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Aggregate Production Planning Using Spreadsheet Solver: Model and Case Study

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ABSTRACT Among existing aggregate production planning (APP) approaches, the spreadsheet solver approach is found to be the most applicable for industries due to the following reasons: (1) the solver on spreadsheet software is readily available on virtually all personal computers, (2) the APP model is relatively easy to formulate in a spreadsheet format, and (3) the results are easy to interpret. This paper presents an APP model and a guideline to develop an optimal aggregate production plan using the spreadsheet solver approach. A manufacturing case study is presented to demonstrate how the guideline can be applied. The developed APP model is also evaluated whether it is satisfactory and can lead to immediate implementation.

KEYWORDS: Aggregate Production Planning (APP), Application in Industries, Spreadsheet Solver, Optimization, Case Study.

INTRODUCTION

Aggregate production planning (APP) is a medium term capacity planning that determines minimum cost workforce and production plans to meet customer demands. Its aim is to determine the production quantity and inventory level in an aggregate term. The aggregate production plan usually covers a time period ranging from 12 to 24 months. Data in the aggregate plan usually are monthly or quarterly data. APP has a strong need when a demand pattern is highly seasonal.

There are many techniques that can solve APP problems such as trial-and-error, linear and non-linear programming, linear decision rule, and simulation search.[1-4] Some of these techniques yield the optimum solution, while others give only acceptable ones. Additionally, some require models that are easy to formulate, while others require complicated models. Spreadsheet software is one of the powerful and practical tools for developing an aggregate production plan since it has a good user interface and optimization capability.

Spreadsheet software has many useful applications in production planning and control. For example, a spreadsheet template can provide multiple regression options.[5] It is helpful in solving forecasting problems when the dependent variable is binary. The spreadsheet models are also used to perform a sensitivity analysis of performance measures in manufacturing environment.[6] It can be used to determine whether available capacity and inventory is above the maximum level or below the minimum level.[7] Kharab also developed a macro program in the spreadsheet software to solve linear programming problems.[8]

The trial-and-error technique for solving APP problem can be performed faster if it is applied on the spreadsheet software. This technique is practical and very easy to understand since it does not require an extensive mathematical background. Since the trials are subjectively determined by a user, it usually takes relatively long time to obtain a feasible and satisfactory solution. Moreover, the solution may not be the optimal one. There are some papers demonstrating the way in which APP problems can be solved using the trial-and-error technique on the spreadsheet software.[9-11]

The spreadsheet solver is an add-in feature found in recent versions of the spreadsheet software such as Lotus 1-2-3, Microsoft Excel, and Borland's Quattro Pro.[12] This feature is capable of optimally solving linear and nonlinear programming problems. Albright et al. demonstrated the use of spreadsheet solver to solve small examples of APP problems.[13] Crandall varied some parameters such as inventory holding cost, back order cost, and hiring and laying off costs, and determined effects of individual parameters on a production plan in a variable demand environment.[14] The spreadsheet solver approach gives an optimal solution, does not require extensive mathematical background, and is easy to understand, to formulate the problem, and to interpret the results. Furthermore, it does not need additional investment on the software because the spreadsheet solver is already included in the spreadsheet software.

At present, most manufacturing companies do not systematically perform APP even though it is an important part for developing the detailed production scheduling due to the following reasons. Firstly, the APP model developed based on the requirements and constraints of their companies is not available. Secondly, most industries are not interested in a complex approach that requires an extensive mathematical background since they lack well-qualified engineers. Thirdly, most industries require an approach that is easy to understand and verify in order to easily convince their management to agree with its solution. Finally, an approach should not require additional investment on any expensive software due to the ongoing economic crisis. Based on these reasons, this study adopts the spreadsheet solver approach.

This paper has the following objectives:

1. To propose a spreadsheet APP model which is based on the general requirements and constraints of industries.
2. To propose a guideline for developing the optimal aggregate production plan using spreadsheet solver approach.
3. To study the effectiveness of the spreadsheet solver approach by evaluating whether the obtained aggregate production plan is satisfactory and can lead to immediate implementation.

