50	3	4	50	3	9	0	3	9	0	3	9	40	3	9	40	3	19	40
[0][0][12]	4	4	10	4	19	0	11	-	-	-	-	-	-	4	4	10	4	8	20	4	8	20	4	9	0	4	9	0	4	19	0
[0][0][13]	4	4	40	4	19	30	11	-	-	-	-	-	-	4	4	40	4	8	50	4	8	50	4	9	30	4	9	30	4	19	30
[0][0][14]	5	4	0	5	18	50	11	-	-	-	-	-	-	5	4	0	5	8	10	5	8	10	5	8	50	5	8	50	5	18	50
[0][0][15]	5	4	10	5	19	0	11	-	-	-	-	-	-	5	4	10	5	8	20	5	8	20	5	9	0	5	9	0	5	19	0
[0][0][16]	7	3	20	7	18	10	11	-	-	-	-	-	-	7	3	20	7	7	30	7	7	30	7	8	10	7	8	10	7	18	10
[0][0][17]	7	5	50	8	11	40	11	-	-	-	-	-	-	7	5	50	8	1	0	8	1	0	8	1	40	8	1	40	8	11	40
[0][0][18]	8	4	10	8	19	0	12	-	-	-	-	-	-	8	4	10	8	8	20	8	8	20	8	9	0	8	9	0	8	19	0
[0][0][19]	9	0	0	9	14	50	12	-	-	-	-	-	-	9	0	0	9	4	10	9	4	10	9	4	50	9	4	50	9	14	50
[0][0][20]	9	1	0	9	15	50	12	-	-	-	-	-	-	9	1	0	9	5	10	9	5	10	9	5	50	9	5	50	9	15	50
[0][0][21]	10	4	0	10	18	50	12	-	-	-	-	-	-	10	4	0	10	8	10	10	8	10	10	8	50	10	8	50	10	18	50
[0][0][22]	10	4	0	10	18	50	12	-	-	-	-	-	-	10	4	0	10	8	10	10	8	10	10	8	50	10	8	50	10	18	50
[0][0][23]	11	0	0	11	14	50	12	-	-	-	-	-	-	11	0	0	11	4	10	11	4	10	11	4	50	11	4	50	11	14	50
[0][0][24]	11	4	0	11	18	50	18	-	-	-	-	-	-	11	4	0	11	8	10	11	8	10	11	8	50	11	8	50	11	18	50
[0][0][25]	12	8	0	14	13	50	18	-	-	-	-	-	-	12	8	0	14	3	10	14	3	10	14	3	50	14	3	50	14	13	50
[0][0][26]	12	8	0	14	13	50	18	-	-	-	-	-	-	12	8	0	14	3	10	14	3	10	14	3	50	14	3	50	14	13	50
[0][0][27]	14	3	50	14	22	40	18	14	3	50	14	7	50	14	7	50	14	12	0	14	12	0	14	12	40	14	12	40	14	22	40
[0][0][28]	15	0	0	15	14	50	18	-	-	-	-	-	-	15	0	0	15	4	10	15	4	10	15	4	50	15	4	50	15	14	50
[0][0][29]	15	4	10	15	19	0	18	15	4	10	15	4	10	15	4	10	15	8	20	15	8	20	15	9	0	15	9	0	15	19	0
[0][0][30]	15	4	10	15	19	0	19	-	-	-	-	-	-	15	4	10	15	8	20	15	8	20	15	9	0	15	9	0	15	19	0
[0][0][31]	16	0	0	16	14	50	19	-	-	-	-	-	-	16	0	0	16	4	10	16	4	10	16	4	50	16	4	50	16	14	50
[0][0][32]	16	0	0	16	14	50	19	-	-	-	-	-	-	16	0	0	16	4	10	16	4	10	16	4	50	16	4	50	16	14	50
[0][0][33]	16	4	10	16	19	0	19	16	4	10	16	4	10	16	4	10	16	8	20	16	8	20	16	9	0	16	9	0	16	19	0
[0][0][34]	17	0	0	17	14	50	19	-	-	-	-	-	-	17	0	0	17	4	10	17	4	10	17	4	50	17	4	50	17	14	50
[0][0][35]	17	0	0	17	14	50	19	-	-	-	-	-	-	17	0	0	17	4	10	17	4	10	17	4	50	17	4	50	17	14	50
[0][0][36]	18	0	0	18	14	50	25	-	-	-	-	-	-	18	0	0	18	4	10	18	4	10	18	4	50	18	4	50	18	14	50
[0][0][37]	18	4	10	18	19	0	25	-	-	-	-	-	-	18	4	10	18	8	20	18	8	20	18	9	0	18	9	0	18	19	0
[0][0][38]	19	0	0	19	14	50	25	-	-	-	-	-	-	19	0	0	19	4	10	19	4	10	19	4	50	19	4	50	19	14	50
[0][0][39]	19	4	10	19	19	0	25	-	-	-	-	-	-	19	4	10	19	8	20	19	8	20	19	9	0	19	9	0	19	19	0
[0][0][40]	19	4	10	19	23	0	25	19	4	10	19	8	10	19	8	10	19	12	20	19	12	20	19	13	0	19	13	0	19	23	0
[0][0][41]	21	0	0	21	14	50	25	21	0	0	21	0	0	21	0	0	21	4	10	21	4	10	21	4	50	21	4	50	21	14	50
[0][0][42]	21	4	10	21	19	0	26	-	-	-	-	-	-	21	4	10	21	8	20	21	8	20	21	9	0	21	9	0	21	19	0
[0][0][43]	21	4	10	21	19	0	26	-	-	-	-	-	-	21	4	10	21	8	20	21	8	20	21	9	0	21	9	0	21	19	0
[0][0][44]	22	0	0	22	14	50	26	-	-	-	-	-	-	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][45]	22	4	10	22	19	0	26	22	4	10	22	4	10	22	4	10	22	8	20	22	8	20	22	9	0	22	9	0	22	19	0
[0][0][46]	22	4	10	22	19	0	26	-	-	-	-	-	-	22	4	10	22	8	20	22	8	20	22	9	0	22	9	0	22	19	0
[0][0][47]	23	0	0	23	14	50	26	23	0	0	23	0	0	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][48]	23	0	0	23	14	50	32	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][49]	23	0	0	23	14	50	32	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][50]	24	0	0	24	14	50	32	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][0][51]	24	0	0	24	14	50	32	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][1][0]	7	7	30	8	17	20	11	7	7	30	8	2	30	8	2	30	8	6	40	8	6	40	8	7	20	8	7	20	8	17	20
[0][1][1]	11	4	50	12	14	40	18	11	4	50	11	8	50	11	8	50	12	4	0	12	4	0	12	4	40	12	4	40	12	14	40
[0][1][2]	18	4	10	18	23	0	25	18	4	10	18	8	10	18	8	10	18	12	20	18	12	20	18	13	0	18	13	0	18	23	0
[0][1][3]	26	0	0	26	18	50	32	26	0	0	26	4	0	26	4	0	26	8	10	26	8	10	26	8	50	26	8	50	26	18	50
[0][2][0]	4	0	0	5	13	10	6	4	0	0	4	8	0	4	8	0	5	2	30	5	2	30	5	3	10	5	3	10	5	13	10
[0][2][1]	9	4	10	10	14	0	12	9	4	10	9	8	10	9	8	10	10	3	20	10	3	20	10	4	0	10	4	0	10	14	0
[0][2][2]	17	0	0	17	22	50	19	17	0	0	17	8	0	17	8	0	17	12	10	17	12	10	17	12	50	17	12	50	17	22	50
[0][2][3]	24	0	0	24	22	50	26	24	0	0	24	8	0	24	8	0	24	12	10	24	12	10	24	12	50	24	12	50	24	22	50
[0][2][4]	25	0	0	25	14	50	32	25	0	0	25	0	0	25	0	0	25	4	10	25	4	10	25	4	50	25	4	50	25	14	50
[0][3][0]	0	8	50	1	12	20	9	-	-	-	-	-	-	0	8	50	1	2	50	1	2	50	1	3	20	1	3	20	1	12	20
[0][3][1]	2	6	40	3	10	10	9	-	-	-	-	-	-	2	6	40	3	0	40	3	0	40	3	1	10	3	1	10	3	10	10
[0][3][2]	2	8	50	3	16	20	9	2	8	50	3	3	10	3	3	10	3	6	50	3	6	50	3	7	20	3	7	20	3	16	20
[0][3][3]	4	0	0	4	13	10	9	-	-	-	-	-	-	4	0	0	4	3	40	4	3	40	4	4	10	4	4	10	4	13	10
[0][3][4]	4	0	30	4	13	40	10	4	0	30	4	0	30	4	0	30	4	4	10	4	4	10	4	4	40	4	4	40	4	13	40
[0][3][5]	5	0	0	5	13	10	10	-	-	-	-	-	-	5	0	0	5	3	40	5	3	40	5	4	10	5	4	10	5	13	10
[0][3][6]	7	1	40	7	14	50	10	-	-	-	-	-	-	7	1	40	7	5	20	7	5	20	7	5	50	7	5	50	7	14	50
[0][3][7]	8	0	0	8	13	10	10	-	-	-	-	-	-	8	0	0	8	3	40	8	3	40	8	4	10	8	4	10	8	13	10
[0][3][8]	9	4	50	9	18	0	16	-	-	-	-	-	-	9	4	50	9	8	30	9	8	30	9	9	0	9	9	0	9	18	0
[0][3][9]	10	8	50	11	13	0	16	-	-	-	-	-	-	10	8	50	11	3	30	11	3	30	11	4	0	11	4	0	11	13	0
[0][3][10]	12	3	50	12	17	0	16	-	-	-	-	-	-	12	3	50	12	7	30	12	7	30	12	8	0	12	8	0	12	17	0
[0][3][11]	14	0	0	14	13	10	16	-	-	-	-	-	-	14	0	0	14	3	40	14	3	40	14	4	10	14	4	10	14	13	10
[0][3][12]	14	0	0	14	17	10	17	14	0	0	14	4	0	14	4	0	14	7	40	14	7	40	14	8	10	14	8	10	14	17	10
[0][3][13]	15	0	0	15	13	10	17	-	-	-	-	-	-	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][3][14]	15	0	0	15	13	10	17	15	0	0	15	0	0	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][3][15]	16	0	0	16	13	10	17	-	-	-	-	-	-	16	0	0	16	3	40	16	3	40	16	4	10	16	4	10	16	13	10
[0][3][16]	17	4	50	17	18	0	23	-	-	-	-	-	-	17	4	50	17	8	30	17	8	30	17	9	0	17	9	0	17	18	0
[0][3][17]	18	0	0	18	13	10	23	-	-	-	-	-	-	18	0	0	18	3	40	18	3	40	18	4	10	18	4	10	18	13	10
[0][3][18]	18	0	0	18	17	10	23	18	0	0	18	4	0	18	4	0	18	7	40	18	7	40	18	8	10	18	8	10	18	17	10
[0][3][19]	19	0	0	19	13	10	23	-	-	-	-	-	-	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][3][20]	19	0	0	19	13	10	24	19	0	0	19	0	0	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][3][21]	21	0	0	21	13	10	24	-	-	-	-	-	-	21	0	0	21	3	40	21	3	40	21	4	10	21	4	10	21	13	10
[0][3][22]	22	0	0	22	13	10	24	-	-	-	-	-	-	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][3][23]	23	0	0	23	13	10	24	-	-	-	-	-	-	23	0	0	23	3	40	23	3	40	23	4	10	23	4	10	23	13	10

Table C.1 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	4	50	0	18	0	8	-	-	-	-	-	-	0	4	50	0	8	30	0	8	30	0	9	0	0	9	0	0	18	0
[0][4][1]	0	8	50	1	16	20	8	0	8	50	1	3	10	1	3	10	1	6	50	1	6	50	1	7	20	1	7	20	1	16	20
[0][4][2]	1	7	20	2	10	50	8	-	-	-	-	-	-	1	7	20	2	1	20	2	1	20	2	1	50	2	1	50	2	10	50
[0][4][3]	3	6	0	4	9	30	8	-	-	-	-	-	-	3	6	0	3	9	40	4	0	0	4	0	30	4	0	30	4	9	30
[0][4][4]	4	9	30	5	13	0	11	-	-	-	-	-	-	4	9	30	5	3	30	5	3	30	5	4	0	5	4	0	5	13	0
[0][4][5]	5	3	10	7	10	40	11	5	3	10	5	7	10	5	7	10	7	1	10	7	1	10	7	1	40	7	1	40	7	10	40
[0][4][6]	7	3	20	7	16	30	11	-	-	-	-	-	-	7	3	20	7	7	0	7	7	0	7	7	30	7	7	30	7	16	30
[0][4][7]	8	1	40	8	14	50	11	-	-	-	-	-	-	8	1	40	8	5	20	8	5	20	8	5	50	8	5	50	8	14	50
[0][4][8]	8	5	50	9	10	0	11	8	5	50	8	5	50	8	5	50	9	0	30	9	0	30	9	1	0	9	1	0	9	10	0
[0][4][9]	9	0	0	9	13	10	15	-	-	-	-	-	-	9	0	0	9	3	40	9	3	40	9	4	10	9	4	10	9	13	10
[0][4][10]	10	4	0	10	17	10	15	-	-	-	-	-	-	10	4	0	10	7	40	10	7	40	10	8	10	10	8	10	10	17	10
[0][4][11]	10	8	10	11	12	20	15	10	8	10	10	8	10	10	8	10	11	2	50	11	2	50	11	3	20	11	3	20	11	12	20
[0][4][12]	11	3	20	11	16	30	15	-	-	-	-	-	-	11	3	20	11	7	0	11	7	0	11	7	30	11	7	30	11	16	30
[0][4][13]	12	3	50	12	17	0	18	-	-	-	-	-	-	12	3	50	12	7	30	12	7	30	12	8	0	12	8	0	12	17	0
[0][4][14]	12	4	40	12	17	50	18	12	4	40	12	4	40	12	4	40	12	8	20	12	8	20	12	8	50	12	8	50	12	17	50
[0][4][15]	14	3	50	14	17	0	18	-	-	-	-	-	-	14	3	50	14	7	30	14	7	30	14	8	0	14	8	0	14	17	0
[0][4][16]	15	0	0	15	13	10	18	-	-	-	-	-	-	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][4][17]	16	0	0	16	17	10	18	16	0	0	16	4	0	16	4	0	16	7	40	16	7	40	16	8	10	16	8	10	16	17	10
[0][4][18]	16	4	50	16	18	0	22	-	-	-	-	-	-	16	4	50	16	8	30	16	8	30	16	9	0	16	9	0	16	18	0
[0][4][19]	17	0	0	17	13	10	22	-	-	-	-	-	-	17	0	0	17	3	40	17	3	40	17	4	10	17	4	10	17	13	10
[0][4][20]	17	4	10	17	17	20	22	17	4	10	17	4	10	17	4	10	17	7	50	17	7	50	17	8	20	17	8	20	17	17	20
[0][4][21]	18	0	0	18	13	10	22	-	-	-	-	-	-	18	0	0	18	3	40	18	3	40	18	4	10	18	4	10	18	13	10
[0][4][22]	19	0	0	19	13	10	25	-	-	-	-	-	-	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][4][23]	21	0	0	21	13	10	25	-	-	-	-	-	-	21	0	0	21	3	40	21	3	40	21	4	10	21	4	10	21	13	10
[0][4][24]	21	0	0	21	17	10	25	21	0	0	21	4	0	21	4	0	21	7	40	21	7	40	21	8	10	21	8	10	21	17	10
[0][4][25]	22	0	0	22	13	10	25	-	-	-	-	-	-	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][4][26]	22	0	0	22	13	10	25	22	0	0	22	0	0	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][5][0]	0	4	50	0	19	50	5	-	-	-	-	-	-	0	4	50	0	8	10	0	8	10	0	8	50	0	8	50	0	19	50
[0][5][1]	2	4	50	2	19	50	5	-	-	-	-	-	-	2	4	50	2	8	10	2	8	10	2	8	50	2	8	50	2	19	50
[0][5][2]	5	9	0	7	14	20	11	-	-	-	-	-	-	5	9	0	7	2	40	7	2	40	7	3	20	7	3	20	7	14	20
[0][5][3]	10	0	0	10	15	0	11	-	-	-	-	-	-	10	0	0	10	3	20	10	3	20	10	4	0	10	4	0	10	15	0
[0][5][4]	11	8	50	12	14	50	18	-	-	-	-	-	-	11	8	50	12	3	10	12	3	10	12	3	50	12	3	50	12	14	50
[0][5][5]	14	4	10	14	19	10	18	-	-	-	-	-	-	14	4	10	14	7	30	14	7	30	14	8	10	14	8	10	14	19	10
[0][5][6]	15	4	10	15	19	10	25	-	-	-	-	-	-	15	4	10	15	7	30	15	7	30	15	8	10	15	8	10	15	19	10
[0][5][7]	16	4	50	16	19	50	25	-	-	-	-	-	-	16	4	50	16	8	10	16	8	10	16	8	50	16	8	50	16	19	50
[0][5][8]	17	4	50	17	19	50	32	-	-	-	-	-	-	17	4	50	17	8	10	17	8	10	17	8	50	17	8	50	17	19	50
[0][5][9]	18	4	50	18	19	50	32	-	-	-	-	-	-	18	4	50	18	8	10	18	8	10	18	8	50	18	8	50	18	19	50
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][2]	1	1	0	1	19	50	4	1	1	0	1	1	0	1	1	0	1	7	0	1	7	0	1	7	50	1	7	50	1	19	50
[1][0][3]	1	1	0	1	19	50	4	1	1	0	1	1	0	1	1	0	1	7	0	1	7	0	1	7	50	1	7	50	1	19	50
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	2	0	0	2	6	0	2	6	0	2	6	50	2	6	50	2	18	50
[1][0][5]	2	6	50	3	12	50	11	2	6	50	2	6	50	2	6	50	2	12	50	3	0	0	3	0	50	3	0	50	3	12	50
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	3	0	0	3	6	0	3	6	0	3	6	50	3	6	50	3	18	50
[1][0][7]	3	12	50	4	18	20	11	3	12	50	3	12	50	3	12	50	4	5	30	4	5	30	4	6	20	4	6	20	4	18	20
[1][0][8]	4	0	0	4	18	50	11	4	0	0	4	0	0	4	0	0	4	6	0	4	6	0	4	6	50	4	6	50	4	18	50
[1][0][9]	5	0	0	5	18	50	11	5	0	0	5	0	0	5	0	0	5	6	0	5	6	0	5	6	50	5	6	50	5	18	50
[1][0][10]	17	0	0	18	14	50	25	17	0	0	17	4	0	17	4	0	18	2	0	18	2	0	18	2	50	18	2	50	18	14	50
[1][0][11]	18	0	0	19	12	50	25	18	0	0	18	2	0	18	2	0	18	8	0	19	0	0	19	0	50	19	0	50	19	12	50
[1][0][12]	19	0	0	19	18	50	25	19	0	0	19	0	0	19	0	0	19	6	0	19	6	0	19	6	50	19	6	50	19	18	50
[1][0][13]	21	0	0	21	18	50	25	21	0	0	21	0	0	21	0	0	21	6	0	21	6	0	21	6	50	21	6	50	21	18	50
[1][0][14]	21	0	0	21	18	50	25	21	0	0	21	0	0	21	0	0	21	6	0	21	6	0	21	6	50	21	6	50	21	18	50
[1][0][15]	22	0	0	22	18	50	32	22	0	0	22	0	0	22	0	0	22	6	0	22	6	0	22	6	50	22	6	50	22	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	23	0	0	23	6	0	23	6	0	23	6	50	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	26	0	0	26	6	0	26	6	0	26	6	50	26	6	50	26	18	50
[1][1][0]	5	0	0	5	22	50	11	5	0	0	5	4	0	5	4	0	5	10	0	5	10	0	5	10	50	5	10	50	5	22	50
[1][1][1]	7	0	0	7	18	50	11	7	0	0	7	0	0	7	0	0	7	6	0	7	6	0	7	6	50	7	6	50	7	18	50
[1][1][2]	8	0	0	8	18	50	11	8	0	0	8	0	0	8	0	0	8	6	0	8	6	0	8	6	50	8	6	50	8	18	50
[1][1][3]	9	0	0	9	18	50	11	9	0	0	9	0	0	9	0	0	9	6	0	9	6	0	9	6	50	9	6	50	9	18	50
[1][1][4]	10	0	0	10	18	50	11	10	0	0	10	0	0	10	0	0	10	6	0	10	6	0	10	6	50	10	6	50	10	18	50
[1][1][5]	11	0	0	11	18	50	18	11	0	0	11	0	0	11	0	0	11	6	0	11	6	0	11	6	50	11	6	50	11	18	50
[1][1][6]	12	0	0	12	18	50	18	12	0	0	12	0	0	12	0	0	12	6	0	12	6	0	12	6	50	12	6	50	12	18	50
[1][1][7]	14	0	0	14	18	50	18	14	0	0	14	0	0	14	0	0	14	6	0	14	6	0	14	6	50	14	6	50	14	18	50
[1][1][8]	15	0	0	15	18	50	18	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][1][9]	16	0	0	16	18	50	18	16	0	0	16	0	0	16	0	0	16	6	0	16	6	0	16	6	50	16	6	50	16	18	50
[1][1][10]	22	0	0	23	14	0	32	22	0	0	22	4	0	22	4	0	23	1	10	23	1	10	23	2	0	23	2	0	23	14	0
[1][1][11]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][1][12]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][2][0]	7	0	0	7	20	50	18	7	0	0	7	2	0	7	2	0	7	8	0	7	8	0	7	8	50	7	8	50	7	20	50
[1][2][1]	8	0	0	8	18	50	18	8	0	0	8	0	0	8	0	0	8	6	0	8	6	0	8	6	50	8	6	50	8	18	50
[1][2][2]	9	0	0	9	18	50	18	9	0	0	9	0	0	9	0	0	9	6	0	9	6	0	9	6	50	9	6	50	9	18	50
[1][2][3]	10	0	0	10	18	50	18	10	0	0	10	0	0	10	0	0	10	6	0	10	6	0	10	6	50	10	6	50	10	18	50
[1][2][4]	11	0	0	11	18	50	18	11	0	0	11	0	0	11	0	0	11	6	0	11	6	0	11	6	50	11	6	50	11	18	50
[1][2][5]	12	0	0	12	18	50	25	12	0	0	12	0	0	12	0	0	12	6	0	12	6	0	12	6	50	12	6	50	12	18	50
[1][2][6]	14	0	0	14	18	50	25	14	0	0	14	0	0	14	0	0	14	6	0	14	6	0	14	6	50	14	6	50	14	18	50
[1][2][7]	15	0	0	15	18	50	25	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][2][8]	16	0	0	16	18	50	25	16	0	0	16	0	0	16	0	0	16	6	0	16	6	0	16	6	50	16	6	50	16	18	50
[1][2][9]	17	0	0	17	18	50	25	17	0	0	17	0	0	17	0	0	17	6	0	17	6	0	17	6	50	17	6	50	17	18	50
[1][2][10]	26	0	0	26	20	50	39	26	0	0	26	2	0	26	2	0	26	8	0	26	8	0	26	8	50	26	8	50	26	20	50
[1][3][0]	0	6	40	1	13	0	25	-	-	-	-	-	-	0	6	40	0	13	10	1	0	0	1	1	0	1	1	0	1	13	0
[1][3][1]	0	6	50	1	13	0	25	-	-	-	-	-	-	0	6	50	0	13	20	1	0	0	1	1	0	1	1	0	1	13	0
[1][3][2]	1	13	0	2	19	10	25	-	-	-	-	-	-	1	13	0	2	6	10	2	6	10	2	7	10	2	7	10	2	19	10
[1][3][3]	1	13	0	2	19	10	25	-	-	-	-	-	-	1	13	0	2	6	10	2	6	10	2	7	10	2	7	10	2	19	10

Table C.1 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[1][3][4]	3	0	0	3	19	30	25	-	-	-	-	-	-	3	0	0	3	6	30	3	6	30	3	7	30	3	7	30	3	19	30
[1][3][5]	3	6	50	4	13	0	25	-	-	-	-	-	-	3	6	50	3	13	20	4	0	0	4	1	0	4	1	0	4	13	0
[1][3][6]	4	6	40	5	13	0	25	-	-	-	-	-	-	4	6	40	4	13	10	5	0	0	5	1	0	5	1	0	5	13	0
[1][3][7]	4	13	0	5	19	10	25	-	-	-	-	-	-	4	13	0	5	6	10	5	6	10	5	7	10	5	7	10	5	19	10
[1][3][8]	5	13	0	7	19	10	25	-	-	-	-	-	-	5	13	0	7	6	10	7	6	10	7	7	10	7	7	10	7	19	10
[1][3][9]	7	6	50	8	13	30	25	-	-	-	-	-	-	7	6	50	8	0	30	8	0	30	8	1	30	8	1	30	8	13	30
[1][3][10]	8	6	10	9	13	0	25	-	-	-	-	-	-	8	6	10	8	12	40	9	0	0	9	1	0	9	1	0	9	13	0
[1][3][11]	9	1	0	9	20	30	25	-	-	-	-	-	-	9	1	0	9	7	30	9	7	30	9	8	30	9	8	30	9	20	30
[1][3][12]	10	0	0	10	19	30	25	-	-	-	-	-	-	10	0	0	10	6	30	10	6	30	10	7	30	10	7	30	10	19	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	10	0	0	10	6	30	10	6	30	10	7	30	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	11	0	0	11	6	30	11	6	30	11	7	30	11	7	30	11	19	30
[1][3][15]	11	0	50	11	20	20	25	-	-	-	-	-	-	11	0	50	11	7	20	11	7	20	11	8	20	11	8	20	11	20	20
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	12	0	0	12	6	30	12	6	30	12	7	30	12	7	30	12	19	30
[1][3][17]	12	0	0	12	19	30	25	-	-	-	-	-	-	12	0	0	12	6	30	12	6	30	12	7	30	12	7	30	12	19	30
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	15	0	0	15	6	30	15	6	30	15	7	30	15	7	30	15	19	30
[1][3][21]	15	0	0	15	19	30	26	-	-	-	-	-	-	15	0	0	15	6	30	15	6	30	15	7	30	15	7	30	15	19	30
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	16	0	0	16	6	30	16	6	30	16	7	30	16	7	30	16	19	30
[1][3][23]	16	0	0	16	19	30	26	-	-	-	-	-	-	16	0	0	16	6	30	16	6	30	16	7	30	16	7	30	16	19	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	17	0	0	17	6	30	17	6	30	17	7	30	17	7	30	17	19	30
[1][3][25]	17	0	0	17	19	30	26	-	-	-	-	-	-	17	0	0	17	6	30	17	6	30	17	7	30	17	7	30	17	19	30
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][4][0]	0	6	40	1	0	40	6	-	-	-	-	-	-	0	6	40	0	12	20	0	12	20	0	13	20	0	13	20	1	0	40
[1][4][1]	1	6	40	2	0	40	6	-	-	-	-	-	-	1	6	40	1	12	20	1	12	20	1	13	20	1	13	20	2	0	40
[1][4][2]	2	6	40	3	0	40	6	-	-	-	-	-	-	2	6	40	2	12	20	2	12	20	2	13	20	2	13	20	3	0	40
[1][4][3]	3	0	50	3	18	50	6	-	-	-	-	-	-	3	0	50	3	6	30	3	6	30	3	7	30	3	7	30	3	18	50
[1][5][0]	0	6	40	0	23	50	20	-	-	-	-	-	-	0	6	40	0	12	0	0	12	0	0	12	50	0	12	50	0	23	50
[1][5][1]	1	6	40	1	23	50	20	-	-	-	-	-	-	1	6	40	1	12	0	1	12	0	1	12	50	1	12	50	1	23	50
[1][5][2]	2	7	10	3	0	20	20	-	-	-	-	-	-	2	7	10	2	12	30	2	12	30	2	13	20	2	13	20	3	0	20
[1][5][3]	3	6	40	3	23	50	20	-	-	-	-	-	-	3	6	40	3	12	0	3	12	0	3	12	50	3	12	50	3	23	50
[1][5][4]	4	6	20	4	23	30	20	-	-	-	-	-	-	4	6	20	4	11	40	4	11	40	4	12	30	4	12	30	4	23	30
[1][5][5]	5	6	50	6	0	0	20	-	-	-	-	-	-	5	6	50	5	12	10	5	12	10	5	13	0	5	13	0	6	0	0
[1][5][6]	7	0	0	7	17	10	20	-	-	-	-	-	-	7	0	0	7	5	20	7	5	20	7	6	10	7	6	10	7	17	10
[1][5][7]	8	0	0	8	17	10	20	-	-	-	-	-	-	8	0	0	8	5	20	8	5	20	8	6	10	8	6	10	8	17	10
[1][5][8]	9	0	0	9	17	10	20	-	-	-	-	-	-	9	0	0	9	5	20	9	5	20	9	6	10	9	6	10	9	17	10
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][1]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][2]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][3]	1	0	0	1	18	0	4	-	-	-	-	-	-	1	0	0	1	5	50	1	5	50	1	6	40	1	6	40	1	18	0
[1][6][4]	1	0	0	1	18	0	4	-	-	-	-	-	-	1	0	0	1	5	50	1	5	50	1	6	40	1	6	40	1	18	0
[1][6][5]	1	0	0	1	18	0	4	-	-	-	-	-	-	1	0	0	1	5	50	1	5	50	1	6	40	1	6	40	1	18	0
[1][6][6]	2	0	0	2	18	0	11	-	-	-	-	-	-	2	0	0	2	5	50	2	5	50	2	6	40	2	6	40	2	18	0
[1][6][7]	2	0	0	2	18	0	11	-	-	-	-	-	-	2	0	0	2	5	50	2	5	50	2	6	40	2	6	40	2	18	0
[1][6][8]	2	6	40	3	0	40	11	-	-	-	-	-	-	2	6	40	2	12	30	2	12	30	2	13	20	2	13	20	3	0	40
[1][6][9]	3	0	0	3	18	0	11	-	-	-	-	-	-	3	0	0	3	5	50	3	5	50	3	6	40	3	6	40	3	18	0
[1][6][10]	3	0	0	3	18	0	11	-	-	-	-	-	-	3	0	0	3	5	50	3	5	50	3	6	40	3	6	40	3	18	0
[1][6][11]	3	6	40	4	0	40	11	-	-	-	-	-	-	3	6	40	3	12	30	3	12	30	3	13	20	3	13	20	4	0	40
[1][6][12]	4	0	0	4	18	0	18	-	-	-	-	-	-	4	0	0	4	5	50	4	5	50	4	6	40	4	6	40	4	18	0
[1][6][13]	4	0	0	4	18	0	18	-	-	-	-	-	-	4	0	0	4	5	50	4	5	50	4	6	40	4	6	40	4	18	0
[1][6][14]	4	1	0	4	19	0	18	-	-	-	-	-	-	4	1	0	4	6	50	4	6	50	4	7	40	4	7	40	4	19	0
[1][6][15]	5	0	0	5	18	0	18	-	-	-	-	-	-	5	0	0	5	5	50	5	5	50	5	6	40	5	6	40	5	18	0
[1][6][16]	5	1	0	5	19	0	18	-	-	-	-	-	-	5	1	0	5	6	50	5	6	50	5	7	40	5	7	40	5	19	0
[1][6][17]	5	6	40	6	0	40	18	-	-	-	-	-	-	5	6	40	5	12	30	5	12	30	5	13	20	5	13	20	6	0	40
[1][6][18]	7	0	0	7	18	0	25	-	-	-	-	-	-	7	0	0	7	5	50	7	5	50	7	6	40	7	6	40	7	18	0
[1][6][19]	7	6	10	8	0	10	25	-	-	-	-	-	-	7	6	10	7	12	0	7	12	0	7	12	50	7	12	50	8	0	10
[1][6][20]	7	6	40	8	12	10	25	-	-	-	-	-	-	7	6	40	7	12	30	8	0	0	8	0	50	8	0	50	8	12	10
[1][6][21]	8	0	50	8	18	50	25	-	-	-	-	-	-	8	0	50	8	6	40	8	6	40	8	7	30	8	7	30	8	18	50
[1][6][22]	8	1	30	8	19	30	25	-	-	-	-	-	-	8	1	30	8	7	20	8	7	20	8	8	10	8	8	10	8	19	30
[1][6][23]	8	12	10	9	17	20	25	-	-	-	-	-	-	8	12	10	9	5	10	9	5	10	9	6	0	9	6	0	9	17	20
[1][6][24]	9	6	0	10	0	0	32	-	-	-	-	-	-	9	6	0	9	11	50	9	11	50	9	12	40	9	12	40	10	0	0
[1][6][25]	9	6	10	10	0	10	32	-	-	-	-	-	-	9	6	10	9	12	0	9	12	0	9	12	50	9	12	50	10	0	10
[1][6][26]	10	0	0	10	18	0	32	-	-	-	-	-	-	10	0	0	10	5	50	10	5	50	10	6	40	10	6	40	10	18	0
[1][6][27]	10	6	40	11	12	10	32	-	-	-	-	-	-	10	6	40	10	12	30	11	0	0	11	0	50	11	0	50	11	12	10
[1][6][28]	10	6	50	11	12	10	32	-	-	-	-	-	-	10	6	50	10	12	40	11	0	0	11	0	50	11	0	50	11	12	10
[1][6][29]	11	0	50	11	18	50	32	-	-	-	-	-	-	11	0	50	11	6	40	11	6	40	11	7	30	11	7	30	11	18	50

