ABSTRACT

Planning plays an important role in precast production management. In practice, however, this work is primarily carried out on a rule-of-thumb basis. A specialized planning model based on simulation technique and genetic algorithm (GA) is presented in this paper for make-to-order precast production. A novel priority rule, the critical precast component (CP) rule, is established for mold considerations during simulation, and a bi-directional simulation is adopted to reduce excessive overtime and precast stock. On this basis, three simulation approaches are designed using different simulation heuristics and directions. To test the validity of the proposed model with different approaches, a planning experiment is carried out. By comparison, it is clear that the Simulation-GA based model using CP rule and bi-directional simulation can generate a satisfying resource plan and production schedule.

1 INTRODUCTION

Precast concrete technology has been widely used in many countries due to many advantages it has over traditional construction methods, such as increased construction speed and higher quality. Production planning is an important managerial task in a plant for prefabrication of concrete elements (Warszawski 1984). As in other manufacturing industries, it usually involves capacity/resource planning and master production schedule development for an intermediate planning horizon (3~18months).

Apparenty, there is no universal planning method which is applicable for all environments. A good method should be well adapted to the problem domain. Based on interviews with precasters in Singapore, the following distinctive features of prefabrication should be taken into account in precast production planning.

First of all, precast production is carried out in a make-to-order manner, i.e., precast components (PCs) are custom-built according to individual project requirements. They must be delivered to the construction site as required by their erection schedules, which usually overrides all other considerations in production planning (Warszawski 1990).

Second, in contrast with other manufacturing processes which have only a single critical resource, precast production involves two critical resources, mold and labor, which dominate the production pace simultaneously or alternately. Thus, both of them should be taken into account in planning work. Mold planning determines proper mold quantity for every mold type involved in a new project, while labor planning arranges reasonable labor force and utilization (in both normal time and overtime) for the entire plant.

Third, a PC can be produced on an exclusive mold, a sharable mold, or both. In order to reduce mold investment, however, precasters tend to use a high percentage of sharable molds to produce PCs of similar types together. A large number of sharable molds inevitably result in more frequent mold changeovers. Time and cost for mold changeover depends on PC production sequence on the sharable mold. Therefore, a planning method should be able to efficiently assign PCs to various molds, as well as allocate time for sequence-dependent mold changeover as needed.

2 REVIEW OF PLANNING METHODS

In this research, planning for precast production is studied in a broad sense, covering mold planning, labor planning and master schedule development. In a generic manufacturing environment, it corresponds to machine requirements planning (MRP#) and aggregate production planning (APP), which have been treated as separate research problems. Behnezad and Khoshnevis (1996) and Nam and Logendran (1992) provided comprehensive reviews of researches in MRP# and APP, respectively. Mathematical
programming is the most commonly used approach to solve these problems. Despite their popularity in academia, the primary disadvantage of analytical models is that they cannot solve a large and complex problem effectively (Lee and Hwang 2001). In precast production planning, for example, it is very difficult to formulate sequence-dependent mold changeovers with a mathematical model. Even if it were simplified as sequence-independent changeovers with mixed-integer programming, as in usual lot-size models, problems still exist. State-of-the-art general mixed integer programming codes are generally inadequate to solve production problems of any realistic size, given that they can handle only a small number of integer variables (Nam and Logendran 1992).

Several planning and scheduling models have been developed specifically for precast concrete production. Warszawski (1984) made a distinction between short and long production series and proposed planning models for both types of series produced on one or several molds. Despite its simplicity, the model only took into account molds as a single resource during the planning process. In Dawood (1995), a simulation model was developed to model production in a precast factory. As noted by the author, the model was only suitable for a make-to-stock environment. A flow shop sequencing model was given by Chan and Hu (2002) for precast production scheduling and a similar model was proposed by Leu and Hwang (2001). Although results from comparison tests seemed good, the scheduling objectives used (i.e., makespan and tardiness penalty) may not be appropriate for precast production. In addition to these limitations, the above models focused on constrained planning or shop-floor scheduling with required resources being given. Therefore, a more comprehensive model is needed where resource (mold and labor) planning is incorporated.