This paper is organized as follows. Firstly, a general APP model based on the situations and general requirements of industries is presented in Section 2. Then, a guideline for developing the optimal aggregate production plan using spreadsheet solver approach is presented in Section 3. A case study to demonstrate the validity of the proposed guideline and to serve as an example for developing the optimal aggregate production plan is presented in Section 4. Finally, results are discussed and concluded in Section 5.

THE APP MODEL

The proposed APP model was developed with the requirements of the situations and general characteristics of industries. Therefore, it is different from models available on textbooks and journals and it seems to be more practical in industries.

Most industries use a monthly planning period for their master production plans. Therefore, the aggregate production plan should also adopt the monthly planning period in order to facilitate the disaggregation of the aggregate plan into the master production plan. The planning horizon of APP must be at least one year in order to cover the entire seasonal cycle.

Parameters and decision variables of the model are defined as follows.

Parameters

m = Number of monthly planning periods in the planning horizon

$n(t)$ = Number of normal workdays in period t

$h(t)$ = Number of holidays that can apply overtime in period t.

RH = Number of regular working hours in each normal workday

OH_n = Number of allowable overtime hours in each normal workday

OH_h = Number of allowable overtime hours in each holiday

$MIN\ W$ = Minimum number of permanent workers that can operate the production line

$MAX\ W$ = Maximum number of permanent workers to operate the production line

K_W = Average productivity rate per man-day of permanent worker

K_{TW} = Average productivity rate per man-day of temporary worker

$D(t)$ = Forecasted demand in period t

$SS(t)$ = Safety stock level in period t

$MAX\ O_n(t)$ = Maximum overtime man-hours that can be applied during normal workday in period t

$MAX\ O_h(t)$ = Maximum overtime man-hours that can be applied during holiday in period t

$MAX\ TW$ = Maximum number of temporary workers that can operate the production line

$MAX\ I$ = Maximum allowable inventory level

$MAX\ Sub$ = Maximum allowable subcontracting units

CW = Average salary per month of a permanent worker

CTW = Average wages per day of a temporary worker

CH = Hiring cost per person of temporary worker

CL = Laying off cost per person of temporary worker
CI = Average inventory holding cost per month per unit of product
COW_n = Overtime cost per man-hour of permanent worker during normal workday
COW_h = Overtime cost per man-hour of permanent worker during holiday
$COTW_n$ = Overtime cost per man-hour of temporary worker during normal workday
$COTW_h$ = Overtime cost per man-hour of temporary worker during holiday
$CSub$ = Subcontracting cost per unit

Decision variables

W = Number of permanent workers
$TW(t)$ = Total number of temporary workers in period t
$H(t)$ = Number of temporary workers to be hired at the beginning of period t
$L(t)$ = Number of temporary workers to be laid off at the end of period t
$OW_n(t)$ = Overtime man-hours of permanent worker during normal workday in period t
$OTW_n(t)$ = Overtime man-hours of temporary worker during normal workday in period t
$OW_h(t)$ = Overtime man-hours of permanent worker during holiday in period t
$OTW_h(t)$ = Overtime man-hours of temporary worker during holiday in period t
$UW(t)$ = Undertime (idle time) man-hours of permanent worker in period t
$UTW(t)$ = Undertime (idle time) man-hours of temporary worker in period t
$P(t)$ = Total production quantity in period t
$I(t)$ = Inventory level in period t
$Sub(t)$ = Amount of subcontracted unit in period t

Objective function

The objective of the APP model is to minimize the sum of permanent worker salary, temporary worker wages, overtime cost of permanent and temporary workers, hiring and laying off cost of temporary workers, subcontracting cost, and inventory holding cost. In this model, the overtime costs of permanent and temporary workers during workdays and holidays are different. Thus, the objective function as shown in equation (1) must take this into consideration. The objective function can be written as shown below.