Table C.2: Detailed Production Schedule Obtained from F_LQ for *Labour Grouping*

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	0	0	0	0	0	0	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][3]	1	1	40	1	16	30	4	-	-	-	-	-	-	1	1	40	1	5	50	1	5	50	1	6	30	1	6	30	1	16	30
[0][0][4]	1	1	40	1	16	30	4	-	-	-	-	-	-	1	1	40	1	5	50	1	5	50	1	6	30	1	6	30	1	16	30
[0][0][5]	1	1	40	1	16	30	4	1	1	40	1	1	40	1	1	40	1	5	50	1	5	50	1	6	30	1	6	30	1	16	30
[0][0][6]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][8]	2	4	50	2	19	40	5	2	4	50	2	4	50	2	4	50	2	9	0	2	9	0	2	9	40	2	9	40	2	19	40
[0][0][9]	3	0	30	3	15	20	5	-	-	-	-	-	-	3	0	30	3	4	40	3	4	40	3	5	20	3	5	20	3	15	20
[0][0][10]	3	2	20	3	17	10	5	-	-	-	-	-	-	3	2	20	3	6	30	3	6	30	3	7	10	3	7	10	3	17	10
[0][0][11]	3	2	20	3	17	10	5	3	2	20	3	2	20	3	2	20	3	6	30	3	6	30	3	7	10	3	7	10	3	17	10
[0][0][12]	4	0	0	4	14	50	11	-	-	-	-	-	-	4	0	0	4	4	10	4	4	10	4	4	50	4	4	50	4	14	50
[0][0][13]	4	2	20	4	17	10	11	-	-	-	-	-	-	4	2	20	4	6	30	4	6	30	4	7	10	4	7	10	4	17	10
[0][0][14]	5	0	0	5	14	50	11	-	-	-	-	-	-	5	0	0	5	4	10	5	4	10	5	4	50	5	4	50	5	14	50
[0][0][15]	5	1	30	5	16	20	11	-	-	-	-	-	-	5	1	30	5	5	40	5	5	40	5	6	20	5	6	20	5	16	20
[0][0][16]	7	0	50	7	15	40	11	-	-	-	-	-	-	7	0	50	7	5	0	7	5	0	7	5	40	7	5	40	7	15	40
[0][0][17]	7	0	50	7	15	40	11	-	-	-	-	-	-	7	0	50	7	5	0	7	5	0	7	5	40	7	5	40	7	15	40
[0][0][18]	8	0	0	8	14	50	12	-	-	-	-	-	-	8	0	0	8	4	10	8	4	10	8	4	50	8	4	50	8	14	50
[0][0][19]	8	2	40	8	17	30	12	-	-	-	-	-	-	8	2	40	8	6	50	8	6	50	8	7	30	8	7	30	8	17	30
[0][0][20]	9	2	40	9	17	30	12	-	-	-	-	-	-	9	2	40	9	6	50	9	6	50	9	7	30	9	7	30	9	17	30
[0][0][21]	9	2	40	9	17	30	12	-	-	-	-	-	-	9	2	40	9	6	50	9	6	50	9	7	30	9	7	30	9	17	30
[0][0][22]	10	1	20	10	16	10	12	-	-	-	-	-	-	10	1	20	10	5	30	10	5	30	10	6	10	10	6	10	10	16	10
[0][0][23]	10	1	20	10	16	10	12	-	-	-	-	-	-	10	1	20	10	5	30	10	5	30	10	6	10	10	6	10	10	16	10
[0][0][24]	10	0	0	10	18	50	18	10	0	0	10	4	0	10	4	0	10	8	10	10	8	10	10	8	50	10	8	50	10	18	50
[0][0][25]	11	0	0	11	14	50	18	11	0	0	11	0	0	11	0	0	11	4	10	11	4	10	11	4	50	11	4	50	11	14	50
[0][0][26]	11	2	30	11	17	20	18	-	-	-	-	-	-	11	2	30	11	6	40	11	6	40	11	7	20	11	7	20	11	17	20
[0][0][27]	11	4	50	11	19	40	18	-	-	-	-	-	-	11	4	50	11	9	0	11	9	0	11	9	40	11	9	40	11	19	40
[0][0][28]	12	0	0	12	14	50	18	12	0	0	12	0	0	12	0	0	12	4	10	12	4	10	12	4	50	12	4	50	12	14	50
[0][0][29]	12	0	30	12	15	20	18	-	-	-	-	-	-	12	0	30	12	4	40	12	4	40	12	5	20	12	5	20	12	15	20
[0][0][30]	12	4	50	12	19	40	19	-	-	-	-	-	-	12	4	50	12	9	0	12	9	0	12	9	40	12	9	40	12	19	40
[0][0][31]	14	3	20	14	18	10	19	-	-	-	-	-	-	14	3	20	14	7	30	14	7	30	14	8	10	14	8	10	14	18	10
[0][0][32]	14	8	10	15	13	30	19	-	-	-	-	-	-	14	8	10	15	2	50	15	2	50	15	3	30	15	3	30	15	13	30
[0][0][33]	15	2	40	15	17	30	19	-	-	-	-	-	-	15	2	40	15	6	50	15	6	50	15	7	30	15	7	30	15	17	30
[0][0][34]	16	2	0	16	16	50	19	-	-	-	-	-	-	16	2	0	16	6	10	16	6	10	16	6	50	16	6	50	16	16	50
[0][0][35]	16	6	10	17	11	30	19	-	-	-	-	-	-	16	6	10	17	0	50	17	0	50	17	1	30	17	1	30	17	11	30
[0][0][36]	17	5	30	18	10	50	25	-	-	-	-	-	-	17	5	30	18	0	10	18	0	10	18	0	50	18	0	50	18	10	50
[0][0][37]	17	1	30	18	10	50	25	17	1	30	17	5	30	17	5	30	18	0	10	18	0	10	18	0	50	18	0	50	18	10	50
[0][0][38]	18	0	0	18	14	50	25	-	-	-	-	-	-	18	0	0	18	4	10	18	4	10	18	4	50	18	4	50	18	14	50
[0][0][39]	19	0	0	19	14	50	25	-	-	-	-	-	-	19	0	0	19	4	10	19	4	10	19	4	50	19	4	50	19	14	50
[0][0][40]	19	0	0	19	14	50	25	19	0	0	19	0	0	19	0	0	19	4	10	19	4	10	19	4	50	19	4	50	19	14	50
[0][0][41]	19	0	0	19	14	50	25	-	-	-	-	-	-	19	0	0	19	4	10	19	4	10	19	4	50	19	4	50	19	14	50
[0][0][42]	21	0	0	21	14	50	26	-	-	-	-	-	-	21	0	0	21	4	10	21	4	10	21	4	50	21	4	50	21	14	50
[0][0][43]	21	0	0	21	14	50	26	21	0	0	21	0	0	21	0	0	21	4	10	21	4	10	21	4	50	21	4	50	21	14	50
[0][0][44]	21	3	30	21	18	20	26	-	-	-	-	-	-	21	3	30	21	7	40	21	7	40	21	8	20	21	8	20	21	18	20
[0][0][45]	22	0	0	22	14	50	26	-	-	-	-	-	-	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][46]	22	0	0	22	14	50	26	22	0	0	22	0	0	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][47]	22	0	0	22	14	50	26	-	-	-	-	-	-	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][48]	23	0	0	23	14	50	32	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][49]	23	0	0	23	14	50	32	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][50]	24	0	0	24	14	50	32	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][0][51]	24	0	0	24	14	50	32	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][1][0]	7	7	30	8	17	20	11	7	7	30	8	2	30	8	2	30	8	6	40	8	6	40	8	7	20	8	7	20	8	17	20
[0][1][1]	11	4	50	12	14	40	18	11	4	50	11	8	50	11	8	50	12	4	0	12	4	0	12	4	40	12	4	40	12	14	40
[0][1][2]	18	4	10	18	23	0	25	18	4	10	18	8	10	18	8	10	18	12	20	18	12	20	18	13	0	18	13	0	18	23	0
[0][1][3]	26	0	0	26	18	50	32	26	0	0	26	4	0	26	4	0	26	8	10	26	8	10	26	8	50	26	8	50	26	18	50
[0][2][0]	4	0	0	5	13	10	6	4	0	0	4	8	0	4	8	0	5	2	30	5	2	30	5	3	10	5	3	10	5	13	10
[0][2][1]	9	4	10	10	14	0	12	9	4	10	9	8	10	9	8	10	10	3	20	10	3	20	10	4	0	10	4	0	10	14	0
[0][2][2]	17	0	0	17	22	50	19	17	0	0	17	8	0	17	8	0	17	12	10	17	12	10	17	12	50	17	12	50	17	22	50
[0][2][3]	24	0	0	24	22	50	26	24	0	0	24	8	0	24	8	0	24	12	10	24	12	10	24	12	50	24	12	50	24	22	50
[0][2][4]	25	0	0	25	14	50	32	25	0	0	25	0	0	25	0	0	25	4	10	25	4	10	25	4	50	25	4	50	25	14	50
[0][3][0]	0	8	50	1	12	20	9	-	-	-	-	-	-	0	8	50	1	2	50	1	2	50	1	3	20	1	3	20	1	12	20
[0][3][1]	2	6	40	3	10	10	9	-	-	-	-	-	-	2	6	40	3	0	40	3	0	40	3	1	10	3	1	10	3	10	10
[0][3][2]	2	8	50	3	16	20	9	2	8	50	3	3	10	3	3	10	3	6	50	3	6	50	3	7	20	3	7	20	3	16	20
[0][3][3]	4	0	0	4	13	10	9	-	-	-	-	-	-	4	0	0	4	3	40	4	3	40	4	4	10	4	4	10	4	13	10
[0][3][4]	4	0	30	4	13	40	10	4	0	30	4	0	30	4	0	30	4	4	10	4	4	10	4	4	40	4	4	40	4	13	40
[0][3][5]	5	0	0	5	13	10	10	-	-	-	-	-	-	5	0	0	5	3	40	5	3	40	5	4	10	5	4	10	5	13	10
[0][3][6]	7	1	40	7	14	50	10	-	-	-	-	-	-	7	1	40	7	5	20	7	5	20	7	5	50	7	5	50	7	14	50
[0][3][7]	8	0	0	8	13	10	10	-	-	-	-	-	-	8	0	0	8	3	40	8	3	40	8	4	10	8	4	10	8	13	10
[0][3][8]	9	4	50	9	18	0	16	-	-	-	-	-	-	9	4	50	9	8	30	9	8	30	9	9	0	9	9	0	9	18	0
[0][3][9]	10	8	50	11	13	0	16	-	-	-	-	-	-	10	8	50	11	3	30	11	3	30	11	4	0	11	4	0	11	13	0
[0][3][10]	12	3	50	12	17	0	16	-	-	-	-	-	-	12	3	50	12	7	30	12	7	30	12	8	0	12	8	0	12	17	0
[0][3][11]	14	0	0	14	13	10	16	-	-	-	-	-	-	14	0	0	14	3	40	14	3	40	14	4	10	14	4	10	14	13	10
[0][3][12]	14	0	0	14	17	10	17	14	0	0	14	4	0	14	4	0	14	7	40	14	7	40	14	8	10	14	8	10	14	17	10
[0][3][13]	15	0	0	15	13	10	17	-	-	-	-	-	-	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][3][14]	15	0	0	15	13	10	17	15	0	0	15	0	0	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][3][15]	16	0	0	16	13	10	17	-	-	-	-	-	-	16	0	0	16	3	40	16	3	40	16	4	10	16	4	10	16	13	10
[0][3][16]	17	4	50	17	18	0	23	-	-	-	-	-	-	17	4	50	17	8	30	17	8	30	17	9	0	17	9	0	17	18	0
[0][3][17]	18	0	0	18	13	10	23	-	-	-	-	-	-	18	0	0	18	3	40	18	3	40	18	4	10	18	4	10	18	13	10
[0][3][18]	18	0	0	18	17	10	23	18	0	0	18	4	0	18	4	0	18	7	40	18	7	40	18	8	10	18	8	10	18	17	10
[0][3][19]	19	0	0	19	13	10	23	-	-	-	-	-	-	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][3][20]	19	0	0	19	13	10	24	19	0	0	19	0	0	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][3][21]	21	0	0	21	13	10	24	-	-	-	-	-	-	21	0	0	21	3	40	21	3	40	21	4	10	21	4	10	21	13	10
[0][3][22]	22	0	0	22	13	10	24	-	-	-	-	-	-	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][3][23]	23	0	0	23	13	10	24	-	-	-	-	-	-	23	0	0	23	3	40	23	3	40	23	4	10	23	4	10	23	13	10

Table C.2 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	4	50	0	18	0	8	-	-	-	-	-	-	0	4	50	0	8	30	0	8	30	0	9	0	0	9	0	0	18	0
[0][4][1]	0	8	50	1	16	20	8	0	8	50	1	3	10	1	3	10	1	6	50	1	6	50	1	7	20	1	7	20	1	16	20
[0][4][2]	1	7	20	2	10	50	8	-	-	-	-	-	-	1	7	20	2	1	20	2	1	20	2	1	50	2	1	50	2	10	50
[0][4][3]	3	6	0	4	9	30	8	-	-	-	-	-	-	3	6	0	3	9	40	4	0	0	4	0	30	4	0	30	4	9	30
[0][4][4]	4	9	30	5	13	0	11	-	-	-	-	-	-	4	9	30	5	3	30	5	3	30	5	4	0	5	4	0	5	13	0
[0][4][5]	5	3	10	7	10	40	11	5	3	10	5	7	10	5	7	10	7	1	10	7	1	10	7	1	40	7	1	40	7	10	40
[0][4][6]	7	3	20	7	16	30	11	-	-	-	-	-	-	7	3	20	7	7	0	7	7	0	7	7	30	7	7	30	7	16	30
[0][4][7]	8	1	40	8	14	50	11	-	-	-	-	-	-	8	1	40	8	5	20	8	5	20	8	5	50	8	5	50	8	14	50
[0][4][8]	8	5	50	9	10	0	11	8	5	50	8	5	50	8	5	50	9	0	30	9	0	30	9	1	0	9	1	0	9	10	0
[0][4][9]	9	0	0	9	13	10	15	-	-	-	-	-	-	9	0	0	9	3	40	9	3	40	9	4	10	9	4	10	9	13	10
[0][4][10]	10	4	0	10	17	10	15	-	-	-	-	-	-	10	4	0	10	7	40	10	7	40	10	8	10	10	8	10	10	17	10
[0][4][11]	10	8	10	11	12	20	15	10	8	10	10	8	10	10	8	10	11	2	50	11	2	50	11	3	20	11	3	20	11	12	20
[0][4][12]	11	3	20	11	16	30	15	-	-	-	-	-	-	11	3	20	11	7	0	11	7	0	11	7	30	11	7	30	11	16	30
[0][4][13]	12	3	50	12	17	0	18	-	-	-	-	-	-	12	3	50	12	7	30	12	7	30	12	8	0	12	8	0	12	17	0
[0][4][14]	12	4	40	12	17	50	18	12	4	40	12	4	40	12	4	40	12	8	20	12	8	20	12	8	50	12	8	50	12	17	50
[0][4][15]	14	3	50	14	17	0	18	-	-	-	-	-	-	14	3	50	14	7	30	14	7	30	14	8	0	14	8	0	14	17	0
[0][4][16]	15	0	0	15	13	10	18	-	-	-	-	-	-	15	0	0	15	3	40	15	3	40	15	4	10	15	4	10	15	13	10
[0][4][17]	16	0	0	16	17	10	18	16	0	0	16	4	0	16	4	0	16	7	40	16	7	40	16	8	10	16	8	10	16	17	10
[0][4][18]	16	4	50	16	18	0	22	-	-	-	-	-	-	16	4	50	16	8	30	16	8	30	16	9	0	16	9	0	16	18	0
[0][4][19]	17	0	0	17	13	10	22	-	-	-	-	-	-	17	0	0	17	3	40	17	3	40	17	4	10	17	4	10	17	13	10
[0][4][20]	17	4	10	17	17	20	22	17	4	10	17	4	10	17	4	10	17	7	50	17	7	50	17	8	20	17	8	20	17	17	20
[0][4][21]	18	0	0	18	13	10	22	-	-	-	-	-	-	18	0	0	18	3	40	18	3	40	18	4	10	18	4	10	18	13	10
[0][4][22]	19	0	0	19	13	10	25	-	-	-	-	-	-	19	0	0	19	3	40	19	3	40	19	4	10	19	4	10	19	13	10
[0][4][23]	21	0	0	21	13	10	25	-	-	-	-	-	-	21	0	0	21	3	40	21	3	40	21	4	10	21	4	10	21	13	10
[0][4][24]	21	0	0	21	17	10	25	21	0	0	21	4	0	21	4	0	21	7	40	21	7	40	21	8	10	21	8	10	21	17	10
[0][4][25]	22	0	0	22	13	10	25	-	-	-	-	-	-	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][4][26]	22	0	0	22	13	10	25	22	0	0	22	0	0	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][5][0]	0	4	50	0	19	50	5	-	-	-	-	-	-	0	4	50	0	8	10	0	8	10	0	8	50	0	8	50	0	19	50
[0][5][1]	2	4	50	2	19	50	5	-	-	-	-	-	-	2	4	50	2	8	10	2	8	10	2	8	50	2	8	50	2	19	50
[0][5][2]	5	9	0	7	14	20	11	-	-	-	-	-	-	5	9	0	7	2	40	7	2	40	7	3	20	7	3	20	7	14	20
[0][5][3]	10	0	0	10	15	0	11	-	-	-	-	-	-	10	0	0	10	3	20	10	3	20	10	4	0	10	4	0	10	15	0
[0][5][4]	11	8	50	12	14	50	18	-	-	-	-	-	-	11	8	50	12	3	10	12	3	10	12	3	50	12	3	50	12	14	50
[0][5][5]	14	4	10	14	19	10	18	-	-	-	-	-	-	14	4	10	14	7	30	14	7	30	14	8	10	14	8	10	14	19	10
[0][5][6]	15	4	10	15	19	10	25	-	-	-	-	-	-	15	4	10	15	7	30	15	7	30	15	8	10	15	8	10	15	19	10
[0][5][7]	16	4	50	16	19	50	25	-	-	-	-	-	-	16	4	50	16	8	10	16	8	10	16	8	50	16	8	50	16	19	50
[0][5][8]	17	4	50	17	19	50	32	-	-	-	-	-	-	17	4	50	17	8	10	17	8	10	17	8	50	17	8	50	17	19	50
[0][5][9]	18	4	50	18	19	50	32	-	-	-	-	-	-	18	4	50	18	8	10	18	8	10	18	8	50	18	8	50	18	19	50
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][2]	1	0	0	1	18	50	4	1	0	0	1	0	0	1	0	0	1	6	0	1	6	0	1	6	50	1	6	50	1	18	50
[1][0][3]	1	0	50	1	19	40	4	1	0	50	1	0	50	1	0	50	1	6	50	1	6	50	1	7	40	1	7	40	1	19	40
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	2	0	0	2	6	0	2	6	0	2	6	50	2	6	50	2	18	50
[1][0][5]	2	0	0	2	18	50	11	2	0	0	2	0	0	2	0	0	2	6	0	2	6	0	2	6	50	2	6	50	2	18	50
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	3	0	0	3	6	0	3	6	0	3	6	50	3	6	50	3	18	50
[1][0][7]	3	0	50	3	19	40	11	3	0	50	3	0	50	3	0	50	3	6	50	3	6	50	3	7	40	3	7	40	3	19	40
[1][0][8]	4	0	0	4	18	50	11	4	0	0	4	0	0	4	0	0	4	6	0	4	6	0	4	6	50	4	6	50	4	18	50
[1][0][9]	5	0	0	5	18	50	11	5	0	0	5	0	0	5	0	0	5	6	0	5	6	0	5	6	50	5	6	50	5	18	50
[1][0][10]	17	0	0	18	13	30	25	17	0	0	17	4	0	17	4	0	18	0	40	18	0	40	18	1	30	18	1	30	18	13	30
[1][0][11]	19	0	0	19	18	50	25	19	0	0	19	0	0	19	0	0	19	6	0	19	6	0	19	6	50	19	6	50	19	18	50
[1][0][12]	19	0	0	19	20	50	25	19	0	0	19	2	0	19	2	0	19	8	0	19	8	0	19	8	50	19	8	50	19	20	50
[1][0][13]	21	0	0	21	18	50	25	21	0	0	21	0	0	21	0	0	21	6	0	21	6	0	21	6	50	21	6	50	21	18	50
[1][0][14]	21	0	0	21	18	50	25	21	0	0	21	0	0	21	0	0	21	6	0	21	6	0	21	6	50	21	6	50	21	18	50
[1][0][15]	22	0	0	22	18	50	32	22	0	0	22	0	0	22	0	0	22	6	0	22	6	0	22	6	50	22	6	50	22	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	23	0	0	23	6	0	23	6	0	23	6	50	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	26	0	0	26	6	0	26	6	0	26	6	50	26	6	50	26	18	50
[1][1][0]	4	0	0	4	22	50	11	4	0	0	4	4	0	4	4	0	4	10	0	4	10	0	4	10	50	4	10	50	4	22	50
[1][1][1]	5	0	50	5	19	40	11	5	0	50	5	0	50	5	0	50	5	6	50	5	6	50	5	7	40	5	7	40	5	19	40
[1][1][2]	7	0	0	7	18	50	11	7	0	0	7	0	0	7	0	0	7	6	0	7	6	0	7	6	50	7	6	50	7	18	50
[1][1][3]	8	0	0	8	18	50	11	8	0	0	8	0	0	8	0	0	8	6	0	8	6	0	8	6	50	8	6	50	8	18	50
[1][1][4]	9	0	0	9	18	50	11	9	0	0	9	0	0	9	0	0	9	6	0	9	6	0	9	6	50	9	6	50	9	18	50
[1][1][5]	10	1	0	10	19	50	18	10	1	0	10	1	0	10	1	0	10	7	0	10	7	0	10	7	50	10	7	50	10	19	50
[1][1][6]	11	0	0	11	18	50	18	11	0	0	11	0	0	11	0	0	11	6	0	11	6	0	11	6	50	11	6	50	11	18	50
[1][1][7]	12	5	0	14	15	20	18	12	5	0	12	5	0	12	5	0	14	2	30	14	2	30	14	3	20	14	3	20	14	15	20
[1][1][8]	15	0	0	15	18	50	18	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][1][9]	16	0	0	16	18	50	18	16	0	0	16	0	0	16	0	0	16	6	0	16	6	0	16	6	50	16	6	50	16	18	50
[1][1][10]	22	0	0	23	14	0	32	22	0	0	22	4	0	22	4	0	23	1	10	23	1	10	23	2	0	23	2	0	23	14	0
[1][1][11]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][1][12]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][2][0]	7	0	0	8	12	50	18	7	0	0	7	2	0	7	2	0	7	8	0	8	0	0	8	0	50	8	0	50	8	12	50
[1][2][1]	9	0	0	9	18	50	18	9	0	0	9	0	0	9	0	0	9	6	0	9	6	0	9	6	50	9	6	50	9	18	50
[1][2][2]	10	0	0	10	18	50	18	10	0	0	10	0	0	10	0	0	10	6	0	10	6	0	10	6	50	10	6	50	10	18	50
[1][2][3]	11	0	0	11	18	50	18	11	0	0	11	0	0	11	0	0	11	6	0	11	6	0	11	6	50	11	6	50	11	18	50
[1][2][4]	12	0	0	12	18	50	18	12	0	0	12	0	0	12	0	0	12	6	0	12	6	0	12	6	50	12	6	50	12	18	50
[1][2][5]	14	0	0	14	18	50	25	14	0	0	14	0	0	14	0	0	14	6	0	14	6	0	14	6	50	14	6	50	14	18	50
[1][2][6]	15	0	0	15	18	50	25	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][2][7]	16	0	0	16	18	50	25	16	0	0	16	0	0	16	0	0	16	6	0	16	6	0	16	6	50	16	6	50	16	18	50
[1][2][8]	17	0	0	17	18	50	25	17	0	0	17	0	0	17	0	0	17	6	0	17	6	0	17	6	50	17	6	50	17	18	50
[1][2][9]	18	0	0	18	18	50	25	18	0	0	18	0	0	18	0	0	18	6	0	18	6	0	18	6	50	18	6	50	18	18	50
[1][2][10]	26	0	0	26	20	50	39	26	0	0	26	2	0	26	2	0	26	8	0	26	8	0	26	8	50	26	8	50	26	20	50
[1][3][0]	0	0	0	0	19	30	25	-	-	-	-	-	-	0	0	0	0	6	30	0	6	30	0	7	30	0	7	30	0	19	30
[1][3][1]	0	0	0	0	19	30	25	-	-	-	-	-	-	0	0	0	0	6	30	0	6	30	0	7	30	0	7	30	0	19	30
[1][3][2]	1	0	50	1	20	20	25	-	-	-	-	-	-	1	0	50	1	7	20	1	7	20	1	8	20	1	8	20	1	20	20
[1][3][3]	1	1	0	1	20	30	25	-	-	-	-	-	-	1	1	0	1	7	30	1	7	30	1	8	30	1	8	30	1	20	30

Table C.2 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[1][3][4]	2	5	30	3	13	0	25	-	-	-	-	-	-	2	5	30	2	12	0	3	0	0	3	1	0	3	1	0	3	13	0
[1][3][5]	2	6	20	3	13	20	25	-	-	-	-	-	-	2	6	20	3	0	20	3	0	20	3	1	20	3	1	20	3	13	20
[1][3][6]	4	0	0	4	19	30	25	-	-	-	-	-	-	4	0	0	4	6	30	4	6	30	4	7	30	4	7	30	4	19	30
[1][3][7]	4	6	20	5	13	20	25	-	-	-	-	-	-	4	6	20	5	0	20	5	0	20	5	1	20	5	1	20	5	13	20
[1][3][8]	5	1	0	5	20	30	25	-	-	-	-	-	-	5	1	0	5	7	30	5	7	30	5	8	30	5	8	30	5	20	30
[1][3][9]	7	5	50	8	16	50	25	-	-	-	-	-	-	7	5	50	8	3	50	8	3	50	8	4	50	8	4	50	8	16	50
[1][3][10]	7	6	20	8	17	20	25	-	-	-	-	-	-	7	6	20	8	4	20	8	4	20	8	5	20	8	5	20	8	17	20
[1][3][11]	9	0	0	9	19	30	25	-	-	-	-	-	-	9	0	0	9	6	30	9	6	30	9	7	30	9	7	30	9	19	30
[1][3][12]	9	2	30	10	13	30	25	-	-	-	-	-	-	9	2	30	10	0	30	10	0	30	10	1	30	10	1	30	10	13	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	10	0	0	10	6	30	10	6	30	10	7	30	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	11	0	0	11	6	30	11	6	30	11	7	30	11	7	30	11	19	30
[1][3][15]	11	0	0	11	19	30	25	-	-	-	-	-	-	11	0	0	11	6	30	11	6	30	11	7	30	11	7	30	11	19	30
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	12	0	0	12	6	30	12	6	30	12	7	30	12	7	30	12	19	30
[1][3][17]	12	0	50	12	20	20	25	-	-	-	-	-	-	12	0	50	12	7	20	12	7	20	12	8	20	12	8	20	12	20	20
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	15	0	0	15	6	30	15	6	30	15	7	30	15	7	30	15	19	30
[1][3][21]	15	0	50	15	20	20	26	-	-	-	-	-	-	15	0	50	15	7	20	15	7	20	15	8	20	15	8	20	15	20	20
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	16	0	0	16	6	30	16	6	30	16	7	30	16	7	30	16	19	30
[1][3][23]	16	1	0	16	20	30	26	-	-	-	-	-	-	16	1	0	16	7	30	16	7	30	16	8	30	16	8	30	16	20	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	17	0	0	17	6	30	17	6	30	17	7	30	17	7	30	17	19	30
[1][3][25]	17	1	30	17	21	0	26	-	-	-	-	-	-	17	1	30	17	8	0	17	8	0	17	9	0	17	9	0	17	21	0
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][4][0]	0	7	30	1	13	0	6	-	-	-	-	-	-	0	7	30	1	0	40	1	0	40	1	1	40	1	1	40	1	13	0
[1][4][1]	2	6	50	3	12	20	6	-	-	-	-	-	-	2	6	50	2	12	30	3	0	0	3	1	0	3	1	0	3	12	20
[1][4][2]	3	12	20	4	17	50	6	-	-	-	-	-	-	3	12	20	4	5	30	4	5	30	4	6	30	4	6	30	4	17	50
[1][4][3]	5	1	20	5	19	20	6	-	-	-	-	-	-	5	1	20	5	7	0	5	7	0	5	8	0	5	8	0	5	19	20
[1][5][0]	0	6	50	1	11	50	20	-	-	-	-	-	-	0	6	50	0	12	10	1	0	0	1	0	50	1	0	50	1	11	50
[1][5][1]	1	11	50	2	16	30	20	-	-	-	-	-	-	1	11	50	2	4	40	2	4	40	2	5	30	2	5	30	2	16	30
[1][5][2]	3	1	20	3	18	30	20	-	-	-	-	-	-	3	1	20	3	6	40	3	6	40	3	7	30	3	7	30	3	18	30
[1][5][3]	4	7	30	5	12	10	20	-	-	-	-	-	-	4	7	30	5	0	20	5	0	20	5	1	10	5	1	10	5	12	10
[1][5][4]	5	12	10	7	16	50	20	-	-	-	-	-	-	5	12	10	7	5	0	7	5	0	7	5	50	7	5	50	7	16	50
[1][5][5]	8	4	50	9	13	30	20	-	-	-	-	-	-	8	4	50	9	1	40	9	1	40	9	2	30	9	2	30	9	13	30
[1][5][6]	10	5	0	11	13	40	20	-	-	-	-	-	-	10	5	0	11	1	50	11	1	50	11	2	40	11	2	40	11	13	40
[1][5][7]	12	5	0	14	13	40	20	-	-	-	-	-	-	12	5	0	14	1	50	14	1	50	14	2	40	14	2	40	14	13	40
[1][5][8]	15	4	10	16	12	0	20	-	-	-	-	-	-	15	4	10	16	0	10	16	0	10	16	1	0	16	1	0	16	12	0
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][1]	0	6	40	1	12	10	4	-	-	-	-	-	-	0	6	40	0	12	30	1	0	0	1	0	50	1	0	50	1	12	10
[1][6][2]	0	6	50	1	12	20	4	-	-	-	-	-	-	0	6	50	1	0	10	1	0	10	1	1	0	1	1	0	1	12	20
[1][6][3]	1	1	40	1	19	40	4	-	-	-	-	-	-	1	1	40	1	7	30	1	7	30	1	8	20	1	8	20	1	19	40
[1][6][4]	1	12	10	2	17	40	4	-	-	-	-	-	-	1	12	10	2	5	30	2	5	30	2	6	20	2	6	20	2	17	40
[1][6][5]	1	12	20	2	17	50	4	-	-	-	-	-	-	1	12	20	2	5	40	2	5	40	2	6	30	2	6	30	2	17	50
[1][6][6]	2	6	30	3	12	10	11	-	-	-	-	-	-	2	6	30	2	12	20	3	0	0	3	0	50	3	0	50	3	12	10
[1][6][7]	3	1	0	3	19	0	11	-	-	-	-	-	-	3	1	0	3	6	50	3	6	50	3	7	40	3	7	40	3	19	0
[1][6][8]	3	1	0	3	19	0	11	-	-	-	-	-	-	3	1	0	3	6	50	3	6	50	3	7	40	3	7	40	3	19	0
[1][6][9]	3	12	10	4	17	40	11	-	-	-	-	-	-	3	12	10	4	5	30	4	5	30	4	6	20	4	6	20	4	17	40
[1][6][10]	4	6	30	5	12	10	11	-	-	-	-	-	-	4	6	30	4	12	20	5	0	0	5	0	50	5	0	50	5	12	10
[1][6][11]	4	6	50	5	12	20	11	-	-	-	-	-	-	4	6	50	5	0	10	5	0	10	5	1	0	5	1	0	5	12	20
[1][6][12]	5	1	10	5	19	10	18	-	-	-	-	-	-	5	1	10	5	7	0	5	7	0	5	7	50	5	7	50	5	19	10
[1][6][13]	5	12	10	7	17	40	18	-	-	-	-	-	-	5	12	10	7	5	30	7	5	30	7	6	20	7	6	20	7	17	40
[1][6][14]	5	12	20	7	17	50	18	-	-	-	-	-	-	5	12	20	7	5	40	7	5	40	7	6	30	7	6	30	7	17	50
[1][6][15]	7	6	30	8	16	0	18	-	-	-	-	-	-	7	6	30	8	3	50	8	3	50	8	4	40	8	4	40	8	16	0
[1][6][16]	8	0	50	8	18	50	18	-	-	-	-	-	-	8	0	50	8	6	40	8	6	40	8	7	30	8	7	30	8	18	50
[1][6][17]	8	4	40	9	14	10	18	-	-	-	-	-	-	8	4	40	9	2	0	9	2	0	9	2	50	9	2	50	9	14	10
[1][6][18]	9	2	50	10	12	20	25	-	-	-	-	-	-	9	2	50	10	0	10	10	0	10	10	1	0	10	1	0	10	12	20
[1][6][19]	9	6	50	10	16	20	25	-	-	-	-	-	-	9	6	50	10	4	10	10	4	10	10	5	0	10	5	0	10	16	20
[1][6][20]	10	1	30	10	19	30	25	-	-	-	-	-	-	10	1	30	10	7	20	10	7	20	10	8	10	10	8	10	10	19	30
[1][6][21]	11	2	40	12	12	10	25	-	-	-	-	-	-	11	2	40	11	8	30	12	0	0	12	0	50	12	0	50	12	12	10
[1][6][22]	11	6	50	12	16	20	25	-	-	-	-	-	-	11	6	50	12	4	10	12	4	10	12	5	0	12	5	0	12	16	20
[1][6][23]	11	6	50	12	16	20	25	-	-	-	-	-	-	11	6	50	12	4	10	12	4	10	12	5	0	12	5	0	12	16	20
[1][6][24]	14	2	40	14	20	40	32	-	-	-	-	-	-	14	2	40	14	8	30	14	8	30	14	9	20	14	9	20	14	20	40
[1][6][25]	14	3	20	15	12	10	32	-	-	-	-	-	-	14	3	20	14	9	10	15	0	0	15	0	50	15	0	50	15	12	10
[1][6][26]	14	6	50	15	15	30	32	-	-	-	-	-	-	14	6	50	15	3	20	15	3	20	15	4	10	15	4	10	15	15	30
[1][6][27]	15	6	50	16	15	30	32	-	-	-	-	-	-	15	6	50	16	3	20	16	3	20	16	4	10	16	4	10	16	15	30
[1][6][28]	16	4	10	17	12	50	32	-	-	-	-	-	-	16	4	10	17	0	40	17	0	40	17	1	30	17	1	30	17	12	50
[1][6][29]	16	6	50	17	15	30	32	-	-	-	-	-	-	16	6	50	17	3	20	17	3	20	17	4	10	17	4	10	17	15	30