In practice, most precasting and manufacturing companies use a simple trial and error approach to develop their production plans (Dawood 1995). There are only some fundamental rules and heuristics for them to follow. Therefore, it cannot guarantee a good result, let alone an optimal one. Based on interviews with Singapore’s precasters, the basic planning steps used in practice are presented below:

1. Mold planning: Mold types are determined at first based on shop drawings. Then, for each mold type, a mold quantity is estimated based on the average demand rate of PC types that can be produced on the mold.
2. PC allocation: PCs are allocated to every mold as early as possible to fully utilize molds and avoid any delay. PCs with early due dates or requiring small mold changeover are dispatched first. If there is any delay incurred, extra mold(s) will be used, and PCs reallocated accordingly.
3. Labor planning: Based on the above master schedule, size of labor force in the plant is determined for every planning period, with the thought of keeping sizes of labor force over periods as steady as possible. If in a period labor hours are not enough for production, overtime will be used as needed.

The actual planning method following the above procedure and adopting a forward process is denoted by $F_{ACT}$ in the paper, and will be used for comparison with other proposed approaches.

3 SIMULATION-GA BASED MODEL

The purpose of planning is to supply orders on time at minimum associated cost (Warszawski 1984). Therefore, as a fundamental requirement, production schedules should meet PC demand without any tardiness. In addition, performance of alternative feasible schedules should be evaluated in terms of total planning-related cost so that the one with the minimum cost is selected for implementation. The total planning-related cost includes mold cost, labor cost and stock-holding cost. Labor cost can be further broken into costs for labor hiring/laying off, normal time (NT) and overtime (OT) consumed.

To meet the above planning objective, a Simulation-GA based model is proposed, as shown in Figure 1. Simulation and GA are different techniques for modeling and heuristic optimization respectively. They are integrated together to form a specialized model for precast production planning.

The power of simulation lies in its capability to accurately represent finite capacity and the current status of a system. Thus, it allows one 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 this research, three different simulation approaches – $F_{TRD}$, $F_{CP}$ and $B_{1}CP$ – are designed for precast production planning. These approaches are different from one another in terms of priority rules (traditional rules or new critical PC rule) and/or simulation directions (single forward simulation or bi-directional simulation), as explained in the next section.

Genetic algorithms are powerful 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 quite hard to solve by conventional optimization techniques. For GA to work in the model, real number representation is used to represent chromosomes. Besides, traditional two-cut-point crossover, uniform mutation and $(\mu+\lambda)$ selection are adopted in this research. For more information of these GA mechanisms, refer to Gen and Cheng (1997) and Fogel (1994).
In this model, mold planning, labor planning and master schedule development are combined together in order to achieve a satisfying solution to the problem as a whole. Thus, decision variables include mold quantity for every mold type in a new project, size of labor force and maximum allowable OT hours for every planning period along the planning horizon. As shown in Figure 1, the planning process is an iterative procedure of progressive improvement. During one planning iteration, F_TRD, F_CP or BI_CP simulation arrives at feasible master production schedules with given values of the decision variables (within constraints of resources), while GA evaluates the performance of the resultant schedules, and based on this, adjusts the decision variables and selects the ones with better performance for the next iteration. The planning cycle is repeated until a satisfying or optimal solution is achieved.

The simulation method used in this model is different from general simulations in terms of the means for advancing the simulation clock. Instead of next-event time advance, fixed-increment time advance has been adopted. With this approach, the simulation clock is advanced in increments of exactly \( \Delta t \) time units, and any events that have occurred during a certain time interval of \( \Delta t \) are considered to occur at the end of the interval (Law and Kelton 2000). Since the planning work for precast production is carried out for an intermediate time period (6~18 months), it makes no sense to consider individual operations and queuing on every mold, which would complicate the problem modeling and solving process. Resources needed for a PC production can be compactly represented in terms of mold hours and labor hours. With an appropriate choice of \( \Delta t \) (e.g., one week), fixed-increment time advance allows production planning to be performed at a reasonable level of detail. It should be noted that, the following definitions of two different time lengths are used in this research.

- Loading bucket (1 day ~ 2 weeks): It is a time interval for advancing the system clock in simulation. 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 mold planning is very sensitive to PCs’ due dates, the 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 labor planning. Size of labor force and maximum allowable OT hours are kept constant within one planning period and can only be adjusted over different periods. A planning period may include several loading buckets.

4 THREE SIMULATION-BASED SCHEDULING APPROACHES

Three different scheduling approaches using different priority rules and/or different simulation directions are developed to generate the master production schedule.

4.1 Forward Scheduling Based on Traditional Rules (F_TRD)

In this approach, the master production schedule is generated with traditional forward simulation. 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. 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:

- 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.
• Lowest mold changeover (LMC) rule: PCs requiring low mold changeovers get high priority in the simulation process. It aims to minimize mold changeover cost.