Min total costs

$$= \sum_{t=1}^{m} [CW(W) + COW_n(OW_n(t)) + COW_h(OW_h(t)) + CTW(TW(t))\,n(t) + COTW_n(OTW_n(t)) + COTW_h(OTW_h(t)) + CH(H(t)) + CL(L(t)) + CSub(Sub(t)) + CI(I(t))] \qquad (1)$$

Constraints

1. Permanent worker constraint

In real industrial situation, most industries do not have a policy to repeatedly hire and lay off permanent workers since laying off incurs a relatively high compensation and results in loss of morale of employees and poor image of the companies. Therefore, the number of permanent workers must be the same for all periods. However, it may be of interest of some industries to know the optimal number of permanent workers that minimizes the total costs. Generally, if the optimal number of permanent workers is higher than the existing number, additional permanent workers can be hired. However, if it is lower than the existing number, there will be no laying off. The company will wait until some permanent workers resign. This practice is different from an assumption of past research papers that allows repeatedly hiring and laying off the permanent workers.[9-10,14-15]

The number of permanent workers should not be less than the minimum limit; otherwise the production line cannot function. Also, it should not be more than the maximum limit; otherwise some workers will be idle.

$$MIN\ W \le W \le MAX\ W \qquad (2)$$

2. Inventory constraints

The inventory in each period is equal to the inventory from the previous period plus the production minus the demand of that period.

$$I(t) = I(t\text{-}1) + P(t) - D(t) \quad \text{for } t = 1, 2, \ldots, m \qquad (3)$$

Moreover, all demands must be satisfied and the inventory level cannot be less than the specified safety stock level.

$$I(t) \ge SS(t) \quad \text{for } t = 1, 2, \ldots, m \qquad (4)$$

The inventory level cannot exceed the maximum allowable limit since there are limited warehouse spaces.

$$I(t) \leq MAX\ I \quad \text{for } t = 1, 2, ..., m \qquad (5)$$

3. Production constraints

The production quantity in each period is equal to the sum of production quantities generated by permanent and temporary workers during regular time and overtime (both regular workdays and holidays), plus subcontracted quantities, minus a loss of production due to undertime (idle time) in that period. Note that undertime can help to reduce unnecessary inventory level during low demand periods. Constraint (6) allows different productivity rates between permanent and temporary workers.

$$\begin{aligned} P(t) = \; & W \quad K_W \quad n(t) + (OW_n(t) + OW_h(t)) \\ & K_W/RH + TW(t) \quad K_{TW} \quad n(t) \\ + \; & (OTW_n(t) + OTW_h(t)) \; K_{TW}/RH + \\ & Sub(t) - UW(t) \quad K_W/RH \\ - \; & UTW(t) \quad K_{TW}/RH \\ & \text{for } t = 1, 2, ..., m \qquad (6) \end{aligned}$$

4. Overtime constraints

The total overtime man-hours of permanent and temporary workers must not exceed the maximum allowable limit. The limit is calculated based on the total number of permanent and temporary workers, number of days, and number of hours in each day that the overtime can be applied.

$$OW_n(t) + OTW_n(t) \leq MAX\ O_n(t) \quad \text{for } t = 1, 2, ..., m \qquad (7)$$

$$OW_h(t) + OTW_h(t) \leq MAX\ O_h(t) \quad \text{for } t = 1, 2, ..., m \qquad (8)$$

where $MAX\ O_n(t) = OH_n \quad n(t)\ (W + TW(t))$ for $t = 1, 2, ..., m$ (9)

and $MAX\ O_h(t) = OH_h \quad h(t)\ (W + TW(t))$ for $t = 1, 2, ..., m$ (10)

Since permanent and temporary workers work as a team in the same production line, the number of overtime man-hours per person applied to both groups must be the same. Thus, Constraints (11) and (12) are required.

$$OW_n(t) / W = OTW_n(t) / TW(t) \quad \text{for } t = 1, 2, ..., m \qquad (11)$$

$$OW_h(t) / W = OTW_h(t) / TW(t) \quad \text{for } t = 1, 2, ..., m \qquad (12)$$

5. Temporary worker constraints

The number of temporary workers in each period is equal to the number of temporary workers in previous period plus the number of temporary workers being hired at the beginning of that period minus the number of temporary workers being laid off at the end of the previous period.

$$TW(t) = TW(t\text{-}1) + H(t) - L(t\text{-}1) \quad \text{for } t = 1, 2, ..., m \qquad (13)$$

The total number of temporary workers in each period cannot exceed the maximum allowable limit since the production line has limited number of workstations where the temporary workers can be assigned.