Table C.3: Detailed Production Schedule Obtained from F_CM for *Labour Grouping*

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	0	0	0	0	0	0	0	0	0	0	4	10	0	4	10	0	4	50	0	4	50	0	14	50
[0][0][3]	1	0	0	1	14	50	4	-	-	-	-	-	-	1	0	0	1	4	10	1	4	10	1	4	50	1	4	50	1	14	50
[0][0][4]	1	0	0	1	14	50	4	-	-	-	-	-	-	1	0	0	1	4	10	1	4	10	1	4	50	1	4	50	1	14	50
[0][0][5]	1	0	0	1	14	50	4	1	0	0	1	0	0	1	0	0	1	4	10	1	4	10	1	4	50	1	4	50	1	14	50
[0][0][6]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][8]	2	0	0	2	14	50	5	2	0	0	2	0	0	2	0	0	2	4	10	2	4	10	2	4	50	2	4	50	2	14	50
[0][0][9]	3	0	0	3	14	50	5	-	-	-	-	-	-	3	0	0	3	4	10	3	4	10	3	4	50	3	4	50	3	14	50
[0][0][10]	3	0	0	3	14	50	5	-	-	-	-	-	-	3	0	0	3	4	10	3	4	10	3	4	50	3	4	50	3	14	50
[0][0][11]	3	0	0	3	14	50	5	3	0	0	3	0	0	3	0	0	3	4	10	3	4	10	3	4	50	3	4	50	3	14	50
[0][0][12]	4	0	0	4	14	50	11	-	-	-	-	-	-	4	0	0	4	4	10	4	4	10	4	4	50	4	4	50	4	14	50
[0][0][13]	4	0	0	4	14	50	11	-	-	-	-	-	-	4	0	0	4	4	10	4	4	10	4	4	50	4	4	50	4	14	50
[0][0][14]	5	0	0	5	14	50	11	-	-	-	-	-	-	5	0	0	5	4	10	5	4	10	5	4	50	5	4	50	5	14	50
[0][0][15]	5	0	0	5	14	50	11	-	-	-	-	-	-	5	0	0	5	4	10	5	4	10	5	4	50	5	4	50	5	14	50
[0][0][16]	7	0	0	7	14	50	11	-	-	-	-	-	-	7	0	0	7	4	10	7	4	10	7	4	50	7	4	50	7	14	50
[0][0][17]	7	4	50	8	10	50	11	-	-	-	-	-	-	7	4	50	8	0	10	8	0	10	8	0	50	8	0	50	8	10	50
[0][0][18]	8	0	50	8	15	40	12	-	-	-	-	-	-	8	0	50	8	5	0	8	5	0	8	5	40	8	5	40	8	15	40
[0][0][19]	9	0	0	9	14	50	12	-	-	-	-	-	-	9	0	0	9	4	10	9	4	10	9	4	50	9	4	50	9	14	50
[0][0][20]	9	1	0	9	15	50	12	-	-	-	-	-	-	9	1	0	9	5	10	9	5	10	9	5	50	9	5	50	9	15	50
[0][0][21]	10	0	0	10	14	50	12	-	-	-	-	-	-	10	0	0	10	4	10	10	4	10	10	4	50	10	4	50	10	14	50
[0][0][22]	10	1	10	10	16	0	12	-	-	-	-	-	-	10	1	10	10	5	20	10	5	20	10	6	0	10	6	0	10	16	0
[0][0][23]	10	0	30	11	10	40	12	10	0	30	10	4	30	10	4	30	10	8	40	11	0	0	11	0	40	11	0	40	11	10	40
[0][0][24]	11	0	0	11	14	50	18	-	-	-	-	-	-	11	0	0	11	4	10	11	4	10	11	4	50	11	4	50	11	14	50
[0][0][25]	11	0	40	11	15	30	18	-	-	-	-	-	-	11	0	40	11	4	50	11	4	50	11	5	30	11	5	30	11	15	30
[0][0][26]	12	0	0	12	14	50	18	12	0	0	12	0	0	12	0	0	12	4	10	12	4	10	12	4	50	12	4	50	12	14	50
[0][0][27]	12	4	50	14	10	50	18	-	-	-	-	-	-	12	4	50	14	0	10	14	0	10	14	0	50	14	0	50	14	10	50
[0][0][28]	12	4	50	14	10	50	18	-	-	-	-	-	-	12	4	50	14	0	10	14	0	10	14	0	50	14	0	50	14	10	50
[0][0][29]	14	0	30	14	15	20	18	14	0	30	14	0	30	14	0	30	14	4	40	14	4	40	14	5	20	14	5	20	14	15	20
[0][0][30]	15	0	40	15	15	30	19	-	-	-	-	-	-	15	0	40	15	4	50	15	4	50	15	5	30	15	5	30	15	15	30
[0][0][31]	15	0	40	15	15	30	19	-	-	-	-	-	-	15	0	40	15	4	50	15	4	50	15	5	30	15	5	30	15	15	30
[0][0][32]	16	0	40	16	15	30	19	-	-	-	-	-	-	16	0	40	16	4	50	16	4	50	16	5	30	16	5	30	16	15	30
[0][0][33]	16	3	50	16	18	40	19	-	-	-	-	-	-	16	3	50	16	8	0	16	8	0	16	8	40	16	8	40	16	18	40
[0][0][34]	17	8	50	18	14	40	19	-	-	-	-	-	-	17	8	50	18	4	0	18	4	0	18	4	40	18	4	40	18	14	40
[0][0][35]	17	8	50	18	14	40	19	-	-	-	-	-	-	17	8	50	18	4	0	18	4	0	18	4	40	18	4	40	18	14	40
[0][0][36]	18	0	0	18	18	50	25	18	0	0	18	4	0	18	4	0	18	8	10	18	8	10	18	8	50	18	8	50	18	18	50
[0][0][37]	19	3	50	19	18	40	25	19	3	50	19	3	50	19	3	50	19	8	0	19	8	0	19	8	40	19	8	40	19	18	40
[0][0][38]	19	8	0	21	13	50	25	-	-	-	-	-	-	19	8	0	21	3	10	21	3	10	21	3	50	21	3	50	21	13	50
[0][0][39]	19	8	10	21	14	0	25	-	-	-	-	-	-	19	8	10	21	3	20	21	3	20	21	4	0	21	4	0	21	14	0
[0][0][40]	21	0	0	21	14	50	25	21	0	0	21	0	0	21	0	0	21	4	10	21	4	10	21	4	50	21	4	50	21	14	50
[0][0][41]	22	0	0	22	14	50	25	-	-	-	-	-	-	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][42]	22	0	0	22	14	50	26	-	-	-	-	-	-	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][43]	22	0	0	22	14	50	26	22	0	0	22	0	0	22	0	0	22	4	10	22	4	10	22	4	50	22	4	50	22	14	50
[0][0][44]	23	0	0	23	14	50	26	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][45]	23	0	0	23	14	50	26	-	-	-	-	-	-	23	0	0	23	4	10	23	4	10	23	4	50	23	4	50	23	14	50
[0][0][46]	24	0	0	24	14	50	26	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][0][47]	24	0	0	24	14	50	26	-	-	-	-	-	-	24	0	0	24	4	10	24	4	10	24	4	50	24	4	50	24	14	50
[0][0][48]	25	0	0	25	14	50	32	-	-	-	-	-	-	25	0	0	25	4	10	25	4	10	25	4	50	25	4	50	25	14	50
[0][0][49]	25	0	0	25	14	50	32	-	-	-	-	-	-	25	0	0	25	4	10	25	4	10	25	4	50	25	4	50	25	14	50
[0][0][50]	26	0	0	26	14	50	32	-	-	-	-	-	-	26	0	0	26	4	10	26	4	10	26	4	50	26	4	50	26	14	50
[0][0][51]	26	0	0	26	14	50	32	-	-	-	-	-	-	26	0	0	26	4	10	26	4	10	26	4	50	26	4	50	26	14	50
[0][1][0]	7	0	0	7	18	50	11	7	0	0	7	4	0	7	4	0	7	8	10	7	8	10	7	8	50	7	8	50	7	18	50
[0][1][1]	9	0	0	9	18	50	18	9	0	0	9	4	0	9	4	0	9	8	10	9	8	10	9	8	50	9	8	50	9	18	50
[0][1][2]	17	0	0	17	18	50	25	17	0	0	17	4	0	17	4	0	17	8	10	17	8	10	17	8	50	17	8	50	17	18	50
[0][1][3]	26	0	0	26	18	50	32	26	0	0	26	4	0	26	4	0	26	8	10	26	8	10	26	8	50	26	8	50	26	18	50
[0][2][0]	4	0	0	5	13	50	6	4	0	0	4	8	0	4	8	0	5	3	10	5	3	10	5	3	50	5	3	50	5	13	50
[0][2][1]	8	0	0	8	18	50	12	8	0	0	8	4	0	8	4	0	8	8	10	8	8	10	8	8	50	8	8	50	8	18	50
[0][2][2]	15	0	0	16	13	50	19	15	0	0	15	8	0	15	8	0	16	3	10	16	3	10	16	3	50	16	3	50	16	13	50
[0][2][3]	23	4	50	24	18	30	26	23	4	50	24	3	40	24	3	40	24	7	50	24	7	50	24	8	30	24	8	30	24	18	30
[0][2][4]	25	0	0	25	14	50	32	25	0	0	25	0	0	25	0	0	25	4	10	25	4	10	25	4	50	25	4	50	25	14	50
[0][3][0]	0	4	10	0	17	20	9	-	-	-	-	-	-	0	4	10	0	7	50	0	7	50	0	8	20	0	8	20	0	17	20
[0][3][1]	1	4	50	1	18	0	9	-	-	-	-	-	-	1	4	50	1	8	30	1	8	30	1	9	0	1	9	0	1	18	0
[0][3][2]	2	4	10	2	17	20	9	-	-	-	-	-	-	2	4	10	2	7	50	2	7	50	2	8	20	2	8	20	2	17	20
[0][3][3]	2	4	50	3	13	0	9	2	4	50	2	8	50	2	8	50	3	3	30	3	3	30	3	4	0	3	4	0	3	13	0
[0][3][4]	3	4	0	3	17	10	10	-	-	-	-	-	-	3	4	0	3	7	40	3	7	40	3	8	10	3	8	10	3	17	10
[0][3][5]	4	0	0	4	13	10	10	-	-	-	-	-	-	4	0	0	4	3	40	4	3	40	4	4	10	4	4	10	4	13	10
[0][3][6]	4	4	50	4	18	0	10	4	4	50	4	4	50	4	4	50	4	8	30	4	8	30	4	9	0	4	9	0	4	18	0
[0][3][7]	5	0	0	5	13	10	10	-	-	-	-	-	-	5	0	0	5	3	40	5	3	40	5	4	10	5	4	10	5	13	10
[0][3][8]	8	2	30	8	15	40	16	-	-	-	-	-	-	8	2	30	8	6	10	8	6	10	8	6	40	8	6	40	8	15	40
[0][3][9]	9	4	50	10	9	30	16	-	-	-	-	-	-	9	4	50	9	8	30	10	0	0	10	0	30	10	0	30	10	9	30
[0][3][10]	11	0	30	11	13	40	16	-	-	-	-	-	-	11	0	30	11	4	10	11	4	10	11	4	40	11	4	40	11	13	40
[0][3][11]	12	0	40	12	13	50	16	-	-	-	-	-	-	12	0	40	12	4	20	12	4	20	12	4	50	12	4	50	12	13	50
[0][3][12]	14	0	50	14	14	0	17	-	-	-	-	-	-	14	0	50	14	4	30	14	4	30	14	5	0	14	5	0	14	14	0
[0][3][13]	14	0	50	14	18	0	17	14	0	50	14	4	50	14	4	50	14	8	30	14	8	30	14	9	0	14	9	0	14	18	0
[0][3][14]	15	5	30	16	9	40	17	15	5	30	15	5	30	15	5	30	16	0	10	16	0	10	16	0	40	16	0	40	16	9	40
[0][3][15]	15	5	30	16	9	40	17	-	-	-	-	-	-	15	5	30	16	0	10	16	0	10	16	0	40	16	0	40	16	9	40
[0][3][16]	17	4	50	17	18	0	23	-	-	-	-	-	-	17	4	50	17	8	30	17	8	30	17	9	0	17	9	0	17	18	0
[0][3][17]	18	4	40	18	17	50	23	-	-	-	-	-	-	18	4	40	18	8	20	18	8	20	18	8	50	18	8	50	18	17	50
[0][3][18]	19	4	0	19	17	10	23	-	-	-	-	-	-	19	4	0	19	7	40	19	7	40	19	8	10	19	8	10	19	17	10
[0][3][19]	21	0	0	21	17	10	23	21	0	0	21	4	0	21	4	0	21	7	40	21	7	40	21	8	10	21	8	10	21	17	10
[0][3][20]	21	4	0	21	17	10	24	-	-	-	-	-	-	21	4	0	21	7	40	21	7	40	21	8	10	21	8	10	21	17	10
[0][3][21]	22	0	0	22	13	10	24	-	-	-	-	-	-	22	0	0	22	3	40	22	3	40	22	4	10	22	4	10	22	13	10
[0][3][22]	22	4	10	22	17	20	24	22	4	10	22	4	10	22	4	10	22	7	50	22	7	50	22	8	20	22	8	20	22	17	20
[0][3][23]	23	0	0	23	13	10	24	-	-	-	-	-	-	23	0	0	23	3	40	23	3	40	23	4	10	23	4	10	23	13	10

Table C.3 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	0	0	0	13	10	8	-	-	-	-	-	-	0	0	0	0	3	40	0	3	40	0	4	10	0	4	10	0	13	10
[0][4][1]	0	4	50	1	13	0	8	0	4	50	0	8	50	0	8	50	1	3	30	1	3	30	1	4	0	1	4	0	1	13	0
[0][4][2]	1	4	0	1	17	10	8	-	-	-	-	-	-	1	4	0	1	7	40	1	7	40	1	8	10	1	8	10	1	17	10
[0][4][3]	2	0	0	2	13	10	8	-	-	-	-	-	-	2	0	0	2	3	40	2	3	40	2	4	10	2	4	10	2	13	10
[0][4][4]	3	4	50	3	18	0	11	-	-	-	-	-	-	3	4	50	3	8	30	3	8	30	3	9	0	3	9	0	3	18	0
[0][4][5]	4	4	10	4	17	20	11	-	-	-	-	-	-	4	4	10	4	7	50	4	7	50	4	8	20	4	8	20	4	17	20
[0][4][6]	5	3	50	5	17	0	11	-	-	-	-	-	-	5	3	50	5	7	30	5	7	30	5	8	0	5	8	0	5	17	0
[0][4][7]	5	8	0	7	16	10	11	5	8	0	7	3	0	7	3	0	7	6	40	7	6	40	7	7	10	7	7	10	7	16	10
[0][4][8]	7	7	10	8	11	30	11	-	-	-	-	-	-	7	7	10	8	2	0	8	2	0	8	2	30	8	2	30	8	11	30
[0][4][9]	8	5	40	9	10	0	15	8	5	40	8	5	40	8	5	40	9	0	30	9	0	30	9	1	0	9	1	0	9	10	0
[0][4][10]	9	5	50	10	10	10	15	-	-	-	-	-	-	9	5	50	10	0	40	10	0	40	10	1	10	10	1	10	10	10	10
[0][4][11]	10	4	50	11	9	30	15	10	4	50	10	4	50	10	4	50	10	8	30	11	0	0	11	0	30	11	0	30	11	9	30
[0][4][12]	11	4	40	11	17	50	15	-	-	-	-	-	-	11	4	40	11	8	20	11	8	20	11	8	50	11	8	50	11	17	50
[0][4][13]	12	0	40	12	13	50	18	12	0	40	12	0	40	12	0	40	12	4	20	12	4	20	12	4	50	12	4	50	12	13	50
[0][4][14]	12	4	50	14	9	30	18	-	-	-	-	-	-	12	4	50	12	8	30	14	0	0	14	0	30	14	0	30	14	9	30
[0][4][15]	16	0	40	16	13	50	18	-	-	-	-	-	-	16	0	40	16	4	20	16	4	20	16	4	50	16	4	50	16	13	50
[0][4][16]	17	0	40	17	13	50	18	-	-	-	-	-	-	17	0	40	17	4	20	17	4	20	17	4	50	17	4	50	17	13	50
[0][4][17]	17	0	40	17	17	50	18	17	0	40	17	4	40	17	4	40	17	8	20	17	8	20	17	8	50	17	8	50	17	17	50
[0][4][18]	18	4	40	18	17	50	22	-	-	-	-	-	-	18	4	40	18	8	20	18	8	20	18	8	50	18	8	50	18	17	50
[0][4][19]	18	8	50	19	13	0	22	18	8	50	18	8	50	18	8	50	19	3	30	19	3	30	19	4	0	19	4	0	19	13	0
[0][4][20]	19	3	50	19	17	0	22	-	-	-	-	-	-	19	3	50	19	7	30	19	7	30	19	8	0	19	8	0	19	17	0
[0][4][21]	21	3	50	21	17	0	22	-	-	-	-	-	-	21	3	50	21	7	30	21	7	30	21	8	0	21	8	0	21	17	0
[0][4][22]	22	4	50	22	18	0	25	-	-	-	-	-	-	22	4	50	22	8	30	22	8	30	22	9	0	22	9	0	22	18	0
[0][4][23]	23	0	0	23	17	10	25	23	0	0	23	4	0	23	4	0	23	7	40	23	7	40	23	8	10	23	8	10	23	17	10
[0][4][24]	23	4	10	23	17	20	25	-	-	-	-	-	-	23	4	10	23	7	50	23	7	50	23	8	20	23	8	20	23	17	20
[0][4][25]	24	0	0	24	13	10	25	-	-	-	-	-	-	24	0	0	24	3	40	24	3	40	24	4	10	24	4	10	24	13	10
[0][4][26]	24	4	10	24	17	20	25	24	4	10	24	4	10	24	4	10	24	7	50	24	7	50	24	8	20	24	8	20	24	17	20
[0][5][0]	0	4	50	0	19	50	5	-	-	-	-	-	-	0	4	50	0	8	10	0	8	10	0	8	50	0	8	50	0	19	50
[0][5][1]	1	4	50	1	19	50	5	-	-	-	-	-	-	1	4	50	1	8	10	1	8	10	1	8	50	1	8	50	1	19	50
[0][5][2]	2	4	50	2	19	50	11	-	-	-	-	-	-	2	4	50	2	8	10	2	8	10	2	8	50	2	8	50	2	19	50
[0][5][3]	3	4	50	3	19	50	11	-	-	-	-	-	-	3	4	50	3	8	10	3	8	10	3	8	50	3	8	50	3	19	50
[0][5][4]	4	4	50	4	19	50	18	-	-	-	-	-	-	4	4	50	4	8	10	4	8	10	4	8	50	4	8	50	4	19	50
[0][5][5]	5	4	10	5	19	10	18	-	-	-	-	-	-	5	4	10	5	7	30	5	7	30	5	8	10	5	8	10	5	19	10
[0][5][6]	11	5	30	12	11	40	25	-	-	-	-	-	-	11	5	30	11	8	50	12	0	0	12	0	40	12	0	40	12	11	40
[0][5][7]	14	5	20	15	11	40	25	-	-	-	-	-	-	14	5	20	14	8	40	15	0	0	15	0	40	15	0	40	15	11	40
[0][5][8]	16	5	30	17	11	40	32	-	-	-	-	-	-	16	5	30	16	8	50	17	0	0	17	0	40	17	0	40	17	11	40
[0][5][9]	18	8	50	19	14	50	32	-	-	-	-	-	-	18	8	50	19	3	10	19	3	10	19	3	50	19	3	50	19	14	50
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	6	50	0	6	50	0	18	50
[1][0][2]	1	3	0	1	21	50	4	1	3	0	1	3	0	1	3	0	1	9	0	1	9	0	1	9	50	1	9	50	1	21	50
[1][0][3]	1	3	0	1	21	50	4	1	3	0	1	3	0	1	3	0	1	9	0	1	9	0	1	9	50	1	9	50	1	21	50
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	2	0	0	2	6	0	2	6	0	2	6	50	2	6	50	2	18	50
[1][0][5]	2	0	50	2	19	40	11	2	0	50	2	0	50	2	0	50	2	6	50	2	6	50	2	7	40	2	7	40	2	19	40
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	3	0	0	3	6	0	3	6	0	3	6	50	3	6	50	3	18	50
[1][0][7]	3	2	0	3	20	50	11	3	2	0	3	2	0	3	2	0	3	8	0	3	8	0	3	8	50	3	8	50	3	20	50
[1][0][8]	4	7	30	5	16	0	11	4	7	30	4	7	30	4	7	30	5	3	10	5	3	10	5	4	0	5	4	0	5	16	0
[1][0][9]	7	0	0	7	18	50	11	7	0	0	7	0	0	7	0	0	7	6	0	7	6	0	7	6	50	7	6	50	7	18	50
[1][0][10]	18	0	0	18	22	50	25	18	0	0	18	4	0	18	4	0	18	10	0	18	10	0	18	10	50	18	10	50	18	22	50
[1][0][11]	19	0	0	19	18	50	25	19	0	0	19	0	0	19	0	0	19	6	0	19	6	0	19	6	50	19	6	50	19	18	50
[1][0][12]	21	0	0	21	18	50	25	21	0	0	21	0	0	21	0	0	21	6	0	21	6	0	21	6	50	21	6	50	21	18	50
[1][0][13]	21	0	0	21	20	50	25	21	0	0	21	2	0	21	2	0	21	8	0	21	8	0	21	8	50	21	8	50	21	20	50
[1][0][14]	22	0	0	22	18	50	25	22	0	0	22	0	0	22	0	0	22	6	0	22	6	0	22	6	50	22	6	50	22	18	50
[1][0][15]	22	0	0	22	18	50	32	22	0	0	22	0	0	22	0	0	22	6	0	22	6	0	22	6	50	22	6	50	22	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	23	0	0	23	6	0	23	6	0	23	6	50	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	26	0	0	26	6	0	26	6	0	26	6	50	26	6	50	26	18	50
[1][1][0]	4	1	0	5	13	30	11	4	1	0	4	5	0	4	5	0	5	0	40	5	0	40	5	1	30	5	1	30	5	13	30
[1][1][1]	7	0	50	7	19	40	11	7	0	50	7	0	50	7	0	50	7	6	50	7	6	50	7	7	40	7	7	40	7	19	40
[1][1][2]	8	0	0	8	18	50	11	8	0	0	8	0	0	8	0	0	8	6	0	8	6	0	8	6	50	8	6	50	8	18	50
[1][1][3]	9	1	40	9	20	30	11	9	1	40	9	1	40	9	1	40	9	7	40	9	7	40	9	8	30	9	8	30	9	20	30
[1][1][4]	10	0	0	10	18	50	11	10	0	0	10	0	0	10	0	0	10	6	0	10	6	0	10	6	50	10	6	50	10	18	50
[1][1][5]	11	0	50	11	19	40	18	11	0	50	11	0	50	11	0	50	11	6	50	11	6	50	11	7	40	11	7	40	11	19	40
[1][1][6]	12	2	50	14	13	0	18	12	2	50	12	2	50	12	2	50	14	0	10	14	0	10	14	1	0	14	1	0	14	13	0
[1][1][7]	15	0	0	15	18	50	18	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][1][8]	16	0	0	16	18	50	18	16	0	0	16	0	0	16	0	0	16	6	0	16	6	0	16	6	50	16	6	50	16	18	50
[1][1][9]	17	0	0	17	18	50	18	17	0	0	17	0	0	17	0	0	17	6	0	17	6	0	17	6	50	17	6	50	17	18	50
[1][1][10]	23	0	0	23	22	50	32	23	0	0	23	4	0	23	4	0	23	10	0	23	10	0	23	10	50	23	10	50	23	22	50
[1][1][11]	24	0	0	24	18	50	32	24	0	0	24	0	0	24	0	0	24	6	0	24	6	0	24	6	50	24	6	50	24	18	50
[1][1][12]	25	0	0	25	18	50	32	25	0	0	25	0	0	25	0	0	25	6	0	25	6	0	25	6	50	25	6	50	25	18	50
[1][2][0]	8	1	30	9	13	40	18	8	1	30	8	3	30	8	3	30	9	0	50	9	0	50	9	1	40	9	1	40	9	13	40
[1][2][1]	10	0	50	10	19	40	18	10	0	50	10	0	50	10	0	50	10	6	50	10	6	50	10	7	40	10	7	40	10	19	40
[1][2][2]	11	0	0	11	18	50	18	11	0	0	11	0	0	11	0	0	11	6	0	11	6	0	11	6	50	11	6	50	11	18	50
[1][2][3]	12	0	0	12	18	50	18	12	0	0	12	0	0	12	0	0	12	6	0	12	6	0	12	6	50	12	6	50	12	18	50
[1][2][4]	14	1	0	14	19	50	18	14	1	0	14	1	0	14	1	0	14	7	0	14	7	0	14	7	50	14	7	50	14	19	50
[1][2][5]	15	0	0	15	18	50	25	15	0	0	15	0	0	15	0	0	15	6	0	15	6	0	15	6	50	15	6	50	15	18	50
[1][2][6]	16	2	20	16	21	10	25	16	2	20	16	2	20	16	2	20	16	8	20	16	8	20	16	9	10	16	9	10	16	21	10
[1][2][7]	17	0	0	17	18	50	25	17	0	0	17	0	0	17	0	0	17	6	0	17	6	0	17	6	50	17	6	50	17	18	50
[1][2][8]	18	2	20	18	21	10	25	18	2	20	18	2	20	18	2	20	18	8	20	18	8	20	18	9	10	18	9	10	18	21	10
[1][2][9]	19	0	0	19	18	50	25	19	0	0	19	0	0	19	0	0	19	6	0	19	6	0	19	6	50	19	6	50	19	18	50
[1][2][10]	26	0	0	26	20	50	39	26	0	0	26	2	0	26	2	0	26	8	0	26	8	0	26	8	50	26	8	50	26	20	50
[1][3][0]	0	6	50	1	16	0	25	-	-	-	-	-	-	0	6	50	1	3	0	1	3	0	1	4	0	1	4	0	1	16	0
[1][3][1]	0	6	50	1	16	0	25	-	-	-	-	-	-	0	6	50	1	3	0	1	3	0	1	4	0	1	4	0	1	16	0
[1][3][2]	2	6	50	3	16	0	25	-	-	-	-	-	-	2	6	50	3	3	0	3	3	0	3	4	0	3	4	0	3	16	0
[1][3][3]	2	7	30	3	16	40	25	-	-	-	-	-	-	2	7	30	3	3	40	3	3	40	3	4	40	3	4	40	3	16	40