• Lowest stock cost (LSC) rule: PCs are loaded based on their unit stock-holding costs, and the PCs 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 used consecutively, with EDD usually being the 1st rule, followed by LMC and LSC. The order corresponds to the relative importance of their planning objectives.

4.2 Forward Scheduling Based on CP Rule (F_CP)

Forward simulation is also used in this approach. Instead of traditional priority rules, a novel priority rule, critical PC (CP) rule, is designed as the 1st rule in the simulation.

In PC production, molds are a most critical resource. A mold is only dedicated to PCs of one type or a few similar types, and a PC could be produced on an exclusive mold, a sharable mold, or both at the same time. In such an environment, mold requirements and availability should be carefully considered in deciding on PC production sequence and allocation to molds. 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.

With CP rule, all PCs to be loaded are divided into 3 categories according to their criticality:

• Due date-related critical PCs (D_PC). D_PC are those PCs that will be due at the end of current loading bucket (CB). They are most urgent PCs and should be loaded in CB at first, otherwise some delays will be incurred.

• Mold-related critical PCs (M_PC). M_PC are defined as PCs that are potentially critical due to the lack of molds. If they are not loaded at CB, there would probably not be enough mold hours available for their production at later buckets.

• Non-critical PCs (N_PC). The PCs 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 mold is used as a single resource. The backward loading is conducted from the last bucket to the bucket right after CB. If there is any amount of PCs left to be loaded in CB, the PC type is identified as M_PC.

In F_CP approach, CP rule is used as the 1st priority rule. For a certain loading bucket, D_PC, M_PC and N_PC are identified first, and they are loaded in order of their criticality, i.e., D_PC are loaded at first, next M_PC, at last N_PC. For PCs of the same criticality, the traditional priority rules are adopted as subordinate rules.

4.3 Bi-directional Scheduling Based on CP Rule (BI_CP)

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. First, certain PCs can be produced much earlier than their due dates, leading to overstock. Second, 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 bi-directional 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 in the forward schedule to reduce the OT unnecessarily used 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:

• Backward simulation is carried out from the due dates backward in time to obtain a non-delay schedule.

• Production time (bucket) of a PC in backward simulation must not be earlier than that in the forward simulation.

• Backward simulation keeps the same profile of PC assignment and production sequence on molds as the forward simulation.

• 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.

5 EXPERIMENTAL TEST

To test the validity of the Simulation-GA based model using the proposed approaches, an experiment of a realistic size planning problem is conducted. The data used in the experiment is set up based on the information collected from a precast plant in Singapore.
5.1 Experiment Description

The experiment 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 mold planning for the project, labor planning and master schedule development for the precast plant.

The planning horizon covers 8 planning periods (0–7), with 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 size of labor force can only be changed from Period 1 onwards. Daily NT and maximum OT hours are 8 hours and 6 hours respectively. Hourly labor costs are S$5 (Singapore dollar) for NT working and S$7.5 for OT. Labor hiring and firing costs are S$400 and S$300 per labor respectively. Table 1 shows relevant information of various PCs and molds in production planning. For Project B, there are 4 exclusive mold types (E3–E6) and 3 sharable mold types (S3–S5) involved in mold planning. For simplicity, assume that a PC production requires 24 mold hours of an exclusive or sharable mold. Therefore, one mold can produce at most 6 PCs in a bucket. The production capacity of a sharable mold will decrease if there is any mold change-over incurred. “Minimum start week” in Table 1 refers to the earliest week when production of a PC type can start. It mainly depends on how long it takes for shop drawing design and mold fabrication. Forecast demand (C) is obtained based on market analysis and described in terms of a typical PC type 16.

A few parameters have direct impacts on the performance of GA and their values need to be determined. Based on preliminary tests, the values of these parameters used in the experiment 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.

5.2 Result Analysis

Production planning is first conducted with the actual planning method, F_ACT, to establish a base production plan (including mold & labor plans, and master production schedule). Then, 3 more production plans are generated with the Simulation-GA based model using F_TRD, F_CP and BI_CP approaches respectively. A large delay penalty is set to ensure no delay is incurred in every resultant schedule. Therefore, performances of various production plans are evaluated based on the total planning-related costs, as shown in Table 2.