$$TW(t) \leq MAX\ TW \quad \text{for } t = 1, 2, ..., m \qquad (14)$$

6. Subcontracting constraints

Number of subcontracting units cannot exceed the maximum allowable limit since subcontractors have limited production capacity.

$$Sub(t) \leq MAX\ Sub \quad \text{for } t = 1, 2, ..., m \qquad (15)$$

7. Non-negativity and Integer conditions

All decision variables are nonnegative and some decision variables representing number of workers, namely, W, $H(t)$, $L(t)$, and $TW(t)$ are integer. Since in real situation the variables W, $H(t)$, $L(t)$, and $TW(t)$ have relatively high values, the integer conditions for these variables can be relaxed in order to reduce the computation time. The solutions can be later rounded to the nearest integer.

In conclusion, the proposed APP model has salient characteristics that make it different from APP models in past research works. Firstly, the proposed APP model explicitly differentiates permanent and temporary workers since policies to manage these groups of workers and labor costs related to these groups are different. Secondly, number of permanent workers must be the same for all periods but the number of temporary workers can be varied by hiring and laying off. Thirdly, total working hours (normal working time plus overtime) for permanent and temporary workers must be the same because both groups work as a team on the same production lines. Finally, the proposed APP model allows different overtime labor costs during normal workdays and holidays since in practice the overtime labor cost during holidays is more expensive than that during normal workdays.

The proposed APP model has been tested in three companies and presented to eight companies in a

Workshop on APP for Thai Industries. Ten out of eleven companies were satisfied with the concepts and results of the proposed model after the model was slightly modified to match some specific requirements of the companies. Only one company requires significant changes on the model.

Guideline for Developing Optimal Aggregate Production Plan Using Spreadsheet Solver

The following guideline is proposed for the companies that are interested in developing their own APP. The objective of this guideline is to provide an easy and practical way to develop the aggregate production plan using the spreadsheet solver. The guideline will recommend steps for developing aggregate production plan and necessary information to be collected. By following this guideline step-by-step, the companies will be able to construct their own aggregate production plan. The recommended steps for developing the aggregate production plan using the spreadsheet solver are summarized in Figure 1.

Step 1. Data collection

Necessary data to be collected for developing APP model are all parameters in the proposed APP model presented in Section 2. In the case that the company does not have certain available information or some information cannot be exactly determined (such as inventory holding cost, and hiring cost), it can be estimated from other known information. For example, the inventory holding cost per year can be estimated to be 20%-30% of the product cost. If necessary, it can be divided by 12 to get the inventory holding cost per unit per month. The hiring cost of temporary workers can be calculated from recruitment costs and training costs for new workers.

It is recommended that a sensitivity analysis to analyze the effect of the estimated values on the obtained solution be performed when the estimated values are used instead of the exact values.

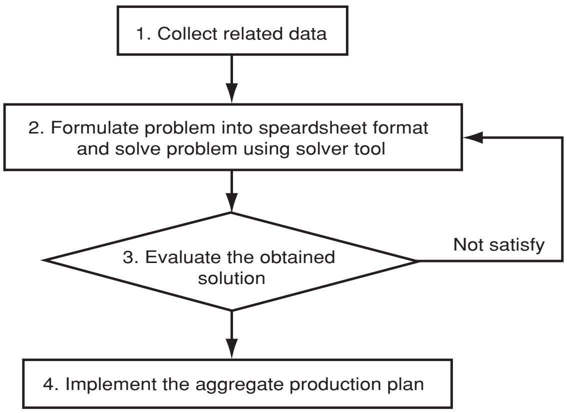

Fig 1. Recommended steps for developing the aggregate production plan.

Step. 2 Formulate APP model in the spreadsheet format

After obtaining the necessary information, a spreadsheet APP model will be formulated following the objective function and constraints discussed earlier. Some constraints of the proposed APP model may be modified or deleted to match specific requirements of each company. The spreadsheet APP model is then solved using the spreadsheet solver.

Step 3. Evaluate the obtained solutions

This step can be done by presenting the constructed spreadsheet APP model and its solutions to related departments of the company, namely, production, personnel, planning, sales and marketing, and warehousing, and let them judge whether the solutions are acceptable. The comparison between the existing aggregate production plan and the optimal plan generated from the APP model may be done in monetary term. If the solution is not acceptable, values of some input parameters may need to be reconsidered or the constraints may need to be modified. The spreadsheet APP model will be revised until the solutions are satisfactory.