Table C.3 <Continued>

Precast	PC							Operation 0						Operation 1						Operation 2						Operation 3					
	ST			FT			Due date	ST			FT			ST			FT			ST			FT			ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min	Day	Hr	Min
[1][3][4]	4	3	10	5	13	0	25	-	-	-	-	-	-	4	3	10	4	9	40	5	0	0	5	1	0	5	1	0	5	13	0
[1][3][5]	4	4	40	5	13	50	25	-	-	-	-	-	-	4	4	40	5	0	50	5	0	50	5	1	50	5	1	50	5	13	50
[1][3][6]	7	0	0	7	19	30	25	-	-	-	-	-	-	7	0	0	7	6	30	7	6	30	7	7	30	7	7	30	7	19	30
[1][3][7]	7	0	0	7	19	30	25	-	-	-	-	-	-	7	0	0	7	6	30	7	6	30	7	7	30	7	7	30	7	19	30
[1][3][8]	8	0	0	8	19	30	25	-	-	-	-	-	-	8	0	0	8	6	30	8	6	30	8	7	30	8	7	30	8	19	30
[1][3][9]	8	0	0	8	19	30	25	-	-	-	-	-	-	8	0	0	8	6	30	8	6	30	8	7	30	8	7	30	8	19	30
[1][3][10]	9	0	0	9	19	30	25	-	-	-	-	-	-	9	0	0	9	6	30	9	6	30	9	7	30	9	7	30	9	19	30
[1][3][11]	9	0	0	9	19	30	25	-	-	-	-	-	-	9	0	0	9	6	30	9	6	30	9	7	30	9	7	30	9	19	30
[1][3][12]	10	0	0	10	19	30	25	-	-	-	-	-	-	10	0	0	10	6	30	10	6	30	10	7	30	10	7	30	10	19	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	10	0	0	10	6	30	10	6	30	10	7	30	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	11	0	0	11	6	30	11	6	30	11	7	30	11	7	30	11	19	30
[1][3][15]	11	0	0	11	19	30	25	-	-	-	-	-	-	11	0	0	11	6	30	11	6	30	11	7	30	11	7	30	11	19	30
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	12	0	0	12	6	30	12	6	30	12	7	30	12	7	30	12	19	30
[1][3][17]	12	0	0	12	19	30	25	-	-	-	-	-	-	12	0	0	12	6	30	12	6	30	12	7	30	12	7	30	12	19	30
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	14	0	0	14	6	30	14	6	30	14	7	30	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	15	0	0	15	6	30	15	6	30	15	7	30	15	7	30	15	19	30
[1][3][21]	15	0	0	15	19	30	26	-	-	-	-	-	-	15	0	0	15	6	30	15	6	30	15	7	30	15	7	30	15	19	30
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	16	0	0	16	6	30	16	6	30	16	7	30	16	7	30	16	19	30
[1][3][23]	16	0	0	16	19	30	26	-	-	-	-	-	-	16	0	0	16	6	30	16	6	30	16	7	30	16	7	30	16	19	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	17	0	0	17	6	30	17	6	30	17	7	30	17	7	30	17	19	30
[1][3][25]	17	0	0	17	19	30	26	-	-	-	-	-	-	17	0	0	17	6	30	17	6	30	17	7	30	17	7	30	17	19	30
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	18	0	0	18	6	30	18	6	30	18	7	30	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	19	0	0	19	6	30	19	6	30	19	7	30	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	21	0	0	21	6	30	21	6	30	21	7	30	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	22	0	0	22	6	30	22	6	30	22	7	30	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	23	0	0	23	6	30	23	6	30	23	7	30	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	24	0	0	24	6	30	24	6	30	24	7	30	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	25	0	0	25	6	30	25	6	30	25	7	30	25	7	30	25	19	30
[1][4][0]	0	6	40	1	14	20	6	-	-	-	-	-	-	0	6	40	1	2	0	1	2	0	1	3	0	1	3	0	1	14	20
[1][4][1]	2	5	40	3	13	20	6	-	-	-	-	-	-	2	5	40	3	1	0	3	1	0	3	2	0	3	2	0	3	13	20
[1][4][2]	4	0	50	4	18	50	6	-	-	-	-	-	-	4	0	50	4	6	30	4	6	30	4	7	30	4	7	30	4	18	50
[1][4][3]	5	1	0	5	19	0	6	-	-	-	-	-	-	5	1	0	5	6	40	5	6	40	5	7	40	5	7	40	5	19	0
[1][5][0]	1	9	50	2	16	40	20	-	-	-	-	-	-	1	9	50	2	4	50	2	4	50	2	5	40	2	5	40	2	16	40
[1][5][1]	3	8	50	4	15	40	20	-	-	-	-	-	-	3	8	50	4	3	50	4	3	50	4	4	40	4	4	40	4	15	40
[1][5][2]	5	7	40	7	14	30	20	-	-	-	-	-	-	5	7	40	7	2	40	7	2	40	7	3	30	7	3	30	7	14	30
[1][5][3]	8	4	50	9	13	20	20	-	-	-	-	-	-	8	4	50	9	1	30	9	1	30	9	2	20	9	2	20	9	13	20
[1][5][4]	10	2	50	11	11	50	20	-	-	-	-	-	-	10	2	50	10	8	10	11	0	0	11	0	50	11	0	50	11	11	50
[1][5][5]	12	4	50	14	13	20	20	-	-	-	-	-	-	12	4	50	14	1	30	14	1	30	14	2	20	14	2	20	14	13	20
[1][5][6]	15	0	50	15	18	0	20	-	-	-	-	-	-	15	0	50	15	6	10	15	6	10	15	7	0	15	7	0	15	18	0
[1][5][7]	16	2	20	16	19	30	20	-	-	-	-	-	-	16	2	20	16	7	40	16	7	40	16	8	30	16	8	30	16	19	30
[1][5][8]	17	2	20	17	19	30	20	-	-	-	-	-	-	17	2	20	17	7	40	17	7	40	17	8	30	17	8	30	17	19	30
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][1]	0	0	0	0	18	0	4	-	-	-	-	-	-	0	0	0	0	5	50	0	5	50	0	6	40	0	6	40	0	18	0
[1][6][2]	0	6	40	1	14	20	4	-	-	-	-	-	-	0	6	40	1	2	10	1	2	10	1	3	0	1	3	0	1	14	20
[1][6][3]	1	4	0	2	12	10	4	-	-	-	-	-	-	1	4	0	1	9	50	2	0	0	2	0	50	2	0	50	2	12	10
[1][6][4]	1	4	0	2	12	10	4	-	-	-	-	-	-	1	4	0	1	9	50	2	0	0	2	0	50	2	0	50	2	12	10
[1][6][5]	2	0	50	2	18	50	4	-	-	-	-	-	-	2	0	50	2	6	40	2	6	40	2	7	30	2	7	30	2	18	50
[1][6][6]	3	4	0	4	12	10	11	-	-	-	-	-	-	3	4	0	3	9	50	4	0	0	4	0	50	4	0	50	4	12	10
[1][6][7]	3	4	40	4	12	20	11	-	-	-	-	-	-	3	4	40	4	0	10	4	0	10	4	1	0	4	1	0	4	12	20
[1][6][8]	3	6	50	4	14	30	11	-	-	-	-	-	-	3	6	50	4	2	20	4	2	20	4	3	10	4	3	10	4	14	30
[1][6][9]	5	1	30	5	19	30	11	-	-	-	-	-	-	5	1	30	5	7	20	5	7	20	5	8	10	5	8	10	5	19	30
[1][6][10]	5	1	50	5	19	50	11	-	-	-	-	-	-	5	1	50	5	7	40	5	7	40	5	8	30	5	8	30	5	19	50
[1][6][11]	5	4	0	7	12	10	11	-	-	-	-	-	-	5	4	0	5	9	50	7	0	0	7	0	50	7	0	50	7	12	10
[1][6][12]	7	3	30	8	12	50	18	-	-	-	-	-	-	7	3	30	8	0	40	8	0	40	8	1	30	8	1	30	8	12	50
[1][6][13]	7	6	50	8	16	10	18	-	-	-	-	-	-	7	6	50	8	4	0	8	4	0	8	4	50	8	4	50	8	16	10
[1][6][14]	8	6	50	9	16	10	18	-	-	-	-	-	-	8	6	50	9	4	0	9	4	0	9	4	50	9	4	50	9	16	10
[1][6][15]	9	2	20	10	12	10	18	-	-	-	-	-	-	9	2	20	9	8	10	10	0	0	10	0	50	10	0	50	10	12	10
[1][6][16]	9	4	50	10	14	10	18	-	-	-	-	-	-	9	4	50	10	2	0	10	2	0	10	2	50	10	2	50	10	14	10
[1][6][17]	10	6	50	11	16	10	18	-	-	-	-	-	-	10	6	50	11	4	0	11	4	0	11	4	50	11	4	50	11	16	10
[1][6][18]	11	4	50	12	14	10	25	-	-	-	-	-	-	11	4	50	12	2	0	12	2	0	12	2	50	12	2	50	12	14	10
[1][6][19]	11	6	50	12	16	10	25	-	-	-	-	-	-	11	6	50	12	4	0	12	4	0	12	4	50	12	4	50	12	16	10
[1][6][20]	12	6	50	14	16	10	25	-	-	-	-	-	-	12	6	50	14	4	0	14	4	0	14	4	50	14	4	50	14	16	10
[1][6][21]	14	2	20	14	20	20	25	-	-	-	-	-	-	14	2	20	14	8	10	14	8	10	14	9	0	14	9	0	14	20	20
[1][6][22]	14	4	50	15	12	10	25	-	-	-	-	-	-	14	4	50	14	10	40	15	0	0	15	0	50	15	0	50	15	12	10
[1][6][23]	15	6	50	16	13	40	25	-	-	-	-	-	-	15	6	50	16	1	30	16	1	30	16	2	20	16	2	20	16	13	40
[1][6][24]	15	6	50	16	13	40	32	-	-	-	-	-	-	15	6	50	16	1	30	16	1	30	16	2	20	16	2	20	16	13	40
[1][6][25]	16	6	50	17	13	40	32	-	-	-	-	-	-	16	6	50	17	1	30	17	1	30	17	2	20	17	2	20	17	13	40
[1][6][26]	17	6	50	18	13	40	32	-	-	-	-	-	-	17	6	50	18	1	30	18	1	30	18	2	20	18	2	20	18	13	40
[1][6][27]	17	6	50	18	13	40	32	-	-	-	-	-	-	17	6	50	18	1	30	18	1	30	18	2	20	18	2	20	18	13	40
[1][6][28]	18	2	20	18	20	20	32	-	-	-	-	-	-	18	2	20	18	8	10	18	8	10	18	9	0	18	9	0	18	20	20
[1][6][29]	19	0	0	19	18	0	32	-	-	-	-	-	-	19	0	0	19	5	50	19	5	50	19	6	40	19	6	40	19	18	0

Table C.4: Detailed Production Schedule Obtained from BI_CM for *Labour Grouping*

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	0	0	0	0	0	0	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][3]	1	0	0	1	14	50	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][4]	1	0	0	1	14	50	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][5]	1	0	0	1	14	50	4	1	0	0	1	0	0	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][6]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][8]	2	0	0	2	14	50	5	2	0	0	2	0	0	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][9]	3	0	0	3	14	50	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][10]	3	0	0	3	14	50	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][11]	3	0	0	3	14	50	5	3	0	0	3	0	0	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][12]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][13]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][14]	5	0	0	5	14	50	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][15]	5	0	0	5	14	50	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][16]	7	0	0	7	14	50	11	-	-	-	-	-	-	-	7	0	0	7	4	10	-	7	4	10	7	4	50	-	7	4	50	7	14	50
[0][0][17]	7	3	50	7	18	40	11	-	-	-	-	-	-	-	7	3	50	7	8	0	-	7	8	0	7	8	40	No	7	8	40	7	18	40
[0][0][18]	8	0	0	8	14	50	12	-	-	-	-	-	-	-	8	0	0	8	4	10	-	8	4	10	8	4	50	-	8	4	50	8	14	50
[0][0][19]	8	3	50	8	18	40	12	-	-	-	-	-	-	-	8	3	50	8	8	0	-	8	8	0	8	8	40	No	8	8	40	8	18	40
[0][0][20]	9	0	0	9	14	50	12	-	-	-	-	-	-	-	9	0	0	9	4	10	-	9	4	10	9	4	50	-	9	4	50	9	14	50
[0][0][21]	9	3	50	9	18	40	12	-	-	-	-	-	-	-	9	3	50	9	8	0	-	9	8	0	9	8	40	No	9	8	40	9	18	40
[0][0][22]	10	0	0	10	14	50	12	-	-	-	-	-	-	-	10	0	0	10	4	10	-	10	4	10	10	4	50	-	10	4	50	10	14	50
[0][0][23]	10	3	50	10	18	40	12	-	-	-	-	-	-	-	10	3	50	10	8	0	-	10	8	0	10	8	40	No	10	8	40	10	18	40
[0][0][24]	10	0	0	10	18	50	18	10	0	0	10	4	0	-	10	4	0	10	8	10	No	10	8	10	10	8	50	No	10	8	50	10	18	50
[0][0][25]	11	0	0	11	14	50	18	-	-	-	-	-	-	-	11	0	0	11	4	10	-	11	4	10	11	4	50	-	11	4	50	11	14	50
[0][0][26]	11	0	0	11	14	50	18	11	0	0	11	0	0	-	11	0	0	11	4	10	-	11	4	10	11	4	50	-	11	4	50	11	14	50
[0][0][27]	11	4	50	12	10	40	18	-	-	-	-	-	-	-	11	4	50	11	9	0	No	12	0	0	12	0	40	-	12	0	40	12	10	40
[0][0][28]	12	0	0	12	14	50	18	12	0	0	12	0	0	-	12	0	0	12	4	10	-	12	4	10	12	4	50	-	12	4	50	12	14	50
[0][0][29]	12	0	40	12	15	30	18	-	-	-	-	-	-	-	12	0	40	12	4	50	-	12	4	50	12	5	30	-	12	5	30	12	15	30
[0][0][30]	14	0	0	14	14	50	19	-	-	-	-	-	-	-	14	0	0	14	4	10	-	14	4	10	14	4	50	-	14	4	50	14	14	50
[0][0][31]	14	0	40	14	16	30	19	-	-	-	-	-	-	-	14	0	40	14	4	50	-	14	4	50	14	5	30	-	14	5	30	14	15	30
[0][0][32]	15	1	40	15	17	30	19	-	-	-	-	-	-	-	15	1	40	15	5	50	-	15	5	50	15	6	30	-	15	6	30	15	16	30
[0][0][33]	15	2	40	16	11	40	19	-	-	-	-	-	-	-	15	2	40	15	6	50	-	15	6	50	15	7	30	-	15	7	30	15	17	30
[0][0][34]	16	1	0	17	11	10	19	-	-	-	-	-	-	-	16	1	0	16	5	10	-	16	5	10	16	5	50	-	16	5	50	16	15	50
[0][0][35]	17	0	0	17	18	50	19	17	0	0	17	4	0	-	17	4	0	17	8	10	No	17	8	10	17	8	50	No	17	8	50	17	18	50
[0][0][36]	16	1	0	18	12	10	25	-	-	-	-	-	-	-	16	1	0	16	5	10	-	16	5	10	16	5	50	-	16	5	50	16	15	50
[0][0][37]	18	1	50	18	14	50	25	18	1	50	18	1	50	-	18	1	50	18	6	0	-	18	6	0	18	6	40	-	18	6	40	18	16	40
[0][0][38]	17	4	10	19	11	0	25	-	-	-	-	-	-	-	17	4	10	17	8	20	No	17	8	20	17	9	0	No	17	9	0	17	19	0
[0][0][39]	19	0	0	19	15	50	25	19	0	0	19	0	0	-	19	0	0	19	4	10	-	19	4	10	19	4	50	-	19	4	50	19	14	50
[0][0][40]	17	6	0	21	11	0	25	-	-	-	-	-	-	-	17	6	0	17	10	10	No	17	10	10	17	10	50	No	17	10	50	17	20	50
[0][0][41]	18	6	40	21	14	50	25	-	-	-	-	-	-	-	18	6	40	18	10	50	No	19	0	0	19	0	40	-	19	0	40	19	10	40
[0][0][42]	21	0	0	21	14	50	26	21	0	0	21	0	0	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][43]	18	7	50	22	14	50	26	-	-	-	-	-	-	-	18	7	50	19	0	50	No	19	0	50	19	1	30	-	19	1	30	19	11	30
[0][0][44]	19	10	40	23	11	0	26	-	-	-	-	-	-	-	19	10	40	21	3	40	No	21	3	40	21	4	20	-	21	4	20	21	14	20
[0][0][45]	21	0	0	23	14	50	26	-	-	-	-	-	-	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][46]	23	0	0	24	14	50	26	-	-	-	-	-	-	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][47]	23	0	0	24	14	50	26	-	-	-	-	-	-	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][48]	24	0	0	25	14	50	32	-	-	-	-	-	-	-	24	0	0	24	4	10	-	24	4	10	24	4	50	-	24	4	50	24	14	50
[0][0][49]	24	0	0	25	14	50	32	-	-	-	-	-	-	-	24	0	0	24	4	10	-	24	4	10	24	4	50	-	24	4	50	24	14	50
[0][0][50]	26	0	0	26	14	50	32	-	-	-	-	-	-	-	26	0	0	26	4	10	-	26	4	10	26	4	50	-	26	4	50	26	14	50
[0][0][51]	26	0	0	26	14	50	32	-	-	-	-	-	-	-	26	0	0	26	4	10	-	26	4	10	26	4	50	-	26	4	50	26	14	50
[0][1][0]	7	0	0	7	18	50	11	7	0	0	7	4	0	-	7	4	0	7	8	10	No	7	8	10	7	8	50	No	7	8	50	7	18	50
[0][1][1]	9	0	0	9	18	50	18	9	0	0	9	4	0	-	9	4	0	9	8	10	No	9	8	10	9	8	50	No	9	8	50	9	18	50
[0][1][2]	16	0	0	16	18	50	25	16	0	0	16	4	0	-	16	4	0	16	8	10	No	16	8	10	16	8	50	No	16	8	50	16	18	50
[0][1][3]	25	0	0	26	10	50	32	25	0	0	25	4	0	-	25	4	0	26	0	10	Yes	26	0	10	26	0	50	-	26	0	50	26	10	50
[0][2][0]	4	0	0	5	11	40	6	4	0	0	4	8	0	-	4	8	0	5	1	0	No	5	1	0	5	1	40	-	5	1	40	5	11	40
[0][2][1]	8	0	0	8	18	50	12	8	0	0	8	4	0	-	8	4	0	8	8	10	No	8	8	10	8	8	50	No	8	8	50	8	18	50
[0][2][2]	14	0	0	15	14	50	19	14	0	0	14	8	0	-	14	8	0	15	1	0	No	15	1	0	15	1	40	-	15	1	40	15	11	40
[0][2][3]	22	0	0	23	14	50	26	22	0	0	22	8	0	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][2][4]	24	0	0	24	15	40	32	24	0	0	24	0	0	-	24	0	0	24	4	10	-	24	4	10	24	4	50	-	24	4	50	24	14	50
[0][3][0]	0	4	10	0	17	20	9	-	-	-	-	-	-	-	0	4	10	0	7	50	-	0	7	50	0	8	20	No	0	8	20	0	17	20
[0][3][1]	1	4	50	1	18	0	9	-	-	-	-	-	-	-	1	4	50	1	8	30	No	1	8	30	1	9	0	No	1	9	0	1	18	0
[0][3][2]	1	10	50	2	16	50	9	1	10	50	2	3	40	No	2	3	40	2	7	20	-	2	7	20	2	7	50	-	2	7	50	2	16	50
[0][3][3]	2	4	50	2	18	0	9	-	-	-	-	-	-	-	2	4	50	2	8	30	No	2	8	30	2	9	0	No	2	9	0	2	18	0
[0][3][4]	3	0	0	3	13	10	10	-	-	-	-	-	-	-	3	0	0	3	3	40	-	3	3	40	3	4	10	-	3	4	10	3	13	10
[0][3][5]	3	4	50	3	18	0	10	3	4	50	3	4	50	-	3	4	50	3	8	30	No	3	8	30	3	9	0	No	3	9	0	3	18	0
[0][3][6]	4	0	0	4	13	10	10	-	-	-	-	-	-	-	4	0	0	4	3	40	-	4	3	40	4	4	10	-	4	4	10	4	13	10
[0][3][7]	5	1	40	5	14	50	10	-	-	-	-	-	-	-	5	1	40	5	5	20	-	5	5	20	5	5	50	-	5	5	50	5	14	50
[0][3][8]	7	8	40	8	12	50	16	-	-	-	-	-	-	-	7	8	40	8	3	20	No	8	3	20	8	3	50	-	8	3	50	8	12	50
[0][3][9]	9	4	50	9	18	0	16	-	-	-	-	-	-	-	9	4	50	9	8	30	No	9	8	30	9	9	0	No	9	9	0	9	18	0
[0][3][10]	10	4	50	10	18	0	16	-	-	-	-	-	-	-	10	4	50	10	8	30	No	10	8	30	10	9	0	No	10	9	0	10	18	0
[0][3][11]	11	3	50	11	17	0	16	-	-	-	-	-	-	-	11	3	50	11	7	30	-	11	7	30	11	8	0	-	11	8	0	11	17	0
[0][3][12]	12	0	0	12	17	10	17	12	0	0	12	4	0	-	12	4	0	12	7	40	-	12	7	40	12	8	10	No	12	8	10	12	17	10
[0][3][13]	12	4	50	12	18	0	17	-	-	-	-	-	-	-	12	4	50	12	8	30	No	12	8	30	12	9	0	No	12	9	0	12	18	0
[0][3][14]	14	5	30	14	18	0	17	14	5	30	14	5	30	-	14	5	30	14	9	10	No	14	9	10	14	9	40	No	14	9	40	14	18	40
[0][3][15]	14	4	50	15	11	40	17	-	-	-	-	-	-	-	14	4	50	14	8	30	No	14	8	30	14	9	0	No	14	9	0	14	18	0
[0][3][16]	15	6	30	16	14	50	23	-	-	-	-	-	-	-	15	6	30	15	10	10	No	15	10	10	15	10	40	No	15	10	40	15	19	40
[0][3][17]	16	5	50	17	14	20	23	-	-	-	-	-	-	-	16	5	50	16	9	30	No	16	9	30	16	10	0	No	16	10	0	16	19	0
[0][3][18]	17	1	50	18	15	20	23	-	-	-	-	-	-	-	17	1	50	17	5	30	-	17	5	30	17	6	0	-	17	6	0	17	15	0
[0][3][19]	17	10	50	19	14	0	23	17	10	50	18	3	40	No	18	3	40	18	7	20	-	18	7	20	18	7	50	-	18	7	50	18	16	50
[0][3][20]	18	6	0	21	10	10	24	-	-	-	-	-	-	-	18	6	0	18	9	40	No	18	9	40	18	10	10	No	18	10	10	18	19	10
[0][3][21]	19	1	30	21	14	10	24	19	1	30	19	1	30	-	19	1	30	19	5	10	-	19	5	10	19	5	40	-	19	5	40	19	14	40
[0][3][22]	19	0	40	22	13	10	24	-	-	-	-	-	-	-	19	0	40	19	4	20	-	19	4	20	19	4	50	-	19	4	50	19	13	50
[0][3][23]	21	4	20	23	14	10	24	-	-	-	-	-	-	-	21	4	20	21	8	0	-	21	8	0	21	8	30	No	21	8	30	21	17	30

Note: "NT only" indicates whether only NT can be used for execution of the operation ("Yes") or not ("No").

Table C.4 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	0	0	0	13	10	8	-	-	-	-	-	-	-	0	0	0	0	3	40	-	0	3	40	0	4	10	-	0	4	10	0	13	10
[0][4][1]	0	4	50	1	10	50	8	0	4	50	0	8	50	No	0	8	50	1	1	20	No	1	1	20	1	1	50	-	1	1	50	1	10	50
[0][4][2]	1	1	50	1	15	0	8	-	-	-	-	-	-	-	1	1	50	1	5	30	-	1	5	30	1	6	0	-	1	6	0	1	15	0
[0][4][3]	2	4	50	2	18	0	8	-	-	-	-	-	-	-	2	4	50	2	8	30	No	2	8	30	2	9	0	No	2	9	0	2	18	0
[0][4][4]	3	4	10	3	17	20	11	-	-	-	-	-	-	-	3	4	10	3	7	50	-	3	7	50	3	8	20	No	3	8	20	3	17	20
[0][4][5]	4	4	10	4	17	20	11	-	-	-	-	-	-	-	4	4	10	4	7	50	-	4	7	50	4	8	20	No	4	8	20	4	17	20
[0][4][6]	4	4	50	5	10	50	11	4	4	50	4	8	50	No	4	8	50	5	1	20	No	5	1	20	5	1	50	-	5	1	50	5	10	50
[0][4][7]	5	1	50	5	15	0	11	-	-	-	-	-	-	-	5	1	50	5	5	30	-	5	5	30	5	6	0	-	5	6	0	5	15	0
[0][4][8]	5	10	50	7	12	50	11	5	10	50	5	10	50	-	5	10	50	7	3	20	No	7	3	20	7	3	50	-	7	3	50	7	12	50
[0][4][9]	7	4	50	7	18	0	15	-	-	-	-	-	-	-	7	4	50	7	8	30	No	7	8	30	7	9	0	No	7	9	0	7	18	0
[0][4][10]	8	4	50	8	18	0	15	-	-	-	-	-	-	-	8	4	50	8	8	30	No	8	8	30	8	9	0	No	8	9	0	8	18	0
[0][4][11]	8	8	40	9	12	50	15	8	8	40	8	8	40	-	8	8	40	9	3	20	No	9	3	20	9	3	50	-	9	3	50	9	12	50
[0][4][12]	9	8	40	10	12	50	15	-	-	-	-	-	-	-	9	8	40	10	3	20	No	10	3	20	10	3	50	-	10	3	50	10	12	50
[0][4][13]	10	8	40	11	12	50	18	10	8	40	10	8	40	-	10	8	40	11	3	20	No	11	3	20	11	3	50	-	11	3	50	11	12	50
[0][4][14]	11	4	50	11	18	0	18	-	-	-	-	-	-	-	11	4	50	11	8	30	No	11	8	30	11	9	0	No	11	9	0	11	18	0
[0][4][15]	12	5	30	14	10	40	18	-	-	-	-	-	-	-	12	5	30	14	0	10	No	14	0	10	14	0	40	-	14	0	40	14	9	40
[0][4][16]	14	9	40	15	13	10	18	-	-	-	-	-	-	-	14	9	40	15	2	10	No	15	2	10	15	2	40	-	15	2	40	15	11	40
[0][4][17]	15	0	0	16	13	20	18	15	0	0	15	4	0	-	15	4	0	15	7	40	-	15	7	40	15	8	10	No	15	8	10	15	17	10
[0][4][18]	16	5	50	17	11	0	22	-	-	-	-	-	-	-	16	5	50	16	9	30	No	16	9	30	16	10	0	No	16	10	0	16	19	0
[0][4][19]	16	8	50	17	15	10	22	16	8	50	16	8	50	-	16	8	50	17	1	20	No	17	1	20	17	1	50	-	17	1	50	17	10	50
[0][4][20]	17	0	0	18	13	10	22	-	-	-	-	-	-	-	17	0	0	17	3	40	-	17	3	40	17	4	10	-	17	4	10	17	13	10
[0][4][21]	18	1	50	19	13	10	22	-	-	-	-	-	-	-	18	1	50	18	5	30	-	18	5	30	18	6	0	-	18	6	0	18	15	0
[0][4][22]	19	4	50	21	14	20	25	-	-	-	-	-	-	-	19	4	50	19	8	30	No	19	8	30	19	9	0	No	19	9	0	19	18	0
[0][4][23]	21	4	50	22	14	0	25	-	-	-	-	-	-	-	21	4	50	21	8	30	No	21	8	30	21	9	0	No	21	9	0	21	18	0
[0][4][24]	21	0	0	23	14	0	25	21	0	0	21	4	0	-	21	4	0	21	7	40	-	21	7	40	21	8	10	No	21	8	10	21	17	10
[0][4][25]	22	0	0	24	10	0	25	-	-	-	-	-	-	-	22	0	0	22	3	40	-	22	3	40	22	4	10	-	22	4	10	22	13	10
[0][4][26]	23	0	0	24	14	10	25	23	0	0	23	0	0	-	23	0	0	23	3	40	-	23	3	40	23	4	10	-	23	4	10	23	13	10
[0][5][0]	0	4	50	0	19	50	5	-	-	-	-	-	-	-	0	4	50	0	8	10	No	0	8	10	0	8	50	No	0	8	50	0	19	50
[0][5][1]	1	4	50	1	19	50	5	-	-	-	-	-	-	-	1	4	50	1	8	10	No	1	8	10	1	8	50	No	1	8	50	1	19	50
[0][5][2]	2	4	50	2	19	50	11	-	-	-	-	-	-	-	2	4	50	2	8	10	No	2	8	10	2	8	50	No	2	8	50	2	19	50
[0][5][3]	3	4	50	3	19	50	11	-	-	-	-	-	-	-	3	4	50	3	8	10	No	3	8	10	3	8	50	No	3	8	50	3	19	50
[0][5][4]	4	4	50	4	19	50	18	-	-	-	-	-	-	-	4	4	50	4	8	10	No	4	8	10	4	8	50	No	4	8	50	4	19	50
[0][5][5]	5	4	50	5	19	50	18	-	-	-	-	-	-	-	5	4	50	5	8	10	No	5	8	10	5	8	50	No	5	8	50	5	19	50
[0][5][6]	15	8	10	22	11	50	25	-	-	-	-	-	-	-	15	8	10	16	0	20	No	16	0	20	16	1	0	-	16	1	0	16	12	0
[0][5][7]	17	9	0	24	11	50	25	-	-	-	-	-	-	-	17	9	0	18	1	10	No	18	1	10	18	1	50	-	18	1	50	18	12	50
[0][5][8]	19	5	40	25	15	0	32	-	-	-	-	-	-	-	19	5	40	19	9	0	No	19	9	0	19	9	40	No	19	9	40	19	20	40
[0][5][9]	21	4	50	26	15	0	32	-	-	-	-	-	-	-	21	4	50	21	8	10	No	21	8	10	21	8	50	No	21	8	50	21	19	50
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][2]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	-	1	9	10	1	10	0	-	1	10	0	1	22	0
[1][0][3]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	-	1	9	10	1	10	0	-	1	10	0	1	22	0
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	-	2	0	0	2	6	0	-	2	6	0	2	6	50	-	2	6	50	2	18	50
[1][0][5]	2	0	50	2	19	40	11	2	0	50	2	0	50	-	2	0	50	2	6	50	-	2	6	50	2	7	40	-	2	7	40	2	19	40
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	-	3	0	0	3	6	0	-	3	6	0	3	6	50	-	3	6	50	3	18	50
[1][0][7]	3	2	30	3	21	20	11	3	2	30	3	2	30	-	3	2	30	3	8	30	-	3	8	30	3	9	20	-	3	9	20	3	21	20
[1][0][8]	4	7	30	5	16	10	11	4	7	30	4	7	30	-	4	7	30	5	3	20	-	5	3	20	5	4	10	-	5	4	10	5	16	10
[1][0][9]	7	0	50	7	19	40	11	7	0	50	7	0	50	-	7	0	50	7	6	50	-	7	6	50	7	7	40	-	7	7	40	7	19	40
[1][0][10]	17	0	0	18	13	40	25	17	0	0	17	4	0	-	17	4	0	18	0	50	-	18	0	50	18	1	40	-	18	1	40	18	13	40
[1][0][11]	19	0	0	19	18	50	25	19	0	0	19	0	0	-	19	0	0	19	6	0	-	19	6	0	19	6	50	-	19	6	50	19	18	50
[1][0][12]	19	6	50	21	18	30	25	19	6	50	19	8	50	-	19	8	50	21	5	40	-	21	5	40	21	6	30	-	21	6	30	21	18	30
[1][0][13]	21	0	0	21	18	50	25	21	0	0	21	0	0	-	21	0	0	21	6	0	-	21	6	0	21	6	50	-	21	6	50	21	18	50
[1][0][14]	22	0	0	22	18	50	25	22	0	0	22	0	0	-	22	0	0	22	6	0	-	22	6	0	22	6	50	-	22	6	50	22	18	50
[1][0][15]	22	0	0	22	18	50	32	22	0	0	22	0	0	-	22	0	0	22	6	0	-	22	6	0	22	6	50	-	22	6	50	22	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	-	23	0	0	23	6	0	-	23	6	0	23	6	50	-	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	-	24	0	0	24	6	0	-	24	6	0	24	6	50	-	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	-	25	0	0	25	6	0	-	25	6	0	25	6	50	-	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	-	26	0	0	26	6	0	-	26	6	0	26	6	50	-	26	6	50	26	18	50
[1][1][0]	4	1	20	5	14	0	11	4	1	20	4	5	20	-	4	5	20	5	1	10	-	5	1	10	5	2	0	-	5	2	0	5	14	0
[1][1][1]	7	0	0	7	18	50	11	7	0	0	7	0	0	-	7	0	0	7	6	0	-	7	6	0	7	6	50	-	7	6	50	7	18	50
[1][1][2]	8	0	0	8	18	50	11	8	0	0	8	0	0	-	8	0	0	8	6	0	-	8	6	0	8	6	50	-	8	6	50	8	18	50
[1][1][3]	9	0	0	9	18	50	11	9	0	0	9	0	0	-	9	0	0	9	6	0	-	9	6	0	9	6	50	-	9	6	50	9	18	50
[1][1][4]	10	0	0	10	18	50	11	10	0	0	10	0	0	-	10	0	0	10	6	0	-	10	6	0	10	6	50	-	10	6	50	10	18	50
[1][1][5]	11	0	0	11	18	50	18	11	0	0	11	0	0	-	11	0	0	11	6	0	-	11	6	0	11	6	50	-	11	6	50	11	18	50
[1][1][6]	12	0	0	12	18	50	18	12	0	0	12	0	0	-	12	0	0	12	6	0	-	12	6	0	12	6	50	-	12	6	50	12	18	50
[1][1][7]	14	0	0	14	18	50	18	14	0	0	14	0	0	-	14	0	0	14	6	0	-	14	6	0	14	6	50	-	14	6	50	14	18	50
[1][1][8]	15	0	0	15	18	50	18	15	0	0	15	0	0	-	15	0	0	15	6	0	-	15	6	0	15	6	50	-	15	6	50	15	18	50
[1][1][9]	16	0	0	16	18	50	18	16	0	0	16	0	0	-	16	0	0	16	6	0	-	16	6	0	16	6	50	-	16	6	50	16	18	50
[1][1][10]	23	0	0	23	22	50	32	23	0	0	23	4	0	-	23	4	0	23	10	0	-	23	10	0	23	10	50	-	23	10	50	23	22	50
[1][1][11]	24	0	0	24	18	50	32	24	0	0	24	0	0	-	24	0	0	24	6	0	-	24	6	0	24	6	50	-	24	6	50	24	18	50
[1][1][12]	25	0	0	25	18	50	32	25	0	0	25	0	0	-	25	0	0	25	6	0	-	25	6	0	25	6	50	-	25	6	50	25	18	50
[1][2][0]	8	0	50	8	21	40	18	8	0	50	8	2	50	-	8	2	50	8	8	50	-	8	8	50	8	9	40	-	8	9	40	8	21	40
[1][2][1]	9	0	50	9	19	40	18	9	0	50	9	0	50	-	9	0	50	9	6	50	-	9	6	50	9	7	40	-	9	7	40	9	19	40
[1][2][2]	10	0	50	10	19	40	18	10	0	50	10	0	50	-	10	0	50	10	6	50	-	10	6	50	10	7	40	-	10	7	40	10	19	40
[1][2][3]	11	0	50	11	19	40	18	11	0	50	11	0	50	-	11	0	50	11	6	50	-	11	6	50	11	7	40	-	11	7	40	11	19	40
[1][2][4]	12	0	50	12	19	40	18	12	0	50	12	0	50	-	12	0	50	12	6	50	-	12	6	50	12	7	40	-	12	7	40	12	19	40
[1][2][5]	14	0	50	14	19	40	25	14	0	50	14	0	50	-	14	0	50	14	6	50	-	14	6	50	14	7	40	-	14	7	40	14	19	40
[1][2][6]	15	1	20	15	20	10	25	15	1	20	15	1	20	-	15	1	20	15	7	20	-	15	7	20	15	8	10	-	15	8	10	15	20	10
[1][2][7]	16	1	20	16	20	10	25	16	1	20	16	1	20	-	16	1	20	16	7	20	-	16	7	20	16	8	10	-	16	8	10	16	20	10
[1][2][8]	17	1	50	17	20	40	25	17	1	50	17	1	50	-	17	1	50	17	7	50	-	17	7	50	17	8	40	-	17	8	40	17	20	40
[1][2][9]	18	1	20	18	20	10	25	18	1	20	18	1	20	-	18	1	20	18	7	20	-	18	7	20	18	8	10	-	18	8	10	18	20	10
[1][2][10]	26	0	0	26	20	50	39	26	0	0	26	2	0	-	26	2	0	26	8	0	-	26	8	0	26	8	50	-	26	8	50	26	20	50
[1][3][0]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	-	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][1]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	-	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][2]	2	6	50	3	16	10	25	-	-	-	-	-	-	-	2	6	50	3	3	10	-	3	3	10	3	4	10	-	3	4	10	3	16	10
[1][3][3]	2	7	30	3	16	50	25	-	-	-	-	-	-	-	2	7	30	3	3	50	-	3	3	50	3	4	50	-	3	4	50	3	16	50

Note: “NT only” indicates whether only NT can be used for execution of the operation (“Yes”) or not (“No”).