### Table 1: PC and Mold Information for Production Planning

<table>
<thead>
<tr>
<th>PC type</th>
<th>Mold type</th>
<th>Labor hours</th>
<th>Stock cost (S$)</th>
<th>PC volume (m3)</th>
<th>Min start week</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E0</td>
<td>12</td>
<td>0.44, 0.88</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>E1</td>
<td>12</td>
<td>0.50, 0.50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>E2</td>
<td>12</td>
<td>0.60, 0.60</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>12</td>
<td>0.70, 0.70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>E4</td>
<td>12</td>
<td>0.80, 0.80</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>E5</td>
<td>12</td>
<td>0.90, 0.90</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 2: Total Planning-Related Costs (S$) in Various Plans

<table>
<thead>
<tr>
<th>Cost category</th>
<th>F_ACT</th>
<th>F_TRD</th>
<th>F_CP</th>
<th>BI_CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mold cost</td>
<td>198,000</td>
<td>213,000</td>
<td>193,000</td>
<td>193,000</td>
</tr>
<tr>
<td>2. Labor cost</td>
<td>278,383</td>
<td>281,003</td>
<td>277,973</td>
<td>272,955</td>
</tr>
<tr>
<td>(1) Hiring &amp; firing</td>
<td>5,600</td>
<td>10,200</td>
<td>7,200</td>
<td>6,300</td>
</tr>
<tr>
<td>(2) NT</td>
<td>257,280</td>
<td>249,600</td>
<td>249,600</td>
<td>263,040</td>
</tr>
<tr>
<td>(3) OT</td>
<td>15,503</td>
<td>21,203</td>
<td>21,173</td>
<td>3,615</td>
</tr>
<tr>
<td>3. Stock cost</td>
<td>17,948</td>
<td>21,316</td>
<td>14,142</td>
<td>11,916</td>
</tr>
<tr>
<td>Total cost</td>
<td>494,331</td>
<td>517,419</td>
<td>485,114</td>
<td>477,871</td>
</tr>
</tbody>
</table>

As expected, BI_CP plan achieves the best performance (lowest overall planning-related 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 plans ranks the second best, which may be attributed to its low mold investment and NT labor cost. F_TRD performs the worst in that it needs extra molds, 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 precast production planning.
5.2.1 Mold Cost

Table 3 gives information on mold quantity and cost generated in the four production plans. It can be seen that F_CP and BI_CP use the smallest quantity of molds or have the best combination of various mold types, resulting in the minimum total mold cost. On the contrary, F_TRD does the worst job in mold planning.

Table 3: Mold Quantity and Cost in Various Plans

<table>
<thead>
<tr>
<th>Mold type</th>
<th>Unit cost</th>
<th>F_ACT</th>
<th>F_TRD</th>
<th>F_CP</th>
<th>BI_CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3</td>
<td>25,000</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E4</td>
<td>27,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E5</td>
<td>27,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S3</td>
<td>32,000</td>
<td>3</td>
<td>96,000</td>
<td>3</td>
<td>96,000</td>
</tr>
<tr>
<td>S4</td>
<td>13,000</td>
<td>2</td>
<td>26,000</td>
<td>2</td>
<td>26,000</td>
</tr>
<tr>
<td>S5</td>
<td>15,000</td>
<td>1</td>
<td>15,000</td>
<td>2</td>
<td>30,000</td>
</tr>
<tr>
<td><strong>Total cost (S$)</strong></td>
<td></td>
<td>198,000</td>
<td>213,000</td>
<td>193,000</td>
<td>193,000</td>
</tr>
</tbody>
</table>

In order to illustrate why this difference in mold quantity happens, consider the production of PC Type 13, 14 and 15. PC 13 can be produced on both exclusive mold E6 and sharable mold S5, whereas PC 14 and 15 can only be made on S5. Through the GA, F_CP generates the best mold combination – three E6 and one S5. Demand of PC 13, 14 and 15 and their production on molds E6 and S5 in F_CP plan are given in Table 4. Since there is a fairly big demand for PC 14 and 15, but only one S5 is available, mold S5 becomes critical for PC 14 and 15. This means production of PC 14 and 15 should start early and take up S5 for a rather long time, otherwise some delays will be incurred. With CP rule adopted, F_CP approach can clearly capture such PC demand and mold requirements. Actually, PC 14 and 15 have been identified as M_PC or D_PC from Week 7 to 15, and thus got loading priority on S5. As a result, the PCs are produced in a reasonable sequence and on proper molds without any delay, as shown in Table 4.