Step 4. Implement the aggregate production plan

After the spreadsheet APP model is satisfactorily developed and solved, the obtained solutions can be implemented. During the implementation of the aggregate production plan, some parameters of the model may be changed, for example, demands, productivity rates, related costs, number of workers, and inventory levels. These parameters should be updated periodically and the APP model is solved to determine the revised aggregate production plan.

Case Study

A case study is presented to demonstrate the validity of the proposed guideline and to serve as an example for developing the optimal APP model. The company under consideration is a medium-sized manufacturer of air conditioning units located in Thailand.

Step 1. Data collection

By visiting and interviewing the company the collected data can be summarized as follows:

1. The planning horizon is 12 months.
2. Forecasted demands, number of holidays that can apply overtime, and number of normal workdays, in each period are shown in Table 1.
3. The regular working hours is 8 hours per day.
4. Numbers of allowable overtime hours for each normal workday and holiday are 2 and 8 hours, respectively.
5. Minimum and maximum numbers of permanent workers to operate the production line are 600 and 1,100 workers, respectively. Maximum number of temporary workers to operate the production line is 500 workers.
6. Average productivity rates of permanent and temporary workers are 5 and 4.5 units per man-day, respectively.
7. Amount of required safety stock in each period is zero.
8. Maximum allowable inventory level is unlimited.
9. Maximum subcontracting units is unlimited.
10. Average monthly salary per permanent worker is 5,500 Baht.
11. Average wage per day per temporary worker is 162 Baht.
12. Each temporary worker cannot be hired longer than four months according to Thai labor law. Otherwise the temporary worker must be transferred to become a permanent one.
13. Average cost of hiring one temporary worker is 1,200 Baht.
14. Laying off cost of temporary worker is negligible.
15. Average inventory holding cost per unit per month is 200 Baht.
16. Overtime costs per man-hour per permanent worker during normal workday and holiday are 34.38 and 45.83 Baht, respectively. Overtime costs per man-hour per temporary worker during normal workday and holiday are 30.38 and 40.50 Baht, respectively.
17. Subcontracting cost is 300 Baht per unit.
18. Amount of inventory at the beginning of the first period is zero.
19. The required amount of inventory at the end of the last period is zero.
20. There are currently 600 permanent workers and it is the company policy to keep the number at this level.
21. The company hired 150, 150, and 100 temporary workers three periods ago, two periods ago, and one period ago. They were hired at the beginning of periods.

Step 2. Formulate the APP model in the spreadsheet format

Based on the collected data, the APP model (in mathematical form) is formulated to clearly show the objective function and constraints as follows.

Objective function

$$\text{Min } Z = \sum_{t=1}^{12} [5500\ W + 34.38\ OW_n(t) + 45.83\ OW_h(t) + 162\ TW(t)\ n(t) + 30.38\ OTW_n(t) + 40.50\ OTW_h(t) + 1200 H(t) + 300\ Sub(t) + 200\ I(t)] \qquad (16)$$

Constraints

1. Permanent worker constraint

$$W = 600 \qquad (17)$$

2. Inventory constraints

$$I(t) = I(t\text{-}1) + P(t) - D(t) \quad \text{for } t = 1, 2, ..., 12 \qquad (18)$$

$$I(t) \geq 0 \quad \text{for } t = 1, 2, ..., 12 \qquad (19)$$

3. Production constraint

$$P(t) = 3000\ n(t) + 0.625\ (OW_n(t) + OW_h(t)) + 4.5\ TW(t)\ n(t)$$

Table 1. Number of workdays and holidays that can apply overtime, and forecasted demand in each period.

period	1	2	3	4	5	6	7	8	9	10	11	12
Number of normal workdays	23	22	25	20	21	24	17	16	18	21	22	17
Number of holidays that can apply OT	4	4	4	4	4	4	4	4	4	4	4	4
Forecasted demand (units)	136,000	140,000	146,000	147,000	160,000	140,000	82,000	38,000	45,000	81,000	105,000	117,000