Table C.4 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[1][3][4]	4	3	20	5	13	0	25	-	-	-	-	-	-	-	4	3	20	4	9	50	-	5	0	0	5	1	0	-	5	1	0	5	13	0
[1][3][5]	4	5	20	5	14	40	25	-	-	-	-	-	-	-	4	5	20	5	1	40	-	5	1	40	5	2	40	-	5	2	40	5	14	40
[1][3][6]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][7]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][8]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][9]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][10]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][11]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][12]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	-	11	0	0	11	6	30	-	11	6	30	11	7	30	-	11	7	30	11	19	30
[1][3][15]	11	0	0	11	19	30	25	-	-	-	-	-	-	-	11	0	0	11	6	30	-	11	6	30	11	7	30	-	11	7	30	11	19	30
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][17]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][21]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][23]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][25]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][4][0]	0	6	40	1	14	30	6	-	-	-	-	-	-	-	0	6	40	1	2	10	-	1	2	10	1	3	10	-	1	3	10	1	14	30
[1][4][1]	2	6	0	3	13	50	6	-	-	-	-	-	-	-	2	6	0	3	1	30	-	3	1	30	3	2	30	-	3	2	30	3	13	50
[1][4][2]	4	0	50	4	18	50	6	-	-	-	-	-	-	-	4	0	50	4	6	30	-	4	6	30	4	7	30	-	4	7	30	4	18	50
[1][4][3]	5	1	0	5	19	0	6	-	-	-	-	-	-	-	5	1	0	5	6	40	-	5	6	40	5	7	40	-	5	7	40	5	19	0
[1][5][0]	1	10	0	2	17	0	20	-	-	-	-	-	-	-	1	10	0	2	5	10	-	2	5	10	2	6	0	-	2	6	0	2	17	0
[1][5][1]	3	9	20	4	16	20	20	-	-	-	-	-	-	-	3	9	20	4	4	30	-	4	4	30	4	5	20	-	4	5	20	4	16	20
[1][5][2]	5	7	40	7	14	40	20	-	-	-	-	-	-	-	5	7	40	7	2	50	-	7	2	50	7	3	40	-	7	3	40	7	14	40
[1][5][3]	8	3	50	9	11	50	20	-	-	-	-	-	-	-	8	3	50	8	9	10	-	9	0	0	9	0	50	-	9	0	50	9	11	50
[1][5][4]	10	3	50	11	11	50	20	-	-	-	-	-	-	-	10	3	50	10	9	10	-	11	0	0	11	0	50	-	11	0	50	11	11	50
[1][5][5]	12	3	50	14	11	50	20	-	-	-	-	-	-	-	12	3	50	12	9	10	-	14	0	0	14	0	50	-	14	0	50	14	11	50
[1][5][6]	15	4	20	16	12	20	20	-	-	-	-	-	-	-	15	4	20	16	0	30	-	16	0	30	16	1	20	-	16	1	20	16	12	20
[1][5][7]	17	4	20	18	12	20	20	-	-	-	-	-	-	-	17	4	20	18	0	30	-	18	0	30	18	1	20	-	18	1	20	18	12	20
[1][5][8]	19	0	0	19	17	10	20	-	-	-	-	-	-	-	19	0	0	19	5	20	-	19	5	20	19	6	10	-	19	6	10	19	17	10
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][1]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][2]	0	6	40	1	14	30	4	-	-	-	-	-	-	-	0	6	40	1	2	20	-	1	2	20	1	3	10	-	1	3	10	1	14	30
[1][6][3]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	-	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][4]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	-	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][5]	2	0	50	2	18	50	4	-	-	-	-	-	-	-	2	0	50	2	6	40	-	2	6	40	2	7	30	-	2	7	30	2	18	50
[1][6][6]	3	4	10	4	12	10	11	-	-	-	-	-	-	-	3	4	10	3	10	0	-	4	0	0	4	0	50	-	4	0	50	4	12	10
[1][6][7]	3	4	50	4	12	40	11	-	-	-	-	-	-	-	3	4	50	4	0	30	-	4	0	30	4	1	20	-	4	1	20	4	12	40
[1][6][8]	3	6	50	4	14	40	11	-	-	-	-	-	-	-	3	6	50	4	2	30	-	4	2	30	4	3	20	-	4	3	20	4	14	40
[1][6][9]	5	2	0	5	20	0	11	-	-	-	-	-	-	-	5	2	0	5	7	50	-	5	7	50	5	8	40	-	5	8	40	5	20	0
[1][6][10]	5	2	40	5	20	40	11	-	-	-	-	-	-	-	5	2	40	5	8	30	-	5	8	30	5	9	20	-	5	9	20	5	20	40
[1][6][11]	5	4	10	7	12	10	11	-	-	-	-	-	-	-	5	4	10	5	10	0	-	7	0	0	7	0	50	-	7	0	50	7	12	10
[1][6][12]	7	3	40	8	12	10	18	-	-	-	-	-	-	-	7	3	40	7	9	30	-	8	0	0	8	0	50	-	8	0	50	8	12	10
[1][6][13]	7	6	50	8	15	10	18	-	-	-	-	-	-	-	7	6	50	8	3	0	-	8	3	0	8	3	50	-	8	3	50	8	15	10
[1][6][14]	8	6	50	9	15	10	18	-	-	-	-	-	-	-	8	6	50	9	3	0	-	9	3	0	9	3	50	-	9	3	50	9	15	10
[1][6][15]	9	3	50	10	12	10	18	-	-	-	-	-	-	-	9	3	50	9	9	40	-	10	0	0	10	0	50	-	10	0	50	10	12	10
[1][6][16]	9	6	50	10	15	10	18	-	-	-	-	-	-	-	9	6	50	10	3	0	-	10	3	0	10	3	50	-	10	3	50	10	15	10
[1][6][17]	10	6	50	11	15	10	18	-	-	-	-	-	-	-	10	6	50	11	3	0	-	11	3	0	11	3	50	-	11	3	50	11	15	10
[1][6][18]	11	3	50	12	12	10	25	-	-	-	-	-	-	-	11	3	50	11	9	40	-	12	0	0	12	0	50	-	12	0	50	12	12	10
[1][6][19]	11	6	50	12	15	10	25	-	-	-	-	-	-	-	11	6	50	12	3	0	-	12	3	0	12	3	50	-	12	3	50	12	15	10
[1][6][20]	12	6	50	14	15	10	25	-	-	-	-	-	-	-	12	6	50	14	3	0	-	14	3	0	14	3	50	-	14	3	50	14	15	10
[1][6][21]	14	3	50	15	12	40	25	-	-	-	-	-	-	-	14	3	50	15	0	30	-	15	0	30	15	1	20	-	15	1	20	15	12	40
[1][6][22]	14	6	50	15	15	40	25	-	-	-	-	-	-	-	14	6	50	15	3	30	-	15	3	30	15	4	20	-	15	4	20	15	15	40
[1][6][23]	15	6	50	16	15	40	25	-	-	-	-	-	-	-	15	6	50	16	3	30	-	16	3	30	16	4	20	-	16	4	20	16	15	40
[1][6][24]	16	4	20	17	13	10	32	-	-	-	-	-	-	-	16	4	20	17	1	0	-	17	1	0	17	1	50	-	17	1	50	17	13	10
[1][6][25]	16	6	50	17	15	40	32	-	-	-	-	-	-	-	16	6	50	17	3	30	-	17	3	30	17	4	20	-	17	4	20	17	15	40
[1][6][26]	17	7	30	18	16	20	32	-	-	-	-	-	-	-	17	7	30	18	4	10	-	18	4	10	18	5	0	-	18	5	0	18	16	20
[1][6][27]	18	1	40	18	19	40	32	-	-	-	-	-	-	-	18	1	40	18	7	30	-	18	7	30	18	8	20	-	18	8	20	18	19	40
[1][6][28]	18	5	0	19	13	50	32	-	-	-	-	-	-	-	18	5	0	19	1	40	-	19	1	40	19	2	30	-	19	2	30	19	13	50
[1][6][29]	19	2	30	19	20	30	32	-	-	-	-	-	-	-	19	2	30	19	8	20	-	19	8	20	19	9	10	-	19	9	10	19	20	30

Note: “NT only” indicates whether only NT can be used for execution of the operation (“Yes”) or not (“No”).

Table C.5: Detailed Production Schedule Obtained from *PC Allocation & Sequencing*

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	0	0	0	0	0	0	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][3]	1	0	0	1	14	50	4	1	0	0	1	0	0	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][4]	1	0	0	1	14	50	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][5]	1	0	0	1	15	40	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][6]	2	0	0	2	14	50	5	2	0	0	2	0	0	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][8]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][9]	3	0	0	3	14	50	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][10]	3	0	0	3	14	50	5	3	0	0	3	0	0	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][11]	3	0	0	3	15	40	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][12]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][13]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][14]	5	0	0	5	15	40	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][15]	5	0	0	5	15	50	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][16]	7	0	0	7	14	50	11	-	-	-	-	-	-	-	7	0	0	7	4	10	-	7	4	10	7	4	50	-	7	4	50	7	14	50
[0][0][17]	7	0	0	7	14	50	11	-	-	-	-	-	-	-	7	0	0	7	4	10	-	7	4	10	7	4	50	-	7	4	50	7	14	50
[0][0][18]	8	0	0	8	14	50	12	-	-	-	-	-	-	-	8	0	0	8	4	10	-	8	4	10	8	4	50	-	8	4	50	8	14	50
[0][0][19]	8	0	0	8	15	50	12	-	-	-	-	-	-	-	8	0	0	8	4	10	-	8	4	10	8	4	50	-	8	4	50	8	14	50
[0][0][20]	9	1	40	9	14	50	12	-	-	-	-	-	-	-	9	1	40	9	5	50	-	9	5	50	9	6	30	-	9	6	30	9	16	30
[0][0][21]	9	3	20	9	17	30	12	-	-	-	-	-	-	-	9	3	20	9	7	30	-	9	7	30	9	8	10	No	9	8	10	9	18	10
[0][0][22]	10	3	10	10	16	0	12	-	-	-	-	-	-	-	10	3	10	10	7	20	-	10	7	20	10	8	0	-	10	8	0	10	18	0
[0][0][23]	10	3	10	10	16	0	12	-	-	-	-	-	-	-	10	3	10	10	7	20	-	10	7	20	10	8	0	-	10	8	0	10	18	0
[0][0][24]	11	3	10	11	15	20	18	-	-	-	-	-	-	-	11	3	10	11	7	20	-	11	7	20	11	8	0	-	11	8	0	11	18	0
[0][0][25]	11	3	10	11	17	40	18	-	-	-	-	-	-	-	11	3	10	11	7	20	-	11	7	20	11	8	0	-	11	8	0	11	18	0
[0][0][26]	12	3	0	14	13	20	18	-	-	-	-	-	-	-	12	3	0	12	7	10	-	12	7	10	12	7	50	-	12	7	50	12	17	50
[0][0][27]	12	3	0	14	13	20	18	-	-	-	-	-	-	-	12	3	0	12	7	10	-	12	7	10	12	7	50	-	12	7	50	12	17	50
[0][0][28]	14	3	0	15	14	50	18	-	-	-	-	-	-	-	14	3	0	14	7	10	-	14	7	10	14	7	50	-	14	7	50	14	17	50
[0][0][29]	14	4	0	15	14	50	18	-	-	-	-	-	-	-	14	4	0	14	8	10	No	14	8	10	14	8	50	No	14	8	50	14	18	50
[0][0][30]	15	0	40	16	15	40	19	-	-	-	-	-	-	-	15	0	40	15	4	50	-	15	4	50	15	5	30	-	15	5	30	15	15	30
[0][0][31]	15	0	40	16	15	40	19	-	-	-	-	-	-	-	15	0	40	15	4	50	-	15	4	50	15	5	30	-	15	5	30	15	15	30
[0][0][32]	16	0	0	17	14	50	19	-	-	-	-	-	-	-	16	0	0	16	4	10	-	16	4	10	16	4	50	-	16	4	50	16	14	50
[0][0][33]	15	4	10	17	16	30	19	15	4	10	15	8	10	No	15	8	10	16	1	10	No	16	1	10	16	1	50	-	16	1	50	16	11	50
[0][0][34]	16	1	50	18	12	50	19	-	-	-	-	-	-	-	16	1	50	16	6	0	-	16	6	0	16	6	40	-	16	6	40	16	16	40
[0][0][35]	17	1	10	18	15	50	19	-	-	-	-	-	-	-	17	1	10	17	5	20	-	17	5	20	17	6	0	-	17	6	0	17	16	0
[0][0][36]	17	4	10	19	14	50	25	-	-	-	-	-	-	-	17	4	10	17	8	20	No	17	8	20	17	9	0	No	17	9	0	17	19	0
[0][0][37]	18	0	0	21	14	50	25	-	-	-	-	-	-	-	18	0	0	18	4	10	-	18	4	10	18	4	50	-	18	4	50	18	14	50
[0][0][38]	18	0	0	21	15	20	25	-	-	-	-	-	-	-	18	0	0	18	4	10	-	18	4	10	18	4	50	-	18	4	50	18	14	50
[0][0][39]	19	0	0	22	14	50	25	-	-	-	-	-	-	-	19	0	0	19	4	10	-	19	4	10	19	4	50	-	19	4	50	19	14	50
[0][0][40]	19	4	10	22	15	40	25	-	-	-	-	-	-	-	19	4	10	19	8	20	No	19	8	20	19	9	0	No	19	9	0	19	19	0
[0][0][41]	21	0	0	23	14	50	25	-	-	-	-	-	-	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][42]	19	0	0	23	15	0	26	19	0	0	19	4	0	-	19	4	0	19	8	10	No	19	8	10	19	8	50	No	19	8	50	19	18	50
[0][0][43]	21	0	0	24	11	40	26	-	-	-	-	-	-	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][44]	21	0	0	24	14	50	26	21	0	0	21	0	0	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][45]	22	0	0	24	14	50	26	-	-	-	-	-	-	-	22	0	0	22	4	10	-	22	4	10	22	4	50	-	22	4	50	22	14	50
[0][0][46]	22	1	0	25	14	50	26	22	1	0	22	1	0	-	22	1	0	22	5	10	-	22	5	10	22	5	50	-	22	5	50	22	15	50
[0][0][47]	22	0	0	25	14	50	26	-	-	-	-	-	-	-	22	0	0	22	4	10	-	22	4	10	22	4	50	-	22	4	50	22	14	50
[0][0][48]	23	0	0	25	14	50	32	-	-	-	-	-	-	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][49]	23	0	0	26	14	50	32	23	0	0	23	0	0	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][50]	23	0	0	26	14	50	32	-	-	-	-	-	-	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][51]	26	0	0	26	14	50	32	-	-	-	-	-	-	-	26	0	0	26	4	10	-	26	4	10	26	4	50	-	26	4	50	26	14	50
[0][1][0]	4	0	0	4	18	50	11	4	0	0	4	4	0	-	4	4	0	4	8	10	No	4	8	10	4	8	50	No	4	8	50	4	18	50
[0][1][1]	12	4	10	15	11	50	18	12	4	10	12	8	10	No	12	8	10	14	3	20	No	14	3	20	14	4	0	-	14	4	0	14	14	0
[0][1][2]	17	1	10	19	15	0	25	17	1	10	17	5	10	-	17	5	10	17	9	20	No	17	9	20	17	10	0	No	17	10	0	17	20	0
[0][1][3]	18	4	10	21	15	50	32	18	4	10	18	4	10	-	18	4	10	18	8	20	No	18	8	20	18	9	0	No	18	9	0	18	19	0
[0][2][0]	5	0	0	5	18	50	6	5	0	0	5	4	0	-	5	4	0	5	8	10	No	5	8	10	5	8	50	No	5	8	50	5	18	50
[0][2][1]	7	4	10	7	19	0	12	7	4	10	7	4	10	-	7	4	10	7	8	20	No	7	8	20	7	9	0	No	7	9	0	7	19	0
[0][2][2]	8	4	50	9	12	40	19	8	4	50	8	4	50	-	8	4	50	9	1	0	Yes	9	1	0	9	1	40	-	9	1	40	9	11	40
[0][2][3]	10	4	10	11	12	50	26	10	4	10	10	4	10	-	10	4	10	10	8	20	No	10	8	20	10	9	0	No	10	9	0	10	19	0
[0][2][4]	11	4	10	12	14	50	32	11	4	10	11	4	10	-	11	4	10	11	8	20	No	11	8	20	11	9	0	No	11	9	0	11	19	0
[0][3][0]	0	4	50	0	18	0	9	-	-	-	-	-	-	-	0	4	50	0	8	30	No	0	8	30	0	9	0	No	0	9	0	0	18	0
[0][3][1]	1	4	10	1	17	20	9	-	-	-	-	-	-	-	1	4	10	1	7	50	-	1	7	50	1	8	20	No	1	8	20	1	17	20
[0][3][2]	2	4	10	2	17	20	9	-	-	-	-	-	-	-	2	4	10	2	7	50	-	2	7	50	2	8	20	No	2	8	20	2	17	20
[0][3][3]	3	4	10	3	17	20	9	-	-	-	-	-	-	-	3	4	10	3	7	50	-	3	7	50	3	8	20	No	3	8	20	3	17	20
[0][3][4]	4	4	10	5	10	0	10	-	-	-	-	-	-	-	4	4	10	4	7	50	-	4	7	50	4	8	20	No	4	8	20	4	17	20
[0][3][5]	5	4	10	8	10	0	10	-	-	-	-	-	-	-	5	4	10	5	7	50	-	5	7	50	5	8	20	No	5	8	20	5	17	20
[0][3][6]	8	0	0	8	17	10	10	8	0	0	8	4	0	-	8	4	0	8	7	40	-	8	7	40	8	8	10	No	8	8	10	8	17	10
[0][3][7]	9	0	0	9	14	10	10	9	0	0	9	0	0	-	9	0	0	9	3	40	-	9	3	40	9	4	10	-	9	4	10	9	13	10
[0][3][8]	10	0	0	10	13	10	16	10	0	0	10	0	0	-	10	0	0	10	3	40	-	10	3	40	10	4	10	-	10	4	10	10	13	10
[0][3][9]	7	4	50	11	9	30	16	-	-	-	-	-	-	-	7	4	50	7	8	30	No	7	8	30	7	9	0	No	7	9	0	7	18	0
[0][3][10]	11	0	0	11	15	20	16	11	0	0	11	0	0	-	11	0	0	11	3	40	-	11	3	40	11	4	10	-	11	4	10	11	13	10
[0][3][11]	12	0	0	12	15	30	16	12	0	0	12	0	0	-	12	0	0	12	3	40	-	12	3	40	12	4	10	-	12	4	10	12	13	10
[0][3][12]	8	8	10	14	10	0	17	-	-	-	-	-	-	-	8	8	10	9	2	50	No	9	2	50	9	3	20	-	9	3	20	9	12	20
[0][3][13]	14	3	0	14	16	30	17	14	3	0	14	3	0	-	14	3	0	14	6	40	-	14	6	40	14	7	10	-	14	7	10	14	16	10
[0][3][14]	15	0	0	15	15	0	17	15	0	0	15	0	0	-	15	0	0	15	3	40	-	15	3	40	15	4	10	-	15	4	10	15	13	10
[0][3][15]	10	8	0	16	11	10	17	-	-	-	-	-	-	-	10	8	0	11	2	40	No	11	2	40	11	3	10	-	11	3	10	11	12	10
[0][3][16]	16	0	0	16	15	20	23	16	0	0	16	0	0	-	16	0	0	16	3	40	-	16	3	40	16	4	10	-	16	4	10	16	13	10
[0][3][17]	17	0	0	17	15	0	23	17	0	0	17	0	0	-	17	0	0	17	3	40	-	17	3	40	17	4	10	-	17	4	10	17	13	10
[0][3][18]	12	7	50	18	10	0	23	-	-	-	-	-	-	-	12	7	50	14	2	30	No	14	2	30	14	3	0	-	14	3	0	14	12	0
[0][3][19]	18	0	0	18	16	0	23	18	0	0	18	0	0	-	18	0	0	18	3	40	-	18	3	40	18	4	10	-	18	4	10	18	13	10
[0][3][20]	19	0	0	19	13	10	24	19	0	0	19	0	0	-	19	0	0	19	3	40	-	19	3	40	19	4	10	-	19	4	10	19	13	10
[0][3][21]	15	5	30	21	9	30	24	-	-	-	-	-	-	-	15	5	30	15	9	10	No	15	9	10	15	9	40	No	15	9	40	15	18	40
[0][3][22]	22	0	0	22	17	10	24	22	0	0	22	4	0	-	22	4	0	22	7	40	-	22	7	40	22	8	10	No	22	8	10	22	17	10
[0][3][23]	16	4	50	23	10	0	24	-	-	-	-	-	-	-	16	4	50	16	8	30	No	16	8	30	16	9	0	No	16	9	0	16	18	0

Note: "NT only" indicates whether only NT can be used for execution of the operation ("Yes") or not ("No").

Table C.5 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	0	0	0	17	10	8	0	0	0	0	4	0	-	0	4	0	0	7	40	-	0	7	40	0	8	10	No	0	8	10	0	17	10
[0][4][1]	0	4	50	0	18	0	8	-	-	-	-	-	-	-	0	4	50	0	8	30	No	0	8	30	0	9	0	No	0	9	0	0	18	0
[0][4][2]	1	0	0	1	13	10	8	1	0	0	1	0	0	-	1	0	0	1	3	40	-	1	3	40	1	4	10	-	1	4	10	1	13	10
[0][4][3]	1	4	50	1	18	0	8	-	-	-	-	-	-	-	1	4	50	1	8	30	No	1	8	30	1	9	0	No	1	9	0	1	18	0
[0][4][4]	2	0	0	2	13	10	11	2	0	0	2	0	0	-	2	0	0	2	3	40	-	2	3	40	2	4	10	-	2	4	10	2	13	10
[0][4][5]	2	4	50	2	18	0	11	-	-	-	-	-	-	-	2	4	50	2	8	30	No	2	8	30	2	9	0	No	2	9	0	2	18	0
[0][4][6]	3	0	0	3	13	10	11	3	0	0	3	0	0	-	3	0	0	3	3	40	-	3	3	40	3	4	10	-	3	4	10	3	13	10
[0][4][7]	3	4	50	3	18	0	11	-	-	-	-	-	-	-	3	4	50	3	8	30	No	3	8	30	3	9	0	No	3	9	0	3	18	0
[0][4][8]	4	0	0	4	13	10	11	4	0	0	4	0	0	-	4	0	0	4	3	40	-	4	3	40	4	4	10	-	4	4	10	4	13	10
[0][4][9]	4	4	50	4	17	20	15	-	-	-	-	-	-	-	4	4	50	4	8	30	No	4	8	30	4	9	0	No	4	9	0	4	18	0
[0][4][10]	5	0	0	5	13	10	15	5	0	0	5	0	0	-	5	0	0	5	3	40	-	5	3	40	5	4	10	-	5	4	10	5	13	10
[0][4][11]	5	4	50	5	17	20	15	-	-	-	-	-	-	-	5	4	50	5	8	30	No	5	8	30	5	9	0	No	5	9	0	5	18	0
[0][4][12]	7	0	0	7	13	10	15	7	0	0	7	0	0	-	7	0	0	7	3	40	-	7	3	40	7	4	10	-	7	4	10	7	13	10
[0][4][13]	7	4	50	7	18	0	18	-	-	-	-	-	-	-	7	4	50	7	8	30	No	7	8	30	7	9	0	No	7	9	0	7	18	0
[0][4][14]	8	4	50	9	10	0	18	-	-	-	-	-	-	-	8	4	50	8	8	30	No	8	8	30	8	9	0	No	8	9	0	8	18	0
[0][4][15]	9	4	10	11	11	10	18	-	-	-	-	-	-	-	9	4	10	9	7	50	-	9	7	50	9	8	20	No	9	8	20	9	17	20
[0][4][16]	10	8	0	12	15	30	18	-	-	-	-	-	-	-	10	8	0	11	2	40	No	11	2	40	11	3	10	-	11	3	10	11	12	10
[0][4][17]	12	7	50	14	16	30	18	-	-	-	-	-	-	-	12	7	50	14	2	30	No	14	2	30	14	3	0	-	14	3	0	14	12	0
[0][4][18]	15	5	30	17	10	50	22	-	-	-	-	-	-	-	15	5	30	15	9	10	No	15	9	10	15	9	40	No	15	9	40	15	18	40
[0][4][19]	16	4	10	18	13	10	22	-	-	-	-	-	-	-	16	4	10	16	7	50	-	16	7	50	16	8	20	No	16	8	20	16	17	20
[0][4][20]	17	6	0	21	10	0	22	-	-	-	-	-	-	-	17	6	0	17	9	40	No	17	9	40	17	10	10	No	17	10	10	17	19	10
[0][4][21]	21	0	0	21	17	10	22	21	0	0	21	4	0	-	21	4	0	21	7	40	-	21	7	40	21	8	10	No	21	8	10	21	17	10
[0][4][22]	18	4	50	22	13	10	25	-	-	-	-	-	-	-	18	4	50	18	8	30	No	18	8	30	18	9	0	No	18	9	0	18	18	0
[0][4][23]	19	4	50	23	14	10	25	-	-	-	-	-	-	-	19	4	50	19	8	30	No	19	8	30	19	9	0	No	19	9	0	19	18	0
[0][4][24]	23	0	0	23	17	10	25	23	0	0	23	4	0	-	23	4	0	23	7	40	-	23	7	40	23	8	10	No	23	8	10	23	17	10
[0][4][25]	21	4	50	24	14	10	25	-	-	-	-	-	-	-	21	4	50	22	0	30	Yes	22	0	30	22	1	0	-	22	1	0	22	10	0
[0][4][26]	24	0	0	24	14	50	25	24	0	0	24	0	0	-	24	0	0	24	3	40	-	24	3	40	24	4	10	-	24	4	10	24	13	10
[0][5][0]	0	4	50	1	11	50	5	-	-	-	-	-	-	-	0	4	50	0	8	10	No	0	8	10	0	8	50	No	0	8	50	0	19	50
[0][5][1]	1	4	50	3	11	50	5	-	-	-	-	-	-	-	1	4	50	1	8	10	No	1	8	10	1	8	50	No	1	8	50	1	19	50
[0][5][2]	2	4	50	5	11	50	11	-	-	-	-	-	-	-	2	4	50	2	8	10	No	2	8	10	2	8	50	No	2	8	50	2	19	50
[0][5][3]	3	4	50	10	12	10	11	-	-	-	-	-	-	-	3	4	50	3	8	10	No	3	8	10	3	8	50	No	3	8	50	3	19	50
[0][5][4]	4	4	50	12	13	20	18	-	-	-	-	-	-	-	4	4	50	4	8	10	No	4	8	10	4	8	50	No	4	8	50	4	19	50
[0][5][5]	5	4	50	16	11	50	18	-	-	-	-	-	-	-	5	4	50	5	8	10	No	5	8	10	5	8	50	No	5	8	50	5	19	50
[0][5][6]	9	8	10	22	11	50	25	-	-	-	-	-	-	-	9	8	10	10	2	30	No	10	2	30	10	3	10	-	10	3	10	10	14	10
[0][5][7]	11	8	0	24	12	0	25	-	-	-	-	-	-	-	11	8	0	12	2	20	No	12	2	20	12	3	0	-	12	3	0	12	14	0
[0][5][8]	14	7	50	25	15	0	32	-	-	-	-	-	-	-	14	7	50	14	11	10	No	15	0	0	15	0	40	-	15	0	40	15	11	40
[0][5][9]	16	8	20	26	15	0	32	-	-	-	-	-	-	-	16	8	20	17	0	30	No	17	0	30	17	1	10	-	17	1	10	17	12	10
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][2]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	No	1	9	10	1	10	0	No	1	10	0	1	22	0
[1][0][3]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	No	1	9	10	1	10	0	No	1	10	0	1	22	0
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	-	2	0	0	2	6	0	-	2	6	0	2	6	50	-	2	6	50	2	18	50
[1][0][5]	2	0	50	2	19	40	11	2	0	50	2	0	50	-	2	0	50	2	6	50	-	2	6	50	2	7	40	-	2	7	40	2	19	40
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	-	3	0	0	3	6	0	-	3	6	0	3	6	50	-	3	6	50	3	18	50
[1][0][7]	3	2	30	3	21	20	11	3	2	30	3	2	30	-	3	2	30	3	8	30	No	3	8	30	3	9	20	No	3	9	20	3	21	20
[1][0][8]	4	7	30	5	16	10	11	4	7	30	4	7	30	-	4	7	30	5	3	20	No	5	3	20	5	4	10	-	5	4	10	5	16	10
[1][0][9]	7	0	50	7	19	40	11	7	0	50	7	0	50	-	7	0	50	7	6	50	-	7	6	50	7	7	40	-	7	7	40	7	19	40
[1][0][10]	8	0	50	8	19	40	25	8	0	50	8	0	50	-	8	0	50	8	6	50	-	8	6	50	8	7	40	-	8	7	40	8	19	40
[1][0][11]	9	0	50	9	19	40	25	9	0	50	9	0	50	-	9	0	50	9	6	50	-	9	6	50	9	7	40	-	9	7	40	9	19	40
[1][0][12]	10	0	50	10	19	40	25	10	0	50	10	0	50	-	10	0	50	10	6	50	-	10	6	50	10	7	40	-	10	7	40	10	19	40
[1][0][13]	21	6	40	22	19	30	25	21	6	40	22	0	40	Yes	22	0	40	22	6	40	-	22	6	40	22	7	30	-	22	7	30	22	19	30
[1][0][14]	22	0	0	22	20	50	25	22	0	0	22	2	0	-	22	2	0	22	8	0	-	22	8	0	22	8	50	No	22	8	50	22	20	50
[1][0][15]	23	0	0	23	18	50	32	23	0	0	23	0	0	-	23	0	0	23	6	0	-	23	6	0	23	6	50	-	23	6	50	23	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	-	23	0	0	23	6	0	-	23	6	0	23	6	50	-	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	-	24	0	0	24	6	0	-	24	6	0	24	6	50	-	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	-	25	0	0	25	6	0	-	25	6	0	25	6	50	-	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	-	26	0	0	26	6	0	-	26	6	0	26	6	50	-	26	6	50	26	18	50
[1][1][0]	4	1	20	5	14	0	11	4	1	20	4	5	20	-	4	5	20	5	1	10	No	5	1	10	5	2	0	-	5	2	0	5	14	0
[1][1][1]	7	0	0	7	18	50	11	7	0	0	7	0	0	-	7	0	0	7	6	0	-	7	6	0	7	6	50	-	7	6	50	7	18	50
[1][1][2]	8	0	0	8	18	50	11	8	0	0	8	0	0	-	8	0	0	8	6	0	-	8	6	0	8	6	50	-	8	6	50	8	18	50
[1][1][3]	9	0	0	9	18	50	11	9	0	0	9	0	0	-	9	0	0	9	6	0	-	9	6	0	9	6	50	-	9	6	50	9	18	50
[1][1][4]	10	0	0	10	18	50	11	10	0	0	10	0	0	-	10	0	0	10	6	0	-	10	6	0	10	6	50	-	10	6	50	10	18	50
[1][1][5]	11	0	50	11	19	40	18	11	0	50	11	0	50	-	11	0	50	11	6	50	-	11	6	50	11	7	40	-	11	7	40	11	19	40
[1][1][6]	12	0	50	12	19	40	18	12	0	50	12	0	50	-	12	0	50	12	6	50	-	12	6	50	12	7	40	-	12	7	40	12	19	40
[1][1][7]	14	1	0	14	19	50	18	14	1	0	14	1	0	-	14	1	0	14	7	0	-	14	7	0	14	7	50	-	14	7	50	14	19	50
[1][1][8]	15	1	20	15	20	10	18	15	1	20	15	1	20	-	15	1	20	15	7	20	-	15	7	20	15	8	10	No	15	8	10	15	20	10
[1][1][9]	16	1	20	16	20	10	18	16	1	20	16	1	20	-	16	1	20	16	7	20	-	16	7	20	16	8	10	No	16	8	10	16	20	10
[1][1][10]	17	1	50	17	20	40	32	17	1	50	17	1	50	-	17	1	50	17	7	50	-	17	7	50	17	8	40	No	17	8	40	17	20	40
[1][1][11]	25	0	0	25	20	50	32	25	0	0	25	2	0	-	25	2	0	25	8	0	-	25	8	0	25	8	50	No	25	8	50	25	20	50
[1][1][12]	26	0	0	26	18	50	32	26	0	0	26	0	0	-	26	0	0	26	6	0	-	26	6	0	26	6	50	-	26	6	50	26	18	50
[1][2][0]	11	0	0	11	20	50	18	11	0	0	11	2	0	-	11	2	0	11	8	0	-	11	8	0	11	8	50	No	11	8	50	11	20	50
[1][2][1]	12	0	0	12	18	50	18	12	0	0	12	0	0	-	12	0	0	12	6	0	-	12	6	0	12	6	50	-	12	6	50	12	18	50
[1][2][2]	14	0	0	14	18	50	18	14	0	0	14	0	0	-	14	0	0	14	6	0	-	14	6	0	14	6	50	-	14	6	50	14	18	50
[1][2][3]	15	0	0	15	18	50	18	15	0	0	15	0	0	-	15	0	0	15	6	0	-	15	6	0	15	6	50	-	15	6	50	15	18	50
[1][2][4]	16	0	0	16	18	50	18	16	0	0	16	0	0	-	16	0	0	16	6	0	-	16	6	0	16	6	50	-	16	6	50	16	18	50
[1][2][5]	17	0	0	17	18	50	25	17	0	0	17	0	0	-	17	0	0	17	6	0	-	17	6	0	17	6	50	-	17	6	50	17	18	50
[1][2][6]	18	1	20	18	20	10	25	18	1	20	18	1	20	-	18	1	20	18	7	20	-	18	7	20	18	8	10	No	18	8	10	18	20	10
[1][2][7]	18	0	0	19	12	50	25	18	0	0	18	2	0	-	18	2	0	18	8	0	-	19	0	0	19	0	50	-	19	0	50	19	12	50
[1][2][8]	19	1	50	19	20	40	25	19	1	50	19	1	50	-	19	1	50	19	7	50	-	19	7	50	19	8	40	No	19	8	40	19	20	40
[1][2][9]	21	0	0	21	18	50	25	21	0	0	21	0	0	-	21	0	0	21	6	0	-	21	6	0	21	6	50	-	21	6	50	21	18	50
[1][2][10]	24	0	0	24	20	50	39	24	0	0	24	2	0	-	24	2	0	24	8	0	-	24	8	0	24	8	50	No	24	8	50	24	20	50
[1][3][0]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	No	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][1]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	No	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][2]	2	6	50	3	16	10	25	-	-	-	-	-	-	-	2	6	50	3	3	10	No	3	3	10	3	4	10	-	3	4	10	3	16	10
[1][3][3]	2	7	30	3	16	50	25	-	-	-	-	-	-	-	2	7	30	3	3	50	No	3	3	50	3	4	50	-	3	4	50	3	16	50

Note: "NT only" indicates whether only NT can be used for execution of the operation ("Yes") or not ("No").