Table 4: Demand of PC Type 13, 14 & 15 and Their Production on E6 & S5 in F_CP Plan

<table>
<thead>
<tr>
<th>PC Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Week</strong></td>
</tr>
<tr>
<td><strong>PC type</strong></td>
</tr>
<tr>
<td><strong>PC Production on E6 &amp; S5</strong></td>
</tr>
<tr>
<td><strong>Week</strong></td>
</tr>
<tr>
<td><strong>E6</strong></td>
</tr>
<tr>
<td><strong>S5</strong></td>
</tr>
</tbody>
</table>

However, the mold combination of three E6 and one S5 does not work with F_TRD approach, as it uses EDD as the first priority rule to dispatch PCs, and ignores the urgent mold requirement by PC 14 and 15. Under this mold combination, S5 would have been occupied by PC 13 for several weeks from Week 6, owing to the earliest due dates. PC 13 has during these weeks. PC 14 and 15 would not get produced until a later week when their due dates become immediate. In this case, the late loading would inevitably cause some delays for PC 14 and 15, considering their relatively large demand. In order to generate a feasible master schedule with respect to due date, one more mold of S5 is added by F_TRD, at the price of extra mold investment.

With the CP rule adopted in its forward simulation, BI_CP can generate the same mold plan as F_CP. Moreover, the best mold 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 molds and sharable molds along the planning horizon separately. At first, the exclusive mold E6 is employed to produce as many of PC 13 as possible in every week. Then, the sharable mold S5 is used for production of PC 14 and 15, and the rest of PC 13. In this way, the unreasonable occupation of S5 by PC 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 mold costs. Owing to its trial-and-error nature, the actual planning method cannot guarantee an optimal solution, especially for a less experienced planner. It is possible that only sharable molds, 3 S3, are used in practice for simplicity, instead of the combination of both exclusive and sharable molds. Hereby, F_ACT gives the same answer as F_TRD to reflect this potential risk.

5.2.2 Labor Cost

It can be seen from Table 2 that of all the four planning approaches, BI_CP makes a good balance among changes in size of labor force over periods (hiring/firing cost), size of labor force in every period (NT cost), and OT consumed in every period (OT cost), thus achieving the lowest overall labor cost. For more specific comparisons among the four approaches, Figure 2 presents the sizes of labor force over periods, and Figure 3 shows the OT consumed over periods.

One main principle of F_ACT is to keep sizes of labor force over periods as stable as possible. This idea on labor planning is implemented in the experiment. As shown in Figure 2, F_ACT provides the minimum variation in size of labor force along the planning horizon. Therefore, it achieves the lowest cost for labor hiring and firing among the four approaches. Nevertheless, the stable sizes of labor force come with a price – relatively high NT cost and OT cost, as shown Table 2 and Figure 3.
As shown in Table 2, 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 sizes of labor force over periods, leading to very large costs for labor hiring and firing. Furthermore, additional OT has to be consumed to offset the shortage of labor hours available in every period.

Among the four production plans, BI_CP consumes the most NT hours, as shown in Table 2. However, it does make sense. Figure 2 and Figure 3 reveal that the high NT effectively avoids both dramatic changes in size of labor force and unnecessary OT. The best performance of BI_CP in overall labor cost is completely attributed to the underlying backward simulation, which pulls back PC production as late as possible and reduces excessive OT by utilizing NT available in the preceding forward simulation.

5.2.3 Stock Cost

The overall stock costs established by the four approaches are given in Table 2. As 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.

More specifically, Figure 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 planning horizon. This could result from the fact that it uses extra molds, as well as a large labor force and excess OT so as to expedite the production of PCs that are not needed until a later stage.

6 CONCLUSION

Precast technology has been and will be more and more extensively utilized in Singapore as well as many other developed countries. There is a need for a specialized planning model to aid precasters in effective production management. The model should effectively capture distinctive features of precast production, and help generate production plans to fully meet PC demand with minimum planning-related cost. Based on this requirement, a Simulation-GA based planning model is proposed for make-to-order precast production. Three simulation approaches – F_TRD, F_CP, and BI_CP – using different heuristics and different scheduling directions are established. A real-size planning example is then used to test their validity. By comparison of the results from the actual planning method (F_ACT) and the Simulation-GA based model with the three different approaches, some valuable findings were made. Among these approaches, BI_CP performs the best, not only in the overall planning-related cost, but also in nearly every cost category. Further analysis revealed that
in BI_CP approach, the CP rule helps generate an optimal mold combination, while backward simulation tends to reduce the excessive overtime and PC stock. In the future, more experiments will be conducted to confirm the validity of the Simulation-GA based model with BI_CP approach for precast production planning.

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