$+ 0.5625\ (OTW_n(t) + OTW_h(t)) + Sub(t) - 0.625\ UW(t) - 0.5625\ UTW(t)$ for $t = 1, 2, ..., 12$ (20)

4. Overtime constraint

$OW_n(t) + OTW_n(t) \leq MAX\ O_n(t)$ for $t = 1, 2, ..., 12$ (21)

$OW_h(t) + OTW_h(t) \leq MAX\ O_h(t)$ for $t = 1, 2, ..., 12$ (22)

where $MAX\ O_n(t) = 2\ n(t)\ (600 + TW(t))$ for $t = 1, 2, ..., 12$ (23)

and $MAX\ O_h(t) = 8\ h(t)\ (600 + TW(t))$ for $t = 1, 2, ..., 12$ (24)

$OW_n(t) / 600 = OTW_n(t) / TW(t)$ for $t = 1, 2, ..., 12$ (25)

$OW_h(t) / 600 = OTW_h(t) / TW(t)$ for $t = 1, 2, ..., 12$ (26)

5. Temporary worker constraint

Thai labor law stated that temporary workers could not be continuously hired longer than four months. After four months they must become permanent workers. Hence, Thai industries will lay off temporary workers after four months if they do not want to transfer them to permanent ones. Therefore, the Constraint (13) that is a general one must be specifically modified into Constraint (27) and (28). Constraint (27) shows that the total number of temporary workers working in the current period is the sum of the numbers of temporary workers hired at the beginning of the last three periods and the current period. Constraint (28) indicates that temporary workers hired three periods ago will be laid off at the end of the current period. APP models developed from literature do not have these constraints.[9-10, 14-15]

$TW(t) = H(t\text{-}3) + H(t\text{-}2) + H(t\text{-}1) + H(t)$ for $t = 1, 2, ..., 12$ (27)

$L(t) = H(t\text{-}3)$ for $t = 1, 2, ..., 12$ (28)

$TW(t) \leq 500$ for $t = 1, 2, ..., 12$ (29)

6. Non-negativity and integer conditions

All decision variables are non-negative. $H(t)$ are integer for $t = 1, 2, ..., 12$.

Spreadsheet model

The spreadsheet APP model is shown in Table 2. The model is divided into two sections. The first section (the top part of the table) is the input data section. All collected information will be entered into the corresponding cells. The second section is the calculation section. There are formulas embedded in cells to calculate the needed output. The decision variables are the number of temporary workers to be hired at the beginning of each period, numbers of overtime man-hours for permanent and temporary workers during normal workdays and holidays in each period, number of undertime man-hours in each period, and number of subcontracted units in each period. The spreadsheet APP model is solved and the optimal aggregate production plan is shown in Table 2. The related costs are calculated and shown in the bottom part of Table 2. The grand total cost which is the objective function of the model is shown in the lower right cell of the table.

Step 3: Evaluate the obtained solutions

After the spreadsheet APP model and the obtained optimal aggregate production plan are presented to the company, there are comments as follows. Firstly, the model has a very good user interface. The outputs (worker plan, production plan, and summary of costs) of the model contain useful information and are easy to understand. The model requires some inputs, which are not currently available, but they are possible to be estimated. Secondly, the model can be verified easily since values of all parameters, decision variables, objective function, and constraints are explicitly shown on only one page. Correctness of mathematical formula can be simply checked using a calculator. Management team of the company is rapidly convinced to trust the correctness of the model.

Thirdly, the obtained optimal aggregate production plan shown in Table 2 is acceptable. During low-demand periods (e.g., August and September), the numbers of temporary workers are very low or zero, there is no overtime work, and some workers must work undertime to avoid producing unnecessary inventories. During moderate-demand periods (e.g., October), some temporary workers are hired, but there is no overtime work and no undertime. During high-demand periods (e.g., January), temporary workers are hired and they must work overtime during workdays. However, there is no overtime work during holidays. During very-high-demand periods (e.g., May), temporary workers are hired, and they must work overtime during workdays and holidays. Subcontracting is not recommended in any period since it is the highest cost alternative. At the end of April (before entering the highest-demand period), creating 1,187 units of inventory is recommended since carrying inventory for one

Table 2. Spreadsheet APP model.