Table C.5 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[1][3][4]	4	3	20	5	13	0	25	-	-	-	-	-	-	-	4	3	20	4	9	50	No	5	0	0	5	1	0	-	5	1	0	5	13	0
[1][3][5]	4	5	20	5	14	40	25	-	-	-	-	-	-	-	4	5	20	5	1	40	No	5	1	40	5	2	40	-	5	2	40	5	14	40
[1][3][6]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][7]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][8]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][9]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][10]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][11]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][12]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	-	11	0	0	11	6	30	-	11	6	30	11	7	30	-	11	7	30	11	19	30
[1][3][15]	11	0	0	11	19	30	25	-	-	-	-	-	-	-	11	0	0	11	6	30	-	11	6	30	11	7	30	-	11	7	30	11	19	30
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][17]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][21]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][23]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][25]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][4][0]	0	6	40	1	14	30	6	-	-	-	-	-	-	-	0	6	40	1	2	10	No	1	2	10	1	3	10	-	1	3	10	1	14	30
[1][4][1]	2	6	0	3	13	50	6	-	-	-	-	-	-	-	2	6	0	3	1	30	No	3	1	30	3	2	30	-	3	2	30	3	13	50
[1][4][2]	4	0	50	4	18	50	6	-	-	-	-	-	-	-	4	0	50	4	6	30	-	4	6	30	4	7	30	-	4	7	30	4	18	50
[1][4][3]	5	1	0	5	19	0	6	-	-	-	-	-	-	-	5	1	0	5	6	40	-	5	6	40	5	7	40	-	5	7	40	5	19	0
[1][5][0]	1	10	0	2	17	0	20	-	-	-	-	-	-	-	1	10	0	2	5	10	No	2	5	10	2	6	0	-	2	6	0	2	17	0
[1][5][1]	3	9	20	4	16	20	20	-	-	-	-	-	-	-	3	9	20	4	4	30	No	4	4	30	4	5	20	-	4	5	20	4	16	20
[1][5][2]	5	7	40	7	14	40	20	-	-	-	-	-	-	-	5	7	40	7	2	50	No	7	2	50	7	3	40	-	7	3	40	7	14	40
[1][5][3]	8	3	50	9	11	50	20	-	-	-	-	-	-	-	8	3	50	8	9	10	No	9	0	0	9	0	50	-	9	0	50	9	11	50
[1][5][4]	10	3	50	11	11	50	20	-	-	-	-	-	-	-	10	3	50	10	9	10	No	11	0	0	11	0	50	-	11	0	50	11	11	50
[1][5][5]	12	4	30	14	12	0	20	-	-	-	-	-	-	-	12	4	30	14	0	10	No	14	0	10	14	1	0	-	14	1	0	14	12	0
[1][5][6]	15	4	20	16	12	20	20	-	-	-	-	-	-	-	15	4	20	16	0	30	No	16	0	30	16	1	20	-	16	1	20	16	12	20
[1][5][7]	17	4	20	18	12	20	20	-	-	-	-	-	-	-	17	4	20	18	0	30	No	18	0	30	18	1	20	-	18	1	20	18	12	20
[1][5][8]	19	0	50	19	18	0	20	-	-	-	-	-	-	-	19	0	50	19	6	10	-	19	6	10	19	7	0	-	19	7	0	19	18	0
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][1]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][2]	0	6	40	1	14	30	4	-	-	-	-	-	-	-	0	6	40	1	2	20	No	1	2	20	1	3	10	-	1	3	10	1	14	30
[1][6][3]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	No	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][4]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	No	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][5]	2	0	50	2	18	50	4	-	-	-	-	-	-	-	2	0	50	2	6	40	-	2	6	40	2	7	30	-	2	7	30	2	18	50
[1][6][6]	3	4	10	4	12	10	11	-	-	-	-	-	-	-	3	4	10	3	10	0	No	4	0	0	4	0	50	-	4	0	50	4	12	10
[1][6][7]	3	4	50	4	12	40	11	-	-	-	-	-	-	-	3	4	50	4	0	30	No	4	0	30	4	1	20	-	4	1	20	4	12	40
[1][6][8]	3	6	50	4	14	40	11	-	-	-	-	-	-	-	3	6	50	4	2	30	No	4	2	30	4	3	20	-	4	3	20	4	14	40
[1][6][9]	5	2	0	5	20	0	11	-	-	-	-	-	-	-	5	2	0	5	7	50	-	5	7	50	5	8	40	No	5	8	40	5	20	0
[1][6][10]	5	2	40	5	20	40	11	-	-	-	-	-	-	-	5	2	40	5	8	30	No	5	8	30	5	9	20	No	5	9	20	5	20	40
[1][6][11]	5	4	10	7	12	10	11	-	-	-	-	-	-	-	5	4	10	5	10	0	No	7	0	0	7	0	50	-	7	0	50	7	12	10
[1][6][12]	7	3	40	8	12	10	18	-	-	-	-	-	-	-	7	3	40	7	9	30	No	8	0	0	8	0	50	-	8	0	50	8	12	10
[1][6][13]	7	6	50	8	15	10	18	-	-	-	-	-	-	-	7	6	50	8	3	0	No	8	3	0	8	3	50	-	8	3	50	8	15	10
[1][6][14]	8	6	50	9	15	10	18	-	-	-	-	-	-	-	8	6	50	9	3	0	No	9	3	0	9	3	50	-	9	3	50	9	15	10
[1][6][15]	9	3	50	10	12	10	18	-	-	-	-	-	-	-	9	3	50	9	9	40	No	10	0	0	10	0	50	-	10	0	50	10	12	10
[1][6][16]	9	6	50	10	15	10	18	-	-	-	-	-	-	-	9	6	50	10	3	0	No	10	3	0	10	3	50	-	10	3	50	10	15	10
[1][6][17]	10	6	50	11	15	10	18	-	-	-	-	-	-	-	10	6	50	11	3	0	No	11	3	0	11	3	50	-	11	3	50	11	15	10
[1][6][18]	11	3	50	12	12	10	25	-	-	-	-	-	-	-	11	3	50	11	9	40	No	12	0	0	12	0	50	-	12	0	50	12	12	10
[1][6][19]	11	7	30	12	15	50	25	-	-	-	-	-	-	-	11	7	30	12	3	40	No	12	3	40	12	4	30	-	12	4	30	12	15	50
[1][6][20]	12	6	50	14	15	10	25	-	-	-	-	-	-	-	12	6	50	14	3	0	No	14	3	0	14	3	50	-	14	3	50	14	15	10
[1][6][21]	14	3	50	15	12	40	25	-	-	-	-	-	-	-	14	3	50	15	0	30	No	15	0	30	15	1	20	-	15	1	20	15	12	40
[1][6][22]	14	6	50	15	15	40	25	-	-	-	-	-	-	-	14	6	50	15	3	30	No	15	3	30	15	4	20	-	15	4	20	15	15	40
[1][6][23]	15	6	50	16	15	40	25	-	-	-	-	-	-	-	15	6	50	16	3	30	No	16	3	30	16	4	20	-	16	4	20	16	15	40
[1][6][24]	16	4	20	17	13	10	32	-	-	-	-	-	-	-	16	4	20	17	1	0	No	17	1	0	17	1	50	-	17	1	50	17	13	10
[1][6][25]	16	6	50	17	15	40	32	-	-	-	-	-	-	-	16	6	50	17	3	30	No	17	3	30	17	4	20	-	17	4	20	17	15	40
[1][6][26]	17	6	50	18	15	40	32	-	-	-	-	-	-	-	17	6	50	18	3	30	No	18	3	30	18	4	20	-	18	4	20	18	15	40
[1][6][27]	18	4	20	19	13	10	32	-	-	-	-	-	-	-	18	4	20	19	1	0	No	19	1	0	19	1	50	-	19	1	50	19	13	10
[1][6][28]	19	0	0	19	18	0	32	-	-	-	-	-	-	-	19	0	0	19	5	50	-	19	5	50	19	6	40	-	19	6	40	19	18	0
[1][6][29]	21	0	0	21	18	0	32	-	-	-	-	-	-	-	21	0	0	21	5	50	-	21	5	50	21	6	40	-	21	6	40	21	18	0

Note: “NT only” indicates whether only NT can be used for execution of the operation (“Yes”) or not (“No”).

Table C.6: Detailed Production Schedule Obtained from *Labour Transferring*

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][0][0]	0	0	0	0	14	50	4	0	0	0	0	0	0	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][1]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][2]	0	0	0	0	14	50	4	-	-	-	-	-	-	-	0	0	0	0	4	10	-	0	4	10	0	4	50	-	0	4	50	0	14	50
[0][0][3]	1	0	0	1	14	50	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][4]	1	0	0	1	15	40	4	1	0	0	1	0	0	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][5]	1	0	0	1	15	50	4	-	-	-	-	-	-	-	1	0	0	1	4	10	-	1	4	10	1	4	50	-	1	4	50	1	14	50
[0][0][6]	2	0	0	2	14	50	5	2	0	0	2	0	0	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][7]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][8]	2	0	0	2	14	50	5	-	-	-	-	-	-	-	2	0	0	2	4	10	-	2	4	10	2	4	50	-	2	4	50	2	14	50
[0][0][9]	3	0	0	3	14	50	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][10]	3	0	0	3	15	40	5	-	-	-	-	-	-	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][11]	3	0	0	3	15	50	5	3	0	0	3	0	0	-	3	0	0	3	4	10	-	3	4	10	3	4	50	-	3	4	50	3	14	50
[0][0][12]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][13]	4	0	0	4	14	50	11	-	-	-	-	-	-	-	4	0	0	4	4	10	-	4	4	10	4	4	50	-	4	4	50	4	14	50
[0][0][14]	5	0	0	5	15	40	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][15]	5	0	0	5	15	50	11	-	-	-	-	-	-	-	5	0	0	5	4	10	-	5	4	10	5	4	50	-	5	4	50	5	14	50
[0][0][16]	7	0	0	7	14	50	11	-	-	-	-	-	-	-	7	0	0	7	4	10	-	7	4	10	7	4	50	-	7	4	50	7	14	50
[0][0][17]	7	4	10	7	19	0	11	-	-	-	-	-	-	-	7	4	10	7	8	20	No	7	8	20	7	9	0	No	7	9	0	7	19	0
[0][0][18]	8	0	0	8	14	50	12	-	-	-	-	-	-	-	8	0	0	8	4	10	-	8	4	10	8	4	50	-	8	4	50	8	14	50
[0][0][19]	8	0	0	8	15	50	12	-	-	-	-	-	-	-	8	0	0	8	4	10	-	8	4	10	8	4	50	-	8	4	50	8	14	50
[0][0][20]	9	0	0	9	14	50	12	-	-	-	-	-	-	-	9	0	0	9	4	10	-	9	4	10	9	4	50	-	9	4	50	9	14	50
[0][0][21]	9	1	40	9	17	30	12	-	-	-	-	-	-	-	9	1	40	9	5	50	-	9	5	50	9	6	30	-	9	6	30	9	16	30
[0][0][22]	10	2	30	10	16	0	12	-	-	-	-	-	-	-	10	2	30	10	6	40	-	10	6	40	10	7	20	-	10	7	20	10	17	20
[0][0][23]	10	2	30	10	16	0	12	-	-	-	-	-	-	-	10	2	30	10	6	40	-	10	6	40	10	7	20	-	10	7	20	10	17	20
[0][0][24]	11	2	30	11	15	20	18	-	-	-	-	-	-	-	11	2	30	11	6	40	-	11	6	40	11	7	20	-	11	7	20	11	17	20
[0][0][25]	11	2	30	11	17	40	18	-	-	-	-	-	-	-	11	2	30	11	6	40	-	11	6	40	11	7	20	-	11	7	20	11	17	20
[0][0][26]	12	2	20	14	13	20	18	-	-	-	-	-	-	-	12	2	20	12	6	30	-	12	6	30	12	7	10	-	12	7	10	12	17	10
[0][0][27]	12	2	20	14	14	0	18	-	-	-	-	-	-	-	12	2	20	12	6	30	-	12	6	30	12	7	10	-	12	7	10	12	17	10
[0][0][28]	14	2	20	15	14	50	18	-	-	-	-	-	-	-	14	2	20	14	6	30	-	14	6	30	14	7	10	-	14	7	10	14	17	10
[0][0][29]	14	2	20	15	15	20	18	-	-	-	-	-	-	-	14	2	20	14	6	30	-	14	6	30	14	7	10	-	14	7	10	14	17	10
[0][0][30]	15	0	0	16	15	50	19	-	-	-	-	-	-	-	15	0	0	15	4	10	-	15	4	10	15	4	50	-	15	4	50	15	14	50
[0][0][31]	15	0	40	17	12	30	19	-	-	-	-	-	-	-	15	0	40	15	4	50	-	15	4	50	15	5	30	-	15	5	30	15	15	30
[0][0][32]	15	4	50	17	16	30	19	15	4	50	15	8	50	No	15	8	50	16	1	50	No	16	1	50	16	2	30	-	16	2	30	16	12	30
[0][0][33]	16	0	0	17	17	20	19	-	-	-	-	-	-	-	16	0	0	16	4	10	-	16	4	10	16	4	50	-	16	4	50	16	14	50
[0][0][34]	16	0	0	18	14	50	19	-	-	-	-	-	-	-	16	0	0	16	4	10	-	16	4	10	16	4	50	-	16	4	50	16	14	50
[0][0][35]	17	0	0	18	17	30	19	-	-	-	-	-	-	-	17	0	0	17	4	10	-	17	4	10	17	4	50	-	17	4	50	17	14	50
[0][0][36]	17	0	0	19	14	50	25	-	-	-	-	-	-	-	17	0	0	17	4	10	-	17	4	10	17	4	50	-	17	4	50	17	14	50
[0][0][37]	18	0	0	21	11	40	25	-	-	-	-	-	-	-	18	0	0	18	4	10	-	18	4	10	18	4	50	-	18	4	50	18	14	50
[0][0][38]	18	0	0	21	14	50	25	-	-	-	-	-	-	-	18	0	0	18	4	10	-	18	4	10	18	4	50	-	18	4	50	18	14	50
[0][0][39]	19	0	0	22	14	50	25	-	-	-	-	-	-	-	19	0	0	19	4	10	-	19	4	10	19	4	50	-	19	4	50	19	14	50
[0][0][40]	19	0	0	22	14	50	25	-	-	-	-	-	-	-	19	0	0	19	4	10	-	19	4	10	19	4	50	-	19	4	50	19	14	50
[0][0][41]	21	0	0	23	14	50	25	-	-	-	-	-	-	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][42]	19	0	0	23	15	40	26	19	0	0	19	4	0	-	19	4	0	19	8	10	No	19	8	10	19	8	50	No	19	8	50	19	18	50
[0][0][43]	21	0	0	24	11	40	26	-	-	-	-	-	-	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][44]	21	0	0	24	14	50	26	21	0	0	21	0	0	-	21	0	0	21	4	10	-	21	4	10	21	4	50	-	21	4	50	21	14	50
[0][0][45]	22	0	0	24	14	50	26	-	-	-	-	-	-	-	22	0	0	22	4	10	-	22	4	10	22	4	50	-	22	4	50	22	14	50
[0][0][46]	22	0	0	25	14	50	26	22	0	0	22	0	0	-	22	0	0	22	4	10	-	22	4	10	22	4	50	-	22	4	50	22	14	50
[0][0][47]	22	0	0	25	14	50	26	-	-	-	-	-	-	-	22	0	0	22	4	10	-	22	4	10	22	4	50	-	22	4	50	22	14	50
[0][0][48]	23	0	0	25	14	50	32	-	-	-	-	-	-	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][49]	23	0	0	26	14	50	32	23	0	0	23	0	0	-	23	0	0	23	4	10	-	23	4	10	23	4	50	-	23	4	50	23	14	50
[0][0][50]	23	1	0	26	14	50	32	-	-	-	-	-	-	-	23	1	0	23	5	10	-	23	5	10	23	5	50	-	23	5	50	23	15	50
[0][0][51]	26	0	0	26	14	50	32	-	-	-	-	-	-	-	26	0	0	26	4	10	-	26	4	10	26	4	50	-	26	4	50	26	14	50
[0][1][0]	4	0	0	4	18	50	11	4	0	0	4	4	0	-	4	4	0	4	8	10	No	4	8	10	4	8	50	No	4	8	50	4	18	50
[0][1][1]	12	4	10	15	11	20	18	12	4	10	12	8	10	No	12	8	10	14	3	20	No	14	3	20	14	4	0	-	14	4	0	14	14	0
[0][1][2]	17	0	0	19	15	40	25	17	0	0	17	4	0	-	17	4	0	17	8	10	No	17	8	10	17	8	50	No	17	8	50	17	18	50
[0][1][3]	18	0	0	21	16	30	32	18	0	0	18	0	0	-	18	0	0	18	4	10	-	18	4	10	18	4	50	-	18	4	50	18	14	50
[0][2][0]	5	0	0	5	18	50	6	5	0	0	5	4	0	-	5	4	0	5	8	10	No	5	8	10	5	8	50	No	5	8	50	5	18	50
[0][2][1]	7	4	10	7	19	0	12	7	4	10	7	4	10	-	7	4	10	7	8	20	No	7	8	20	7	9	0	No	7	9	0	7	19	0
[0][2][2]	8	4	50	9	12	40	19	8	4	50	8	4	50	-	8	4	50	9	1	0	Yes	9	1	0	9	1	40	-	9	1	40	9	11	40
[0][2][3]	10	4	10	11	12	50	26	10	4	10	10	4	10	-	10	4	10	10	8	20	No	10	8	20	10	9	0	No	10	9	0	10	19	0
[0][2][4]	11	4	10	12	17	10	32	11	4	10	11	4	10	-	11	4	10	11	8	20	No	11	8	20	11	9	0	No	11	9	0	11	19	0
[0][3][0]	0	4	50	0	18	0	9	-	-	-	-	-	-	-	0	4	50	0	8	30	No	0	8	30	0	9	0	No	0	9	0	0	18	0
[0][3][1]	1	0	0	1	13	10	9	-	-	-	-	-	-	-	1	0	0	1	3	40	-	1	3	40	1	4	10	-	1	4	10	1	13	10
[0][3][2]	2	0	0	3	10	0	9	-	-	-	-	-	-	-	2	0	0	2	3	40	-	2	3	40	2	4	10	-	2	4	10	2	13	10
[0][3][3]	3	4	50	5	10	0	9	-	-	-	-	-	-	-	3	4	50	3	8	30	No	3	8	30	3	9	0	No	3	9	0	3	18	0
[0][3][4]	4	4	50	7	13	10	10	-	-	-	-	-	-	-	4	4	50	4	8	30	No	4	8	30	4	9	0	No	4	9	0	4	18	0
[0][3][5]	8	0	0	8	17	10	10	8	0	0	8	4	0	-	8	4	0	8	7	40	-	8	7	40	8	8	10	No	8	8	10	8	17	10
[0][3][6]	5	4	50	9	10	0	10	-	-	-	-	-	-	-	5	4	50	5	8	30	No	5	8	30	5	9	0	No	5	9	0	5	18	0
[0][3][7]	9	3	20	9	14	10	10	9	3	20	9	3	20	-	9	3	20	9	7	0	-	9	7	0	9	7	30	-	9	7	30	9	16	30
[0][3][8]	10	0	0	10	13	10	16	10	0	0	10	0	0	-	10	0	0	10	3	40	-	10	3	40	10	4	10	-	10	4	10	10	13	10
[0][3][9]	7	4	50	11	11	10	16	-	-	-	-	-	-	-	7	4	50	7	8	30	No	7	8	30	7	9	0	No	7	9	0	7	18	0
[0][3][10]	11	0	0	11	15	20	16	11	0	0	11	0	0	-	11	0	0	11	3	40	-	11	3	40	11	4	10	-	11	4	10	11	13	10
[0][3][11]	12	0	0	12	15	30	16	12	0	0	12	0	0	-	12	0	0	12	3	40	-	12	3	40	12	4	10	-	12	4	10	12	13	10
[0][3][12]	8	4	50	14	9	30	17	-	-	-	-	-	-	-	8	4	50	8	8	30	No	8	8	30	8	9	0	No	8	9	0	8	18	0
[0][3][13]	14	4	0	14	16	30	17	14	4	0	14	4	0	-	14	4	0	14	7	40	-	14	7	40	14	8	10	No	14	8	10	14	17	10
[0][3][14]	15	0	40	15	14	30	17	15	0	40	15	0	40	-	15	0	40	15	4	20	-	15	4	20	15	4	50	-	15	4	50	15	13	50
[0][3][15]	9	4	50	16	10	0	17	-	-	-	-	-	-	-	9	4	50	9	8	30	No	9	8	30	9	9	0	No	9	9	0	9	18	0
[0][3][16]	16	2	30	16	14	40	23	16	2	30	16	2	30	-	16	2	30	16	6	10	-	16	6	10	16	6	40	-	16	6	40	16	15	40
[0][3][17]	17	4	50	17	17	20	23	17	4	50	17	4	50	-	17	4	50	17	8	30	No	17	8	30	17	9	0	No	17	9	0	17	18	0
[0][3][18]	10	7	20	18	11	40	23	-	-	-	-	-	-	-	10	7	20	11	2	0	No	11	2	0	11	2	30	-	11	2	30	11	11	30
[0][3][19]	18	4	50	18	17	20	23	18	4	50	18	4	50	-	18	4	50	18	8	30	No	18	8	30	18	9	0	No	18	9	0	18	18	0
[0][3][20]	19	4	50	19	17	20	24	19	4	50	19	4	50	-	19	4	50	19	8	30	No	19	8	30	19	9	0	No	19	9	0	19	18	0
[0][3][21]	12	7	10	21	10	50	24	-	-	-	-	-	-	-	12	7	10	14	1	50	No	14	1	50	14	2	20	-	14	2	20	14	11	20
[0][3][22]	22	0	0	22	17	10	24	22	0	0	22	4	0	-	22	4	0	22	7	40	-	22	7	40	22	8	10	No	22	8	10	22	17	10
[0][3][23]	15	4	50	23	10	0	24	-	-	-	-	-	-	-	15	4	50	15	8	30	No	15	8	30	15	9	0	No	15	9	0	15	18	0

Note: "NT only" indicates whether only NT can be used for execution of the operation ("Yes") or not ("No").

Table C.6 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[0][4][0]	0	0	0	0	17	10	8	0	0	0	0	4	0	-	0	4	0	0	7	40	-	0	7	40	0	8	10	No	0	8	10	0	17	10
[0][4][1]	0	4	50	1	10	0	8	-	-	-	-	-	-	-	0	4	50	0	8	30	No	0	8	30	0	9	0	No	0	9	0	0	18	0
[0][4][2]	1	4	10	1	17	20	8	1	4	10	1	4	10	-	1	4	10	1	7	50	-	1	7	50	1	8	20	No	1	8	20	1	17	20
[0][4][3]	1	4	50	2	13	10	8	-	-	-	-	-	-	-	1	4	50	1	8	30	No	1	8	30	1	9	0	No	1	9	0	1	18	0
[0][4][4]	2	4	50	2	17	20	11	2	4	50	2	4	50	-	2	4	50	2	8	30	No	2	8	30	2	9	0	No	2	9	0	2	18	0
[0][4][5]	2	4	10	3	13	10	11	-	-	-	-	-	-	-	2	4	10	2	7	50	-	2	7	50	2	8	20	No	2	8	20	2	17	20
[0][4][6]	3	4	10	3	17	20	11	3	4	10	3	4	10	-	3	4	10	3	7	50	-	3	7	50	3	8	20	No	3	8	20	3	17	20
[0][4][7]	3	0	0	4	13	10	11	-	-	-	-	-	-	-	3	0	0	3	3	40	-	3	3	40	3	4	10	-	3	4	10	3	13	10
[0][4][8]	4	4	10	4	17	20	11	4	4	10	4	4	10	-	4	4	10	4	7	50	-	4	7	50	4	8	20	No	4	8	20	4	17	20
[0][4][9]	4	0	0	5	13	10	15	-	-	-	-	-	-	-	4	0	0	4	3	40	-	4	3	40	4	4	10	-	4	4	10	4	13	10
[0][4][10]	5	4	10	5	17	20	15	5	4	10	5	4	10	-	5	4	10	5	7	50	-	5	7	50	5	8	20	No	5	8	20	5	17	20
[0][4][11]	7	0	0	7	13	10	15	7	0	0	7	0	0	-	7	0	0	7	3	40	-	7	3	40	7	4	10	-	7	4	10	7	13	10
[0][4][12]	5	0	0	8	10	0	15	-	-	-	-	-	-	-	5	0	0	5	3	40	-	5	3	40	5	4	10	-	5	4	10	5	13	10
[0][4][13]	7	0	0	11	9	30	18	-	-	-	-	-	-	-	7	0	0	7	3	40	-	7	3	40	7	4	10	-	7	4	10	7	13	10
[0][4][14]	8	8	10	12	13	10	18	-	-	-	-	-	-	-	8	8	10	9	2	50	No	9	2	50	9	3	20	-	9	3	20	9	12	20
[0][4][15]	10	7	20	15	9	30	18	-	-	-	-	-	-	-	10	7	20	11	2	0	No	11	2	0	11	2	30	-	11	2	30	11	11	30
[0][4][16]	12	7	10	16	14	40	18	-	-	-	-	-	-	-	12	7	10	14	1	50	No	14	1	50	14	2	20	-	14	2	20	14	11	20
[0][4][17]	15	5	30	17	13	10	18	-	-	-	-	-	-	-	15	5	30	15	9	10	No	15	9	10	15	9	40	No	15	9	40	15	18	40
[0][4][18]	16	4	50	18	13	10	22	-	-	-	-	-	-	-	16	4	50	16	8	30	No	16	8	30	16	9	0	No	16	9	0	16	18	0
[0][4][19]	17	4	50	19	13	10	22	-	-	-	-	-	-	-	17	4	50	17	8	30	No	17	8	30	17	9	0	No	17	9	0	17	18	0
[0][4][20]	18	4	50	21	15	0	22	-	-	-	-	-	-	-	18	4	50	18	8	30	No	18	8	30	18	9	0	No	18	9	0	18	18	0
[0][4][21]	21	0	0	21	17	10	22	21	0	0	21	4	0	-	21	4	0	21	7	40	-	21	7	40	21	8	10	No	21	8	10	21	17	10
[0][4][22]	19	4	50	22	14	0	25	-	-	-	-	-	-	-	19	4	50	19	8	30	No	19	8	30	19	9	0	No	19	9	0	19	18	0
[0][4][23]	21	4	50	23	14	10	25	-	-	-	-	-	-	-	21	4	50	21	8	30	No	21	8	30	21	9	0	No	21	9	0	21	18	0
[0][4][24]	23	0	0	23	17	10	25	23	0	0	23	4	0	-	23	4	0	23	7	40	-	23	7	40	23	8	10	No	23	8	10	23	17	10
[0][4][25]	22	4	50	24	14	20	25	-	-	-	-	-	-	-	22	4	50	23	0	30	Yes	23	0	30	23	1	0	-	23	1	0	23	10	0
[0][4][26]	24	0	0	24	14	50	25	24	0	0	24	0	0	-	24	0	0	24	3	40	-	24	3	40	24	4	10	-	24	4	10	24	13	10
[0][5][0]	0	4	50	1	11	50	5	-	-	-	-	-	-	-	0	4	50	0	8	10	No	0	8	10	0	8	50	No	0	8	50	0	19	50
[0][5][1]	1	4	50	3	11	50	5	-	-	-	-	-	-	-	1	4	50	1	8	10	No	1	8	10	1	8	50	No	1	8	50	1	19	50
[0][5][2]	2	4	50	5	11	50	11	-	-	-	-	-	-	-	2	4	50	2	8	10	No	2	8	10	2	8	50	No	2	8	50	2	19	50
[0][5][3]	3	4	50	10	12	10	11	-	-	-	-	-	-	-	3	4	50	3	8	10	No	3	8	10	3	8	50	No	3	8	50	3	19	50
[0][5][4]	4	4	50	12	13	20	18	-	-	-	-	-	-	-	4	4	50	4	8	10	No	4	8	10	4	8	50	No	4	8	50	4	19	50
[0][5][5]	5	4	50	16	12	30	18	-	-	-	-	-	-	-	5	4	50	5	8	10	No	5	8	10	5	8	50	No	5	8	50	5	19	50
[0][5][6]	9	7	30	22	11	50	25	-	-	-	-	-	-	-	9	7	30	10	1	50	No	10	1	50	10	2	30	-	10	2	30	10	13	30
[0][5][7]	11	7	20	24	12	10	25	-	-	-	-	-	-	-	11	7	20	12	1	40	No	12	1	40	12	2	20	-	12	2	20	12	13	20
[0][5][8]	14	7	10	25	15	0	32	-	-	-	-	-	-	-	14	7	10	14	10	30	No	15	0	0	15	0	40	-	15	0	40	15	11	40
[0][5][9]	16	6	40	26	15	0	32	-	-	-	-	-	-	-	16	6	40	16	10	0	No	16	10	0	16	10	40	No	16	10	40	16	21	40
[1][0][0]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][1]	0	0	0	0	18	50	4	0	0	0	0	0	0	-	0	0	0	0	6	0	-	0	6	0	0	6	50	-	0	6	50	0	18	50
[1][0][2]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	No	1	9	10	1	10	0	No	1	10	0	1	22	0
[1][0][3]	1	3	10	1	22	0	4	1	3	10	1	3	10	-	1	3	10	1	9	10	No	1	9	10	1	10	0	No	1	10	0	1	22	0
[1][0][4]	2	0	0	2	18	50	4	2	0	0	2	0	0	-	2	0	0	2	6	0	-	2	6	0	2	6	50	-	2	6	50	2	18	50
[1][0][5]	2	0	50	2	19	40	11	2	0	50	2	0	50	-	2	0	50	2	6	50	-	2	6	50	2	7	40	-	2	7	40	2	19	40
[1][0][6]	3	0	0	3	18	50	11	3	0	0	3	0	0	-	3	0	0	3	6	0	-	3	6	0	3	6	50	-	3	6	50	3	18	50
[1][0][7]	3	4	10	4	12	50	11	3	4	10	3	4	10	-	3	4	10	3	10	10	No	4	0	0	4	0	50	-	4	0	50	4	12	50
[1][0][8]	5	1	0	5	19	50	11	5	1	0	5	1	0	-	5	1	0	5	7	0	-	5	7	0	5	7	50	-	5	7	50	5	19	50
[1][0][9]	7	0	50	7	19	40	11	7	0	50	7	0	50	-	7	0	50	7	6	50	-	7	6	50	7	7	40	-	7	7	40	7	19	40
[1][0][10]	8	1	20	8	20	10	25	8	1	20	8	1	20	-	8	1	20	8	7	20	-	8	7	20	8	8	10	No	8	8	10	8	20	10
[1][0][11]	9	0	50	9	19	40	25	9	0	50	9	0	50	-	9	0	50	9	6	50	-	9	6	50	9	7	40	-	9	7	40	9	19	40
[1][0][12]	10	0	50	10	19	40	25	10	0	50	10	0	50	-	10	0	50	10	6	50	-	10	6	50	10	7	40	-	10	7	40	10	19	40
[1][0][13]	21	6	40	22	19	30	25	21	6	40	22	0	40	Yes	22	0	40	22	6	40	-	22	6	40	22	7	30	-	22	7	30	22	19	30
[1][0][14]	22	0	0	22	20	50	25	22	0	0	22	2	0	-	22	2	0	22	8	0	-	22	8	0	22	8	50	No	22	8	50	22	20	50
[1][0][15]	23	0	0	23	18	50	32	23	0	0	23	0	0	-	23	0	0	23	6	0	-	23	6	0	23	6	50	-	23	6	50	23	18	50
[1][0][16]	23	0	0	23	18	50	32	23	0	0	23	0	0	-	23	0	0	23	6	0	-	23	6	0	23	6	50	-	23	6	50	23	18	50
[1][0][17]	24	0	0	24	18	50	32	24	0	0	24	0	0	-	24	0	0	24	6	0	-	24	6	0	24	6	50	-	24	6	50	24	18	50
[1][0][18]	25	0	0	25	18	50	32	25	0	0	25	0	0	-	25	0	0	25	6	0	-	25	6	0	25	6	50	-	25	6	50	25	18	50
[1][0][19]	26	0	0	26	18	50	32	26	0	0	26	0	0	-	26	0	0	26	6	0	-	26	6	0	26	6	50	-	26	6	50	26	18	50
[1][1][0]	4	0	50	5	13	30	11	4	0	50	4	4	50	-	4	4	50	5	0	40	No	5	0	40	5	1	30	-	5	1	30	5	13	30
[1][1][1]	7	0	0	7	18	50	11	7	0	0	7	0	0	-	7	0	0	7	6	0	-	7	6	0	7	6	50	-	7	6	50	7	18	50
[1][1][2]	8	0	0	8	18	50	11	8	0	0	8	0	0	-	8	0	0	8	6	0	-	8	6	0	8	6	50	-	8	6	50	8	18	50
[1][1][3]	9	0	0	9	18	50	11	9	0	0	9	0	0	-	9	0	0	9	6	0	-	9	6	0	9	6	50	-	9	6	50	9	18	50
[1][1][4]	10	0	0	10	18	50	11	10	0	0	10	0	0	-	10	0	0	10	6	0	-	10	6	0	10	6	50	-	10	6	50	10	18	50
[1][1][5]	11	0	0	11	18	50	18	11	0	0	11	0	0	-	11	0	0	11	6	0	-	11	6	0	11	6	50	-	11	6	50	11	18	50
[1][1][6]	12	0	0	12	18	50	18	12	0	0	12	0	0	-	12	0	0	12	6	0	-	12	6	0	12	6	50	-	12	6	50	12	18	50
[1][1][7]	14	0	0	14	18	50	18	14	0	0	14	0	0	-	14	0	0	14	6	0	-	14	6	0	14	6	50	-	14	6	50	14	18	50
[1][1][8]	15	1	20	15	20	10	18	15	1	20	15	1	20	-	15	1	20	15	7	20	-	15	7	20	15	8	10	No	15	8	10	15	20	10
[1][1][9]	16	0	0	16	18	50	18	16	0	0	16	0	0	-	16	0	0	16	6	0	-	16	6	0	16	6	50	-	16	6	50	16	18	50
[1][1][10]	17	4	20	18	15	10	32	17	4	20	17	4	20	-	17	4	20	18	2	20	Yes	18	2	20	18	3	10	-	18	3	10	18	15	10
[1][1][11]	25	0	0	25	20	50	32	25	0	0	25	2	0	-	25	2	0	25	8	0	-	25	8	0	25	8	50	No	25	8	50	25	20	50
[1][1][12]	26	0	0	26	18	50	32	26	0	0	26	0	0	-	26	0	0	26	6	0	-	26	6	0	26	6	50	-	26	6	50	26	18	50
[1][2][0]	11	0	0	11	20	50	18	11	0	0	11	2	0	-	11	2	0	11	8	0	-	11	8	0	11	8	50	No	11	8	50	11	20	50
[1][2][1]	12	0	50	12	19	40	18	12	0	50	12	0	50	-	12	0	50	12	6	50	-	12	6	50	12	7	40	-	12	7	40	12	19	40
[1][2][2]	14	0	50	14	19	40	18	14	0	50	14	0	50	-	14	0	50	14	6	50	-	14	6	50	14	7	40	-	14	7	40	14	19	40
[1][2][3]	15	0	0	15	18	50	18	15	0	0	15	0	0	-	15	0	0	15	6	0	-	15	6	0	15	6	50	-	15	6	50	15	18	50
[1][2][4]	16	1	20	16	20	10	18	16	1	20	16	1	20	-	16	1	20	16	7	20	-	16	7	20	16	8	10	No	16	8	10	16	20	10
[1][2][5]	17	0	0	17	18	50	25	17	0	0	17	0	0	-	17	0	0	17	6	0	-	17	6	0	17	6	50	-	17	6	50	17	18	50
[1][2][6]	18	1	10	18	20	0	25	18	1	10	18	1	10	-	18	1	10	18	7	10	-	18	7	10	18	8	0	-	18	8	0	18	20	0
[1][2][7]	19	1	50	19	20	40	25	19	1	50	19	1	50	-	19	1	50	19	7	50	-	19	7	50	19	8	40	No	19	8	40	19	20	40
[1][2][8]	19	0	0	19	20	50	25	19	0	0	19	2	0	-	19	2	0	19	8	0	-	19	8	0	19	8	50	No	19	8	50	19	20	50
[1][2][9]	21	0	0	21	18	50	25	21	0	0	21	0	0	-	21	0	0	21	6	0	-	21	6	0	21	6	50	-	21	6	50	21	18	50
[1][2][10]	24	0	0	24	20	50	39	24	0	0	24	2	0	-	24	2	0	24	8	0	-	24	8	0	24	8	50	No	24	8	50	24	20	50
[1][3][0]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	No	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][1]	0	6	50	1	16	10	25	-	-	-	-	-	-	-	0	6	50	1	3	10	No	1	3	10	1	4	10	-	1	4	10	1	16	10
[1][3][2]	2	6	50	3	16	10	25	-	-	-	-	-	-	-	2	6	50	3	3	10	No	3	3	10	3	4	10	-	3	4	10	3	16	10
[1][3][3]	2	7	30	3	16	50	25	-	-	-	-	-	-	-	2	7	30	3	3	50	No	3	3	50	3	4	50	-	3	4	50	3	16	50

Note: “NT only” indicates whether only NT can be used for execution of the operation (“Yes”) or not (“No”).

Table C.6 <Continued>

Precast	PC							Operation 0							Operation 1							Operation 2							Operation 3					
	ST			FT			Due date	ST			FT			NT only	ST			FT			NT only	ST			FT			NT only	ST			FT		
	Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min		Day	Hr	Min	Day	Hr	Min
[1][3][4]	4	3	20	5	13	0	25	-	-	-	-	-	-	-	4	3	20	4	9	50	No	5	0	0	5	1	0	-	5	1	0	5	13	0
[1][3][5]	4	5	10	5	14	30	25	-	-	-	-	-	-	-	4	5	10	5	1	30	No	5	1	30	5	2	30	-	5	2	30	5	14	30
[1][3][6]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][7]	7	0	0	7	19	30	25	-	-	-	-	-	-	-	7	0	0	7	6	30	-	7	6	30	7	7	30	-	7	7	30	7	19	30
[1][3][8]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][9]	8	0	0	8	19	30	25	-	-	-	-	-	-	-	8	0	0	8	6	30	-	8	6	30	8	7	30	-	8	7	30	8	19	30
[1][3][10]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][11]	9	0	0	9	19	30	25	-	-	-	-	-	-	-	9	0	0	9	6	30	-	9	6	30	9	7	30	-	9	7	30	9	19	30
[1][3][12]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][13]	10	0	0	10	19	30	25	-	-	-	-	-	-	-	10	0	0	10	6	30	-	10	6	30	10	7	30	-	10	7	30	10	19	30
[1][3][14]	11	0	0	11	19	30	25	-	-	-	-	-	-	-	11	0	0	11	6	30	-	11	6	30	11	7	30	-	11	7	30	11	19	30
[1][3][15]	11	0	50	11	20	20	25	-	-	-	-	-	-	-	11	0	50	11	7	20	-	11	7	20	11	8	20	No	11	8	20	11	20	20
[1][3][16]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][17]	12	0	0	12	19	30	25	-	-	-	-	-	-	-	12	0	0	12	6	30	-	12	6	30	12	7	30	-	12	7	30	12	19	30
[1][3][18]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][19]	14	0	0	14	19	30	25	-	-	-	-	-	-	-	14	0	0	14	6	30	-	14	6	30	14	7	30	-	14	7	30	14	19	30
[1][3][20]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][21]	15	0	0	15	19	30	26	-	-	-	-	-	-	-	15	0	0	15	6	30	-	15	6	30	15	7	30	-	15	7	30	15	19	30
[1][3][22]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][23]	16	0	0	16	19	30	26	-	-	-	-	-	-	-	16	0	0	16	6	30	-	16	6	30	16	7	30	-	16	7	30	16	19	30
[1][3][24]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][25]	17	0	0	17	19	30	26	-	-	-	-	-	-	-	17	0	0	17	6	30	-	17	6	30	17	7	30	-	17	7	30	17	19	30
[1][3][26]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][27]	18	0	0	18	19	30	26	-	-	-	-	-	-	-	18	0	0	18	6	30	-	18	6	30	18	7	30	-	18	7	30	18	19	30
[1][3][28]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][29]	19	0	0	19	19	30	26	-	-	-	-	-	-	-	19	0	0	19	6	30	-	19	6	30	19	7	30	-	19	7	30	19	19	30
[1][3][30]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][31]	21	0	0	21	19	30	26	-	-	-	-	-	-	-	21	0	0	21	6	30	-	21	6	30	21	7	30	-	21	7	30	21	19	30
[1][3][32]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][33]	22	0	0	22	19	30	26	-	-	-	-	-	-	-	22	0	0	22	6	30	-	22	6	30	22	7	30	-	22	7	30	22	19	30
[1][3][34]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][35]	23	0	0	23	19	30	26	-	-	-	-	-	-	-	23	0	0	23	6	30	-	23	6	30	23	7	30	-	23	7	30	23	19	30
[1][3][36]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][37]	24	0	0	24	19	30	26	-	-	-	-	-	-	-	24	0	0	24	6	30	-	24	6	30	24	7	30	-	24	7	30	24	19	30
[1][3][38]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][3][39]	25	0	0	25	19	30	26	-	-	-	-	-	-	-	25	0	0	25	6	30	-	25	6	30	25	7	30	-	25	7	30	25	19	30
[1][4][0]	0	6	40	1	14	30	6	-	-	-	-	-	-	-	0	6	40	1	2	10	No	1	2	10	1	3	10	-	1	3	10	1	14	30
[1][4][1]	2	6	0	3	13	50	6	-	-	-	-	-	-	-	2	6	0	3	1	30	No	3	1	30	3	2	30	-	3	2	30	3	13	50
[1][4][2]	4	1	20	4	19	20	6	-	-	-	-	-	-	-	4	1	20	4	7	0	-	4	7	0	4	8	0	-	4	8	0	4	19	20
[1][4][3]	5	1	30	5	19	30	6	-	-	-	-	-	-	-	5	1	30	5	7	10	-	5	7	10	5	8	10	No	5	8	10	5	19	30
[1][5][0]	1	10	0	2	17	0	20	-	-	-	-	-	-	-	1	10	0	2	5	10	No	2	5	10	2	6	0	-	2	6	0	2	17	0
[1][5][1]	3	9	10	4	16	10	20	-	-	-	-	-	-	-	3	9	10	4	4	20	No	4	4	20	4	5	10	-	4	5	10	4	16	10
[1][5][2]	5	4	30	7	11	50	20	-	-	-	-	-	-	-	5	4	30	5	9	50	No	7	0	0	7	0	50	-	7	0	50	7	11	50
[1][5][3]	8	3	50	9	11	50	20	-	-	-	-	-	-	-	8	3	50	8	9	10	No	9	0	0	9	0	50	-	9	0	50	9	11	50
[1][5][4]	10	3	50	11	11	50	20	-	-	-	-	-	-	-	10	3	50	10	9	10	No	11	0	0	11	0	50	-	11	0	50	11	11	50
[1][5][5]	12	3	50	14	11	50	20	-	-	-	-	-	-	-	12	3	50	12	9	10	No	14	0	0	14	0	50	-	14	0	50	14	11	50
[1][5][6]	15	4	20	16	12	20	20	-	-	-	-	-	-	-	15	4	20	16	0	30	No	16	0	30	16	1	20	-	16	1	20	16	12	20
[1][5][7]	17	3	0	18	12	10	20	-	-	-	-	-	-	-	17	3	0	18	0	20	Yes	18	0	20	18	1	10	-	18	1	10	18	12	10
[1][5][8]	19	1	50	19	19	0	20	-	-	-	-	-	-	-	19	1	50	19	7	10	-	19	7	10	19	8	0	-	19	8	0	19	19	0
[1][6][0]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][1]	0	0	0	0	18	0	4	-	-	-	-	-	-	-	0	0	0	0	5	50	-	0	5	50	0	6	40	-	0	6	40	0	18	0
[1][6][2]	0	6	40	1	14	30	4	-	-	-	-	-	-	-	0	6	40	1	2	20	No	1	2	20	1	3	10	-	1	3	10	1	14	30
[1][6][3]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	No	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][4]	1	4	10	2	12	10	4	-	-	-	-	-	-	-	1	4	10	1	10	0	No	2	0	0	2	0	50	-	2	0	50	2	12	10
[1][6][5]	2	0	50	2	18	50	4	-	-	-	-	-	-	-	2	0	50	2	6	40	-	2	6	40	2	7	30	-	2	7	30	2	18	50
[1][6][6]	3	2	30	3	20	30	11	-	-	-	-	-	-	-	3	2	30	3	8	20	No	3	8	20	3	9	10	No	3	9	10	3	20	30
[1][6][7]	3	4	50	4	12	40	11	-	-	-	-	-	-	-	3	4	50	4	0	30	No	4	0	30	4	1	20	-	4	1	20	4	12	40
[1][6][8]	3	6	50	4	14	40	11	-	-	-	-	-	-	-	3	6	50	4	2	30	No	4	2	30	4	3	20	-	4	3	20	4	14	40
[1][6][9]	4	8	0	5	15	50	11	-	-	-	-	-	-	-	4	8	0	5	3	40	No	5	3	40	5	4	30	-	5	4	30	5	15	50
[1][6][10]	5	2	30	5	20	30	11	-	-	-	-	-	-	-	5	2	30	5	8	20	No	5	8	20	5	9	10	No	5	9	10	5	20	30
[1][6][11]	5	7	50	7	15	40	11	-	-	-	-	-	-	-	5	7	50	7	3	30	No	7	3	30	7	4	20	-	7	4	20	7	15	40
[1][6][12]	7	4	20	8	12	40	18	-	-	-	-	-	-	-	7	4	20	8	0	30	No	8	0	30	8	1	20	-	8	1	20	8	12	40
[1][6][13]	7	6	50	8	15	10	18	-	-	-	-	-	-	-	7	6	50	8	3	0	No	8	3	0	8	3	50	-	8	3	50	8	15	10
[1][6][14]	8	6	50	9	15	10	18	-	-	-	-	-	-	-	8	6	50	9	3	0	No	9	3	0	9	3	50	-	9	3	50	9	15	10
[1][6][15]	9	3	50	10	12	10	18	-	-	-	-	-	-	-	9	3	50	9	9	40	No	10	0	0	10	0	50	-	10	0	50	10	12	10
[1][6][16]	9	6	50	10	15	10	18	-	-	-	-	-	-	-	9	6	50	10	3	0	No	10	3	0	10	3	50	-	10	3	50	10	15	10
[1][6][17]	10	6	50	11	15	10	18	-	-	-	-	-	-	-	10	6	50	11	3	0	No	11	3	0	11	3	50	-	11	3	50	11	15	10
[1][6][18]	11	3	50	12	12	10	25	-	-	-	-	-	-	-	11	3	50	11	9	40	No	12	0	0	12	0	50	-	12	0	50	12	12	10
[1][6][19]	11	6	50	12	15	10	25	-	-	-	-	-	-	-	11	6	50	12	3	0	No	12	3	0	12	3	50	-	12	3	50	12	15	10
[1][6][20]	12	6	50	14	15	10	25	-	-	-	-	-	-	-	12	6	50	14	3	0	No	14	3	0	14	3	50	-	14	3	50	14	15	10
[1][6][21]	14	3	50	15	12	40	25	-	-	-	-	-	-	-	14	3	50	15	0	30	No	15	0	30	15	1	20	-	15	1	20	15	12	40
[1][6][22]	14	6	50	15	15	40	25	-	-	-	-	-	-	-	14	6	50	15	3	30	No	15	3	30	15	4	20	-	15	4	20	15	15	40
[1][6][23]	15	6	50	16	15	40	25	-	-	-	-	-	-	-	15	6	50	16	3	30	No	16	3	30	16	4	20	-	16	4	20	16	15	40
[1][6][24]	16	4	20	17	14	20	32	-	-	-	-	-	-	-	16	4	20	17	2	10	Yes	17	2	10	17	3	0	-	17	3	0	17	14	20
[1][6][25]	16	6	50	17	15	40	32	-	-	-	-	-	-	-	16	6	50	17	3	30	No	17	3	30	17	4	20	-	17	4	20	17	15	40
[1][6][26]	17	6	50	18	15	40	32	-	-	-	-	-	-	-	17	6	50	18	3	30	No	18	3	30	18	4	20	-	18	4	20	18	15	40
[1][6][27]	18	3	10	19	13	10	32	-	-	-	-	-	-	-	18	3	10	19	1	0	Yes	19	1	0	19	1	50	-	19	1	50	19	13	10
[1][6][28]	18	4	20	19	13	10	32	-	-	-	-	-	-	-	18	4	20	19	1	0	No	19	1	0	19	1	50	-	19	1	50	19	13	10
[1][6][29]	21	0	0	21	18	0	32	-	-	-	-	-	-	-	21	0	0	21	5	50	-	21	5	50	21	6	40	-	21	6	40	21	18	0

Note: "NT only" indicates whether only NT can be used for execution of the operation ("Yes") or not ("No").

Table C.7: OT Hours Consumed in PC Group 0 in Various Schedules

Day	Compared approach			IPSMPP			
	Labor Grouping			*Labor Grouping*	*PC Allocation & Sequencing*		*Labor Transferring*
	F_EDD	F_LQ	F_CM	BI_CM	1	2	
0	7.8	17.7	5.2	9.5	9.5	4.3	2.3
1	7.0	12.0	4.8	5.2	5.2	2.7	0.7
2	7.5	16.7	5.2	6.5	4.0	2.7	0.7
3	6.7	13.3	4.8	5.2	2.7	2.7	0.7
4	8.7	15.3	7.2	15.8	8.7	2.3	2.3
5	9.0	11.8	2.5	3.2	4.3	2.3	2.3
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	4.3	12.0	5.0	5.7	2.0	4.0	4.0
8	4.0	12.3	3.3	5.7	4.0	0.3	0.3
9	4.0	13.7	4.3	5.7	2.7	0.0	0.0
10	5.7	10.8	2.3	5.7	0.0	0.0	0.0
11	4.2	12.7	4.2	4.0	0.0	0.0	0.0
12	5.7	9.3	4.3	2.3	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	10.2	9.0	4.0	2.0	0.0	0.0	0.0
15	4.5	4.5	6.0	0.0	0.0	0.0	0.0
16	6.8	9.0	3.8	1.7	0.0	0.0	0.0
17	14.8	6.0	6.0	1.7	0.0	0.0	0.7
18	14.8	5.0	5.8	0.0	0.0	0.0	0.7
19	12.0	8.5	5.3	0.0	0.0	0.0	0.7
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	4.3	2.7	0.7	0.0	0.0	0.3	0.3
22	4.0	5.2	2.7	0.0	0.0	0.3	0.3
23	0.0	6.3	3.3	0.0	0.0	0.3	0.3
24	9.7	0.0	1.7	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	1.7	1.7	1.7	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**157.2**	**215.5**	**94.1**	**79.7**	**43.0**	**22.3**	**16.3**

Table C.8: OT Hours Consumed in PC Group 1 in Various Schedules

Day	Compared approach			IPSMPP		
	Labor Grouping			*Labor Grouping*	*PC Allocation & Sequencing*	*Labor Transferring*
	F_EDD	F_LQ	F_CM	BI_CM		
0	62.0	53.0	28.0	26.0	26.0	26.0
1	32.5	7.0	23.5	24.5	24.5	24.5
2	62.5	52.0	21.0	19.5	19.5	19.5
3	48.0	1.5	26.5	25.5	25.5	26.0
4	30.0	62.0	26.0	25.0	25.0	25.0
5	40.5	4.0	14.5	18.5	18.5	16.0
6	0.0	0.0	0.0	0.0	0.0	0.0
7	45.0	4.5	4.0	9.5	9.5	10.0
8	16.5	3.0	6.0	13.5	8.5	9.0
9	30.0	4.5	4.0	10.0	10.0	10.0
10	27.5	2.0	2.5	8.5	8.5	8.5
11	1.0	4.5	4.0	10.0	12.5	13.5
12	0.0	4.0	6.0	8.5	10.0	8.5
13	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	11.5	11.0	7.0	7.0	7.0
15	0.0	9.0	19.0	7.5	7.5	7.5
16	0.0	9.5	14.5	7.5	7.5	4.0
17	0.0	7.0	20.5	12.5	9.0	3.5
18	0.0	0.0	15.0	5.0	4.0	3.5
19	0.0	2.5	0.0	7.0	2.0	4.5
20	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	2.5	0.0	0.0	0.0
22	2.5	2.5	0.0	0.0	2.5	2.5
23	0.0	0.0	8.5	8.5	0.0	0.0
24	0.0	0.0	0.0	0.0	2.5	2.5
25	0.0	0.0	0.0	0.0	2.5	2.5
26	2.5	2.5	2.5	2.5	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0
Total	**400.5**	**246.5**	**259.5**	**256.5**	**242.5**	**234.0**

Table C.9: PC Assignment to Moulds and Production Sequence on Every Mould in *Labour Grouping*

PC group	Mould	PC quantity	PCs allocated										
0	S[0][0][0]	20	[0][0][2]	[0][0][5]	[0][0][8]	[0][0][11]	[0][2][0]	[0][1][0]	[0][2][1]	[0][1][1]	[0][0][24]	[0][0][27]	[0][0][30]
			[0][2][2]	[0][1][2]	[0][0][39]	[0][0][40]	[0][0][45]	[0][0][46]	[0][2][3]	[0][2][4]	[0][1][3]		
	E[0][0]	41	[0][0][0]	[0][0][1]	[0][0][3]	[0][0][4]	[0][0][6]	[0][0][7]	[0][0][9]	[0][0][10]	[0][0][12]	[0][0][13]	[0][0][14]
			[0][0][15]	[0][0][16]	[0][0][17]	[0][0][18]	[0][0][19]	[0][0][20]	[0][0][21]	[0][0][22]	[0][0][23]	[0][0][25]	[0][0][26]
			[0][0][28]	[0][0][29]	[0][0][31]	[0][0][32]	[0][0][33]	[0][0][34]	[0][0][35]	[0][0][36]	[0][0][37]	[0][0][38]	[0][0][41]
			[0][0][42]	[0][0][43]	[0][0][44]	[0][0][47]	[0][0][48]	[0][0][49]	[0][0][50]	[0][0][51]			
	S[0][1][0]	15	[0][4][1]	[0][3][3]	[0][3][6]	[0][4][7]	[0][4][9]	[0][4][11]	[0][4][13]	[0][3][12]	[0][3][14]	[0][4][17]	[0][4][20]
			[0][3][19]	[0][3][21]	[0][4][24]	[0][4][26]							
	E[0][1]	18	[0][3][0]	[0][3][1]	[0][3][2]	[0][3][4]	[0][3][5]	[0][3][7]	[0][3][8]	[0][3][9]	[0][3][10]	[0][3][11]	[0][3][13]
			[0][3][15]	[0][3][16]	[0][3][17]	[0][3][18]	[0][3][20]	[0][3][22]	[0][3][23]				
	E[0][2]	18	[0][4][0]	[0][4][2]	[0][4][3]	[0][4][4]	[0][4][5]	[0][4][6]	[0][4][8]	[0][4][10]	[0][4][12]	[0][4][14]	[0][4][15]
			[0][4][16]	[0][4][18]	[0][4][19]	[0][4][21]	[0][4][22]	[0][4][23]	[0][4][25]				
1	S[1][0][0]	22	[1][0][0]	[1][0][2]	[1][0][4]	[1][0][7]	[1][0][8]	[1][0][9]	[1][2][0]	[1][2][1]	[1][2][2]	[1][2][3]	[1][2][4]
			[1][2][5]	[1][2][6]	[1][2][7]	[1][2][8]	[1][2][9]	[1][0][13]	[1][0][15]	[1][1][10]	[1][1][11]	[1][1][12]	[1][2][10]
	S[1][0][1]	22	[1][0][1]	[1][0][3]	[1][0][5]	[1][0][6]	[1][1][0]	[1][1][1]	[1][1][2]	[1][1][3]	[1][1][4]	[1][1][5]	[1][1][6]
			[1][1][7]	[1][1][8]	[1][1][9]	[1][0][10]	[1][0][11]	[1][0][12]	[1][0][14]	[1][0][16]	[1][0][17]	[1][0][18]	[1][0][19]

Table C.10: PC Assignment to Moulds and Production Sequence on Every Mould in *PC Allocation & Sequencing*

PC group	Mould	PC quantity	PCs allocated
0	S[0][0][0]	18	[0][0][0] [0][0][2] [0][0][5] [0][0][17] [0][1][0] [0][2][0] [0][2][1] [0][2][2] [0][2][3] [0][2][4] [0][1][1]
			[0][0][30] [0][1][2] [0][1][3] [0][0][39] [0][0][43] [0][0][46] [0][0][49]
	E[0][0]	43	[0][0][1] [0][0][3] [0][0][4] [0][0][6] [0][0][7] [0][0][8] [0][0][9] [0][0][10] [0][0][11] [0][0][12] [0][0][13]
			[0][0][14] [0][0][15] [0][0][16] [0][0][18] [0][0][19] [0][0][20] [0][0][21] [0][0][22] [0][0][23] [0][0][24] [0][0][25]
			[0][0][26] [0][0][27] [0][0][28] [0][0][29] [0][0][31] [0][0][32] [0][0][33] [0][0][34] [0][0][35] [0][0][36] [0][0][37]
			[0][0][38] [0][0][40] [0][0][41] [0][0][42] [0][0][44] [0][0][45] [0][0][47] [0][0][48] [0][0][50] [0][0][51]
	S[0][1][0]	22	[0][4][0] [0][4][1] [0][4][3] [0][4][4] [0][4][6] [0][4][9] [0][4][16] [0][3][4] [0][3][6] [0][3][8] [0][3][9]
			[0][3][11] [0][3][12] [0][3][14] [0][3][16] [0][3][17] [0][3][18] [0][3][19] [0][4][20] [0][3][22] [0][4][22] [0][4][26]
	E[0][1]	12	[0][3][0] [0][3][1] [0][3][2] [0][3][3] [0][3][5] [0][3][7] [0][3][10] [0][3][13] [0][3][15] [0][3][20] [0][3][21]
			[0][3][23]
	E[0][2]	17	[0][4][2] [0][4][5] [0][4][7] [0][4][8] [0][4][10] [0][4][11] [0][4][12] [0][4][13] [0][4][14] [0][4][15] [0][4][17]
			[0][4][18] [0][4][19] [0][4][21] [0][4][23] [0][4][24] [0][4][25]
1	S[1][0][0]	22	[1][0][0] [1][0][2] [1][0][4] [1][0][7] [1][0][8] [1][0][9] [1][0][12] [1][0][13] [1][0][14] [1][2][0] [1][2][1]
			[1][2][2] [1][2][3] [1][2][4] [1][2][5] [1][2][6] [1][2][8] [1][0][15] [1][0][19] [1][2][9] [1][1][11] [1][1][12]
	S[1][0][1]	22	[1][0][1] [1][0][3] [1][0][5] [1][0][6] [1][1][0] [1][1][1] [1][1][2] [1][1][3] [1][1][4] [1][1][5] [1][1][6]
			[1][1][7] [1][1][8] [1][1][9] [1][1][10] [1][2][7] [1][2][10] [1][0][10] [1][0][11] [1][0][16] [1][0][17] [1][0][18]

Table C.11: Labour Transfer Sequences of PC Group 1 in Modules of *PC Allocation & Sequencing* and *Labour Transferring*

PC Allocation & Sequencing						***Labor Transferring***					
S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould	S/N	Mould	No. of PC on each mould
1	E[1][3]	1	65	E[1][3]	20	1	S[1][0][1]	1	65	S[1][0][1]	12
2	E[1][3]	2	66	E[1][0]	17	2	E[1][3]	1	66	E[1][3]	17
3	S[1][0][0]	1	67	E[1][0]	18	3	E[1][3]	2	67	E[1][3]	18
4	S[1][0][1]	1	68	S[1][0][0]	11	4	S[1][0][0]	1	68	E[1][0]	18
5	E[1][1]	1	69	S[1][0][1]	11	5	S[1][0][1]	2	69	E[1][0]	19
6	E[1][3]	3	70	E[1][2]	6	6	E[1][1]	1	70	E[1][0]	20
7	E[1][0]	1	71	E[1][3]	21	7	E[1][3]	3	71	S[1][0][0]	12
8	E[1][0]	2	72	E[1][0]	19	8	E[1][0]	1	72	E[1][2]	6
9	S[1][0][0]	2	73	E[1][0]	20	9	E[1][0]	2	73	E[1][0]	21
10	S[1][0][1]	2	74	S[1][0][0]	12	10	S[1][0][0]	2	74	E[1][3]	19
11	E[1][3]	4	75	S[1][0][1]	12	11	S[1][0][1]	3	75	E[1][0]	22
12	E[1][3]	5	76	E[1][3]	22	12	E[1][3]	4	76	S[1][0][0]	13
13	E[1][2]	1	77	E[1][3]	23	13	E[1][3]	5	77	E[1][3]	20
14	S[1][0][1]	3	78	E[1][0]	21	14	E[1][2]	1	78	S[1][0][1]	13
15	E[1][3]	6	79	E[1][0]	22	15	S[1][0][1]	4	79	E[1][2]	7
16	S[1][0][0]	3	80	S[1][0][0]	13	16	E[1][3]	6	80	E[1][3]	21
17	E[1][1]	2	81	S[1][0][1]	13	17	S[1][0][0]	3	81	E[1][0]	23
18	E[1][0]	3	82	E[1][2]	7	18	E[1][1]	2	82	S[1][0][1]	14
19	E[1][0]	4	83	E[1][3]	24	19	E[1][0]	3	83	E[1][0]	24
20	S[1][0][1]	4	84	E[1][0]	23	20	E[1][0]	4	84	S[1][0][0]	14
21	S[1][0][0]	4	85	E[1][0]	24	21	S[1][0][1]	5	85	E[1][3]	22
22	E[1][3]	7	86	S[1][0][0]	14	22	E[1][3]	7	86	E[1][3]	23
23	E[1][3]	8	87	S[1][0][1]	14	23	S[1][0][0]	4	87	E[1][0]	25
24	E[1][3]	9	88	E[1][3]	25	24	E[1][3]	8	88	E[1][0]	26
25	E[1][2]	2	89	E[1][3]	26	25	E[1][3]	9	89	E[1][0]	27
26	E[1][1]	3	90	E[1][0]	25	26	E[1][2]	2	90	E[1][0]	28
27	S[1][0][1]	5	91	E[1][0]	26	27	E[1][1]	3	91	S[1][0][0]	15
28	E[1][0]	5	92	S[1][0][0]	15	28	S[1][0][1]	6	92	E[1][0]	29
29	E[1][0]	6	93	S[1][0][1]	15	29	S[1][0][1]	7	93	E[1][2]	8
30	S[1][0][0]	5	94	E[1][2]	8	30	E[1][0]	5	94	E[1][3]	24
31	E[1][1]	4	95	E[1][3]	27	31	E[1][0]	6	95	E[1][3]	25
32	E[1][3]	10	96	E[1][0]	27	32	S[1][0][0]	5	96	E[1][0]	30
33	E[1][3]	11	97	E[1][0]	28	33	E[1][1]	4	97	E[1][3]	26
34	E[1][3]	12	98	S[1][0][1]	16	34	E[1][3]	10	98	E[1][0]	31
35	E[1][2]	3	99	S[1][0][0]	16	35	E[1][3]	11	99	S[1][0][1]	15
36	E[1][0]	7	100	E[1][3]	28	36	E[1][2]	3	100	S[1][0][0]	16
37	E[1][0]	8	101	E[1][3]	29	37	E[1][0]	7	101	S[1][0][1]	16
38	S[1][0][1]	6	102	E[1][0]	29	38	E[1][0]	8	102	E[1][3]	27
39	S[1][0][0]	6	103	E[1][0]	30	39	E[1][0]	9	103	E[1][3]	28
40	E[1][3]	13	104	E[1][2]	9	40	S[1][0][1]	8	104	E[1][0]	32
41	E[1][3]	14	105	S[1][0][0]	17	41	S[1][0][1]	9	105	E[1][0]	33
42	E[1][0]	9	106	S[1][0][1]	17	42	S[1][0][0]	6	106	S[1][0][1]	17
43	E[1][0]	10	107	E[1][3]	30	43	E[1][3]	12	107	S[1][0][0]	17
44	S[1][0][1]	7	108	E[1][0]	31	44	E[1][3]	13	108	S[1][0][1]	18
45	S[1][0][0]	7	109	E[1][0]	32	45	S[1][0][1]	10	109	E[1][3]	29
46	E[1][2]	4	110	S[1][0][0]	18	46	E[1][0]	10	110	E[1][0]	34
47	E[1][3]	15	111	E[1][0]	33	47	S[1][0][0]	7	111	E[1][0]	35
48	E[1][0]	11	112	E[1][0]	34	48	E[1][2]	4	112	S[1][0][0]	18
49	E[1][0]	12	113	S[1][0][1]	18	49	S[1][0][0]	8	113	E[1][0]	36
50	S[1][0][1]	8	114	E[1][0]	35	50	E[1][0]	11	114	S[1][0][0]	19
51	S[1][0][0]	8	115	E[1][0]	36	51	E[1][0]	12	115	E[1][3]	30
52	E[1][3]	16	116	S[1][0][0]	19	52	E[1][0]	13	116	E[1][0]	37
53	E[1][3]	17	117	S[1][0][1]	19	53	S[1][0][1]	11	117	S[1][0][1]	19
54	E[1][0]	13	118	E[1][0]	37	54	S[1][0][0]	9	118	E[1][0]	38
55	E[1][0]	14	119	E[1][0]	38	55	E[1][3]	14	119	E[1][0]	39
56	S[1][0][1]	9	120	S[1][0][0]	20	56	E[1][3]	15	120	S[1][0][0]	20
57	S[1][0][0]	9	121	S[1][0][1]	20	57	E[1][3]	16	121	S[1][0][1]	20
58	E[1][2]	5	122	E[1][0]	39	58	E[1][0]	14	122	E[1][0]	40
59	E[1][3]	18	123	E[1][0]	40	59	E[1][0]	15	123	S[1][0][0]	21
60	E[1][0]	15	124	S[1][0][0]	21	60	S[1][0][0]	10	124	S[1][0][1]	21
61	E[1][0]	16	125	S[1][0][1]	21	61	E[1][2]	5	125	S[1][0][0]	22
62	S[1][0][0]	10	126	S[1][0][0]	22	62	E[1][0]	16	126	E[1][2]	9
63	S[1][0][1]	10	127	S[1][0][1]	22	63	E[1][0]	17	127	S[1][0][1]	22
64	E[1][3]	19				64	S[1][0][0]	11			

Appendix D: Adjusted Algorithm for M_PC Identification

Compared to the original algorithm given in Section 5.2.2.2 of Chapter 5, the adjusted algorithm for M_PC identification is applicable to a broader scope, where every PC type in a PC family sharing a certain sharable mould may have different amounts of mould hours for production. In this case, M_PC identification is still based on BLWMO (Backward Loading with Mould Only), as discussed before. Nevertheless, "PC Gap" is represented in terms of mould time needed instead of PC amount to be loaded. To be exact, during BLWMO, "PC Gap" for every bucket from the last bucket to CB is defined as the mould time needed by the amount of PCs with their due dates later than the bucket, but with their production to be incurred at the bucket and earlier bucket(s). Based on the new definition of "PC Gap", Table D.1 presents in detail the adjusted algorithm for M_PC identification.

Table D.1: Algorithm for M_PC Identification

Parameters:

- $t = 1, 2, ..., T$: loading bucket in planning horizon;
- CB : current loading bucket. $1 \leq CB \leq T$;
- $p = 1, 2, ..., P$: type of PCs;
- $e = 1, 2, ..., E$: type of exclusive mould;
- $s = 1, 2, ..., S$: type of sharable mould;
- p_e^E : the PC type that can be produced with exclusive mould type e;
- b_s : the number of PC types that can be produced with sharable mould type s;
- $a = 1, 2, ..., b_s$: the serial number of PC types that can be produced with sharable mould type s;
- $p_{s,a}^S$: the corresponding PC type of the a th PC type that can be produced with sharable mould type s;
- m_p^E : exclusive mould type that can be used for production of PC type p.
- m_p^S : sharable mould type that can be used for production of PC type p.
- For every PC type p, if $m_p^E > 0$ and $m_p^S = 0$, then the PC type p is E_PC; if $m_p^E = 0$ and $m_p^S > 0$, then the PC type p is S_PC; if $m_p^E > 0$ and $m_p^S > 0$, then the PC type p is B_PC.

- m_p^T: mould hours needed per PC of PC type p (excluding hours for mould changeover).
- α_s: the multiplier to account for mould changeover time needed for PC production on a sharable mould type s. $\alpha_s \geq 1.0$. $\alpha_{m_p^S} m_p^T$ is the total mould hours needed for production of one PC p on sharable mould m_p^S (including hours for mould changeover).
- $d_{p,t}$: demand of PC type p at the end of bucket t.
- $d_{p,t}^E$: demand of PC type p at the end of bucket t to be loaded on exclusive mould.
- $d_{p,t}^S$: demand of PC type p at the end of bucket t to be loaded on sharable mould.
- For every PC type p, $d_{p,t} = d_{p,t}^E + d_{p,t}^S$; If $m_p^E = 0$, then $d_{p,t}^E = 0$ and $d_{p,t}^S = d_{p,t}$; if $m_p^S = 0$, then $d_{p,t}^S = 0$ and $d_{p,t}^E = d_{p,t}$;
- $e_{e,t}$: working hours of exclusive mould type e available at bucket t;
- $s_{s,t}$: working hours of sharable mould type s available at bucket t;
- g_t: PC Gap at bucket t on a certain mould type obtained from BLWMO. If $g_t = 0$, it is called g^0 and the corresponding bucket t is t^0. The minimum g_t among several consecutive buckets is represented by $g^{\min}$, and the bucket with $g^{\min}$ is $t^{\min}$. $g_{e,t}$, g_e^0, $g_e^{\min}$, t_e^0 and $t_e^{\min}$ are for exclusive mould e, and $g_{s,t}$, g_s^0, $g_s^{\min}$, t_s^0 and $t_s^{\min}$ are for sharable mould s.
- v_p^E (CV for E_PC type p): the mould time needed by the amount of E_PC type p that is critical and should be tried for loading in CB, otherwise some delay is expected to be incurred due to lack of mould.
- $c_p^{\max}$ (MCA for S_PC or B_PC type p): the maximum amount that S_PC or B_PC type p would contribute to CV of its PC family.
- v_s^F (CV for PC family s): the mould time needed by the amount of all related PC types $p_{s,a}^S$ ($a = 1,2,...,b_s$) in PC family s that is critical and should be tried for loading in CB, otherwise some delay is expected to be incurred due to lack of mould.

Procedure:

[1] Initialize $d_{p,t}^E$ and $d_{p,t}^S$. For every PC type p ($p = 1,2,...,P$),

[1.1] if $m_p^S = 0$ (E_PC), let $d_{p,t}^E = d_{p,t}$ ($t = 1,2,...,T$);

[1.2] else if $m_p^E = 0$ (S_PC), let $d_{p,t}^S = d_{p,t}$ ($t = 1,2,...,T$);

[1.3] else (B_PC), let $d_{p,t}^E = d_{p,t}$ and $d_{p,t}^S = 0$ ($t = 1,2,...,T$);

[2] On every exclusive mould type e ($e = 1,2,..., E$), BLWMO_E is conducted for the corresponding PC type p_e^E, resulting in $g_{e,CB}$.

[2.1] Initialize $g_{e,t}$. For every bucket t ($t = 1,2,...,T$), let $g_{e,t} = 0$.

[2.2] At every bucket t from T to CB+1, load $d^E_{p^E_e,t}$ to mould type e,

[2.2.1] if $g_{e,t} + d^E_{p^E_e,t} m^T_{p^E_e} > e_{e,t}$, then let $g_{e,t-1} = g_{e,t} + d_{p^E_e,t} m^T_{p^E_e} - e_{e,t}$ and $e_{e,t} = 0$;

[2.2.2] else if $g_{e,t} + d_{p^E_e,t} m^T_{p^E_e} \le e_{e,t}$, then let $g_{e,t-1} = 0$ and $e_{e,t} = e_{e,t} - (g_{e,t} + d_{p^E_e,t} m^T_{p^E_e})$;

[2.3] if $m^S_{p^E_e} = 0$ (E_PC),

[2.3.1] if $g_{e,CB} = 0$, then the PC type p^E_e is N_PC;

[2.3.2] Else if $g_{e,CB} > 0$, then the PC type p^E_e is M_PC and $v^E_{p^E_e} = g_{e,CB}$;

[2.4] Else if $m^S_{p^E_e} > 0$ (B_PC),

[2.4.1] if $g_{e,CB} = 0$, then the PC type p^E_e is N_PC;

[2.4.2] else if $g_{e,CB} > 0$, PC transfer is needed. Go to [3] to calculate $d^S_{p^E_e,t}$.

[3] For every exclusive mould e ($e = 1,2,...,E$), if $m^S_{p^E_e} > 0$ and $g_{e,CB} > 0$ in BLWMO_E, calculate $d^S_{p^E_e,t}$ for B_PC type p^E_e;

[3.1] From CB onwards, find the first t^0_e with g^0_e;

[3.2] From CB to $t^0_e - 1$, find $t^{\min}_e$ with $g^{\min}_e$;

[3.3] Let $d^S_{p^E_e,t^0_e} = g^{\min}_e / m^T_{p^E_e}$ and $d^E_{p^E_e,t^0_e} = d^E_{p^E_e,t^0_e} - g^{\min}_e / m^T_{p^E_e}$;

[3.4] Adjust $g_{e,t}$. For every bucket t from CB to $t^0_e - 1$, let $g_{e,t} = g_{e,t} - g^{\min}_e$;

[3.5] if $t^{\min}_e > CB$, then $t^0_e = t^{\min}_e$ and go to [3.2];

[3.6] else if $t^{\min}_e = CB$, then go to [3.1] and start for next exclusive mould, if any;

[4] In every PC family s ($s = 1,2,...,S$), BLWMO_S is conducted on the sharable mould type s for all the S_PC and B_PC types $p^S_{s,a}$ ($a = 1,2,...,b_s$) in the family, resulting in $g_{s,CB}$.

[4.1] Initialize $g_{s,t}$. For every bucket t ($t = 1,2,...,T$), let $g_{s,t} = 0$.

[4.2] At every bucket t from T to CB+1, load demand of all PC type $p^S_{s,a}$ ($a = 1,2,...,b_s$) to mould type s;

[4.2.1] if $g_{s,t} + \alpha_s \sum_{a=1}^{b_s} d_{p^S_{s,a},t} m^T_{p^S_{s,a}} > s_{s,t}$, then let

$$g_{s,t-1} = g_{s,t} + \alpha_s \sum_{a=1}^{b_s} d_{p^S_{s,a},t} m^T_{p^S_{s,a}} - s_{s,t} \text{ and } s_{s,t} = 0;$$

[4.2.2] else if $g_{s,t} + \alpha_s \sum_{a=1}^{b_s} d_{p^S_{s,a},t} m^T_{p^S_{s,a}} \le s_{s,t}$, then let $g_{s,t-1} = 0$ and

$$s_{s,t} = s_{s,t} - (g_{s,t} + \alpha_s \sum_{a=1}^{b_s} d_{p^S_{s,a},t} m^T_{p^S_{s,a}});$$

[4.3] If $g_{s,CB} = 0$, then every PC type $p_{s,a}^{S}$ ($a = 1, 2, ..., b_s$) is N_PC;

[4.4] Else if $g_{s,CB} > 0$, then let $v_s^F = g_{s,CB}$ and go to step[5];

[5] For every PC family s ($s = 1, 2, ..., S$) with $g_{s,CB} > 0$, calculate $c_{p_{s,a}^S}^{\max}$ and determine PC criticality for every S_PC or B_PC type $p_{s,a}^{S}$ ($a = 1, 2, ..., b_s$) in the family.

[5.1] Let $c_{p_{s,a}^S}^{\max} = 0$;

[5.2] Let $c^{\max} = g_{s,CB}$ ($c^{\max}$ is the mould time needed by the amount of PC left currently for $c_{p_{s,a}^S}^{\max}$ calculation);

[5.3] For every bucket t from CB+1 onwards,

[5.3.1] If $c^{\max} \le \alpha_s d_{p_{s,a}^S,t}^{S} m_{p_{s,a}^S}^{T}$, then let $c_{p_{s,a}^S}^{\max} = c_{p_{s,a}^S}^{\max} + c^{\max}$; break out of loop;

[5.3.2] Else if $c^{\max} > \alpha_s d_{p_{s,a}^S,t}^{S} m_{p_{s,a}^S}^{T}$, then let $c_{p_{s,a}^S}^{\max} = c_{p_{s,a}^S}^{\max} + \alpha_s d_{p_{s,a}^S,t}^{S} m_{p_{s,a}^S}^{T}$ and $c^{\max} = c^{\max} - \alpha_s d_{p_{s,a}^S,t}^{S} m_{p_{s,a}^S}^{T}$;

[5.3.3] If $c^{\max} > g_{s,t}$, then let $c^{\max} = g_{s,t}$;

[5.3.4] If $c^{\max} = 0$, then break out of loop;

[5.4] If $c_{p_{s,a}^S}^{\max} > 0$, then the PC type $p_{s,a}^{S}$ is M_PC; else if $c_{p_{s,a}^S}^{\max} = 0$, then the PC type $p_{s,a}^{S}$ is N_PC.

Appendix E: PC Loading Algorithms in Simulation(D)

Detailed PC loading algorithms in Simulation(D) are given in Appendix E, including

Table **Page**

Table E.1: Parameters and Functions Used for PC Loading Algorithms in Simulation(D)

Parameters:

- $(integer)\ g$: the PC group of a PC;
- $(integer)\ p$: the PC type in a PC group;
- $(integer)\ i$: the serial number of a PC in a PC type;
- $PC_{g,p,i}$: represents the ith PC of PC type p in PC group g;
- $(integer)\ a$: the serial number of operations for a PC production; a = 0 stands for mould changeover, 1 for preparation before concrete pouring, 2 for concrete pouring, and 3 for curing;
- $(string)\ r$: represents whether the priority rule are used absolutely ("absolute") or relatively ("relative");
- $(double)\ Due_{g,p,i}$: represents the due time of $PC_{g,p,i}$;
- $(double)\ D_{g,p,a}$: represents the duration of the ath operation of a PC of PC type p in PC group g;
- $(integer)\ L_{g,p}$: number of labour needed for production of a PC of PC type p in PC group g;
- $(double)\ MCO_{g,p,i}$: mould changeover time needed for $PC_{g,p,i}$. If $PC_{g,p,i}$ is assigned to an exclusive mould type, then $MCO_{g,p,i} = 0$; Otherwise, if $PC_{g,p,i}$ is assigned to an individual sharable mould, then $MCO_{g,p,i}$ is dependent on both $PC_{g,p,i}$ itself and the preceding PC on the sharable mould;
- $(double)\ ST^{B}_{g,p,i}$, $FT^{B}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the backward simulation;
- $(double)\ ST^{B}_{g,p,i,a}$, $FT^{B}_{g,p,i,a}$: ST and FT of the ath operation of $PC_{g,p,i}$ production in the backward simulation;
- $(double)\ ST^{BLWMO}_{g,p,i}$, $FT^{BLWMO}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in BLWMO;
- $(double)\ ST^{BLWMO}_{g,p,i,a}$, $FT^{BLWMO}_{g,p,i,a}$: ST and FT of the ath operation of $PC_{g,p,i}$ production in BLWMO;
- $(double)\ ST^{F1}_{g,p,i}$, $FT^{F1}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the 1st forward simulation;
- $(double)\ ST^{F1}_{g,p,i,a}$, $FT^{F1}_{g,p,i,a}$: ST and FT of the ath operation of $PC_{g,p,i}$ production in the 1st forward simulation;
- $(double)\ ST^{F2}_{g,p,i}$, $FT^{F2}_{g,p,i}$: ST and FT of $PC_{g,p,i}$ production in the 2nd forward simulation;
- $(double)\ ST^{F2}_{g,p,i,a}$, $FT^{F2}_{g,p,i,a}$: ST and FT of the ath operation of $PC_{g,p,i}$ production in the 2nd forward simulation;
- $(double)\ cur\_t$: current point of time when $PC_{g,p,i}$ is tried for loading;
- $(boolean)\ v$: indicates whether $PC_{g,p,i}$ is loadable (true) or not (false);

Referenced functions:

- $(integer)\ n\_Lab\_All((double)\ t, (integer)\ g)$: return the labour size initially available in PC group g at the point of time t;
- $(integer)\ n\_Mld\_All((double)\ t, PC_{g,p,i})$: return the mould quantity, which is initially available at the point of time t, of exclusive mould type or individual sharable mould assigned for $PC_{g,p,i}$ production;
- $(integer)\ n\_Lab\_Cur((integer)\ g)$: return the labour size currently available in group g.
- $(integer)\ n\_Mld\_Cur(PC_{g,p,i})$: return the mould quantity, which is currently available, of exclusive mould type or individual sharable mould assigned for $PC_{g,p,i}$ production;
- $(integer)\ Calender((integer)\ d)$: indicate whether day d is working day (1) or holiday (0);
- $(character)\ Zone((double)\ t,\ (integer)\ g)$: indicates which time zone that point of time t falls into in PC group g. Zone = ‘N’, ‘O’, or ‘B’ represent that t falls into NT, OT, or BT zone respectively;
- $(double)\ Plus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,\ (boolean)\ preemptive)$ see Table 6.3;
- $(double)\ Minus((integer)\ g,\ (double)\ t1,\ (double)\ t2,\ (string)\ time,\ (boolean)\ preemptive)$ see Table 6.4;

Table E.2: Algorithm of Trying for PC Loading in BLWMO

Parameters and referenced functions:
Refer to Table E.1.

Procedure:

[1] Let $v = false$;

[2] If $cur\_t \le Due_{g,p,i}$ and $n\_mld\_cur(PC_{g,p,i}) \ge 1$, then

[2.1] Let $ST^{BLWMO}_{g,p,i,3} = Minus(g,\ cur\_t,\ D_{g,p,3},\ "N+O+B",\ false)$;

[2.2] If $ST^{BLWMO}_{g,p,i,3} \ge Min\_T$, then let $ST^{BLWMO}_{g,p,i,2} = Minus(g,\ ST^{BLWMO}_{g,p,i,3},\ D_{g,p,2},\ "N+O",\ false)$;

[2.3] If $ST^{BLWMO}_{g,p,i,2} \ge Min\_T$, then let $ST^{BLWMO}_{g,p,i,1} = Minus(g,\ ST^{BLWMO}_{g,p,i,2},\ D_{g,p,1},\ "N+O",\ true)$;

[2.4] If $ST^{BLWMO}_{g,p,i,1} \ge Min\_T$, then let $ST^{BLWMO}_{g,p,i,0} = Minus(g,\ ST^{BLWMO}_{g,p,i,1},\ MCO_{g,p,i},\ "N+O",\ true)$;

[2.5] If $ST^{BLWMO}_{g,p,i,0} \ge Min\_T$ and $n\_mld\_cur(PC_{g,p,i}) + n\_mld\_all(ST^{BLWMO}_{g,p,i,0},\ PC_{g,p,i}) - n\_mld\_all(cur\_t,\ PC_{g,p,i}) \ge 1$, then let $v = true$;

[3] If $v = false$, then for every operation a ($a = 0,1,2,3$) of $PC_{g,p,i}$, let $ST^{BLWMO}_{g,p,i,a} = Min\_T - 1$.

Table E.3: Algorithm of Trying for PC Loading in the 1st Forward Simulation

Parameters and referenced functions:
Refer to Table E.1.

Procedure:

[1] Let $v = false$;

[2] If $Calender(Day(cur\_t)) = 0$ or $Zone(cur\_t,\ g) = 'B'$, then let $v = false$;

[3] Else if $n\_lab\_cur(g) \geq L_{g,p}$ and $n\_mld\_cur(PC_{g,p,i}) \geq 1$, then

[3.1] Let $FT^{F1}_{g,p,i,0} = Plus(g,\ cur\_t,\ MCO_{g,p,i},\ "N+O",\ true)$;

[3.2] If $FT^{F1}_{g,p,i,0} \leq Max\_T$, then let
$FT^{F1}_{g,p,i,1} = Plus(g,\ FT^{F1}_{g,p,i,0},\ D_{g,p,1},\ "N+O",\ true)$;

[3.3] If $FT^{F1}_{g,p,i,1} \leq Max\_T$, then let
$FT^{F1}_{g,p,i,2} = Plus(g,\ FT^{F1}_{g,p,i,1},\ D_{g,p,2},\ "N+O",\ false)$;

[3.4] If $FT^{F1}_{g,p,i,2} \leq Max\_T$, then let
$FT^{F1}_{g,p,i,3} = Plus(g,\ FT^{F1}_{g,p,i,2},\ D_{g,p,3},\ "N+O+B",\ false)$;

[3.5] If $FT^{F1}_{g,p,i,3} \leq Max\_T$, $\begin{array}{l} n\_lab\_cur(g) + n\_lab\_all(FT^{F1}_{g,p,i,2},\ g) \\ -n\_lab\_all(cur\_t,\ g) \geq L_{g,p} \end{array}$, and
$\begin{array}{l} n\_mld\_cur(PC_{g,p,i}) + n\_mld\_all(FT^{F1}_{g,p,i,3},\ PC_{g,p,i}) \\ -n\_mld\_all(cur\_t,\ PC_{g,p,i}) \geq 1 \end{array}$, then let $v = true$;

[4] If $v = false$, then for every operation a ($a = 0,1,2,3$) of $PC_{g,p,i}$, let
$FT^{F1}_{g,p,i,a} = Max\_T + 1$.

Table E.4: Algorithm of Trying for Execution of Operation 3 in the Backward Simulation

Parameters and referenced functions: Refer to Table E.1.   ***Procedure:***   [1] Let $v = false$;   [2] If $cur\_t \le Due_{g,p,i}$ and $n\_mld\_cur(PC_{g,p,i}) \ge 1$, then   [2.1] Let $ST^{B}_{g,p,i,3} = Minus(g,\ cur\_t,\ D_{g,p,3},\ "N+O+B",\ false)$;   [2.2] Let $v = true$;

Table E.5: Algorithm of Trying for Execution of Operation 2~0 in the Backward Simulation

Parameters and referenced functions:
Refer to Table E.1.

Procedure:
[1] Let $v = false$;
[2] If $Calender(Day(cur\_t)) = 0$ or $Zone(cur\_t,\ g) = 'B'$, then let $v = false$;
[3] Else if $Zone(cur\_t,\ g) = 'O'$ and $cur\_t > FT^{F1}_{g,p,i,2}$, then let $v = false$;
[4] Else if $Zone(cur\_t,\ g) = 'N'$ and $cur\_t > FT^{F1}_{g,p,i,2}$, then try to execute operations with NT as much as possible:
  [4.1] If $n\_lab\_cur(g) \geq L_{g,p}$, then
    [4.1.1] let $ST^{B}_{g,p,i,2} = Minus(g,\ cur\_t,\ D_{g,p,2},\ "N",\ false)$;
    [4.1.2] if $Day(ST^{B}_{g,p,i,2}) = Day(cur\_t)$, then
      [4.1.2.1] Let $ST^{B}_{g,p,i,1} = Minus(g,\ ST^{B}_{g,p,i,2},\ D_{g,p,1},\ "N",\ true)$;
      [4.1.2.2] If $ST^{B}_{g,p,i,1} < ST^{F1}_{g,p,i,1}$, then let $ST^{B}_{g,p,i,1} = Minus(g,\ ST^{B}_{g,p,i,2},\ D_{g,p,1},\ "N+O",\ true)$;
      [4.1.2.3] Let $ST^{B}_{g,p,i,0} = Minus(g,\ ST^{B}_{g,p,i,1},\ MCO_{g,p,i},\ "N",\ true)$;
      [4.1.2.4] If $ST^{B}_{g,p,i,0} < ST^{F1}_{g,p,i,0}$, then let $ST^{B}_{g,p,i,0} = Minus(g,\ ST^{B}_{g,p,i,1},\ MCO_{g,p,i},\ "N+O",\ true)$;
      [4.1.2.5] If $\begin{array}{l} n\_lab\_cur(g) + n\_lab\_all(ST^{B}_{g,p,i,0},\ g) \\ -n\_lab\_all(cur\_t,\ g) \geq L_{g,p} \end{array}$, then let $v = true$;
[5] Else if $r = "absolute"$, then set ST and FT of every operation equal to those in the 1st forward simulation
  [5.1] For every operation a ($a = 0,1,2$) of $PC_{g,p,i}$, let $ST^{B}_{g,p,i,a} = ST^{F1}_{g,p,i,a}$;
  [5.2] Let $v = true$;
[6] Else if $r = "relative"$, then try to execute operations with both NT and OT:
  [6.1] If $n\_lab\_cur(g) \geq L_{g,p}$, then
    [6.1.1] let $ST^{B}_{g,p,i,2} = Minus(g,\ cur\_t,\ D_{g,p,2},\ "N+O",\ false)$;
    [6.1.2] if $Day(ST^{B}_{g,p,i,2}) = Day(cur\_t)$, then
      [6.1.2.1] Let $ST^{B}_{g,p,i,1} = Minus(g,\ ST^{B}_{g,p,i,2},\ D_{g,p,1},\ "N+O",\ true)$;
      [6.1.2.2] If $ST^{B}_{g,p,i,1} \geq Min\_T$, then let $ST^{B}_{g,p,i,0} = Minus(g,\ ST^{B}_{g,p,i,1},\ MCO_{g,p,i},\ "N+O",\ true)$;
      [6.1.2.3] If $ST^{B}_{g,p,i,0} \geq Min\_T$,

$$n\_lab\_cur(g) + n\_lab\_all(ST^{B}_{g,p,i,0},\ g) - n\_lab\_all(cur\_t,\ g) \ge L_{g,p},$$

$$n\_mld\_cur(PC_{g,p,i}) + n\_mld\_all(ST^{B}_{g,p,i,0},\ PC_{g,p,i}) - n\_mld\_all(cur\_t,\ PC_{g,p,i}) \ge 0$$, then let

$v = true$;

[7] If $v = false$, then for every operation a ($a = 0,1,2$) of $PC_{g,p,i}$, let $ST^{B}_{g,p,i,a} = Min\_T - 1$.

Table E.6: Algorithm of Trying for PC Loading in the 2nd Forward Simulation

Parameters and referenced functions:
Refer to Table E.1.

Procedure:

[1] Let $v = false$;

[2] If $Calender(Day(cur\_t)) = 0$ or $Zone(cur\_t,\ g) = 'B'$, then let $v = false$;

[3] Else if $n\_lab\_cur(g) \geq L_{g,p}$ and $n\_mld\_cur(PC_{g,p,i}) \geq 1$, then

[3.1] Let $FT^{F2}_{g,p,i,0} = Plus(g,\ cur\_t,\ MCO_{g,p,i},\ "N",\ true)$;

[3.2] If $FT^{F2}_{g,p,i,0} > FT^{B}_{g,p,i,0}$, then let
$FT^{F2}_{g,p,i,0} = Plus(g,\ cur\_t,\ MCO_{g,p,i},\ "N+O",\ true)$

[3.3] If $FT^{F2}_{g,p,i,0} \leq Max\_T$, then

[3.3.1] Let $FT^{F2}_{g,p,i,1} = Plus(g,\ FT^{F2}_{g,p,i,0},\ D_{g,p,1},\ "N",\ true)$;

[3.3.2] If $FT^{F2}_{g,p,i,1} > FT^{B}_{g,p,i,1}$, then let
$FT^{F2}_{g,p,i,1} = Plus(g,\ FT^{F2}_{g,p,i,0},\ D_{g,p,1},\ "N+O",\ true)$;

[3.4] If $FT^{F2}_{g,p,i,1} \leq Max\_T$, then

[3.4.1] Let $FT^{F2}_{g,p,i,2} = Plus(g,\ FT^{F2}_{g,p,i,1},\ D_{g,p,2},\ "N",\ false)$;

[3.4.2] If $FT^{F2}_{g,p,i,2} > FT^{B}_{g,p,i,2}$, then let
$FT^{F2}_{g,p,i,2} = Plus(g,\ FT^{F2}_{g,p,i,1},\ D_{g,p,2},\ "N+O",\ false)$;

[3.5] If $FT^{F2}_{g,p,i,2} \leq Max\_T$, then let
$FT^{F2}_{g,p,i,3} = Plus(g,\ FT^{F2}_{g,p,i,2},\ D_{g,p,3},\ "N+O+B",\ false)$;

[3.6] If $FT^{F2}_{g,p,i,3} \leq Max\_T$, $\begin{matrix} n\_lab\_cur(g) + n\_lab\_all(FT^{F2}_{g,p,i,2},\ g) \\ -n\_lab\_all(cur\_t,\ g) \geq L_{g,p} \end{matrix}$ and
$\begin{matrix} n\_mld\_cur(PC_{g,p,i}) + n\_mld\_all(FT^{F2}_{g,p,i,3},\ PC_{g,p,i}) \\ -n\_mld\_all(cur\_t,\ PC_{g,p,i}) \geq 1 \end{matrix}$, then let $v = true$;

[4] If $v = false$, then for every operation a ($a = 0,1,2,3$) of $PC_{g,p,i}$, let
$FT^{F2}_{g,p,i,a} = Max\_T + 1$.