Input Data						
		Average salary of each permanent worker, CW	5,500		Average wages per day of each temporary worker, CTW	162
Beginning inventory, I(0)	0	Allowable OT hour in each normal workday, OI_n	2		Hiring cost per person of temporary worker, CH	1,200
Target ending inventory, I(T12)	0	Allowable OT hour in each holiday, OI_h	8		Max no. of temporary workers, MAX TW	500
Maximum number of permanent workers, MAX W	1,100	Average productivity rate per man-day of permanent worker, K_W	5.00		Average productivity rate per man-day of temporary worker, K_{TW}	4.50
Regular working hour in each normal workday, RW	8	OT cost of permanent worker during normal workday, COW_n	34.38		OT cost of temporary worker during normal workday, $COTW_n$	30.38
Average inventory holding cost/unit/month, CI	200	OT cost of permanent worker during holiday, COW_h	45.83		OT cost of temporary worker during holiday, $COTW_h$	40.50
Subcontracting cost/unit, CSub	300					
Safety Stock Level, SS(t)	0			No. of workers being hired in last 3 months, H(t)	Month -3: 150 / Month -2: 150	Month -1: 100

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
No. of normal workdays, n(t)		23	22	21	20	22	24	17	16	18	21	22	17	246
No. of working holiday, h(t)		4	4	4	4	4	4	4	4	4	4	4	4	48
Forecasted demand, D(t)		136,000	148,000	146,000	147,000	168,000	140,000	82,000	38,000	45,000	81,000	105,000	117,000	1,357,000
Worker Plan		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
No. of Permanent Workers, W		600	600	600	600	600	600	600	600	600	600	600	600	7,200
No. of Temporary Workers, TW(t)		500	460	500	500	500	385	200	100	0	190	384	500	4,214
No. of hired temp worker (beginning of period), H(t)		100	115	185	100	100	0	0	0	0	190	200	106	1,300
No. of laid off temp worker (ending of period), L(t)		150	158	100	100	113	185	100	100	0	0	0	0	1,000
Maximum OT during normal workdays, $MAX\,O_n(t)$		50,600	46,844	55,000	44,000	46,200	47,297	27,200	22,400	21,600	33,200	40,750	37,400	
Total Overtime hour during normal workday		25,087	46,844	24,736	44,000	46,200	43,839	25,764	0	0	0	0	37,400	
Normal OT man-hours for permanent workers, $OW_n(t)$		13,943	26,400	13,486	24,000	25,200	26,749	19,323	0	0	0	0	20,400	
Normal OT man-hours for temporary workers, $OTW_n(t)$		11,619	20,444	11,238	20,000	21,000	17,100	6,441	0	0	0	0	17,000	
Normal OT hour for each worker		23	44	22	40	42	45	32	0	0	0	0	34	
Maximum OT during holiday, $MAX\,O_h(t)$		35,200	34,058	35,200	35,200	35,200	31,531	25,600	22,400	19,200	25,293	30,809	35,200	
Total Overtime hour during holiday		0	0	0	28,390	35,200	0	0	0	0	0	0	9,114	
Holiday OT man-hour for permanent workers, $OW_h(t)$		0	0	0	15,486	19,200	0	0	0	0	0	0	4,971	
Holiday OT man-hour for temporary workers, $OTW_h(t)$		0	0	0	12,903	16,000	0	0	0	0	0	0	4,143	
Holiday OT hour for each worker		0	0	0	26	32	0	0	0	0	0	0	8	
Total Undertime		0	0	0	0	0	0	0	3,490	1,800	0	0	0	
Undertime man-hour for permanent workers, UW(t)		0	0	0	0	0	0	0	2,991	1,800	0	0	0	
Undertime man-hour for temporary workers, UTW(t)		0	0	0	0	0	0	0	499	0	0	0	0	
Undertime hour for each worker		0	0	0	0	0	0	0	5	3	0	0	0	
Production Plan		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Production from permanent workers		69,000	66,000	73,000	60,000	65,000	72,000	51,000	33,043	45,000	63,000	66,000	51,000	714,043
Production from temporary workers		51,750	48,000	36,250	45,000	47,250	41,618	13,500	4,957	0	15,000	39,000	38,250	403,175
Normal OT production of permanent workers		8,714	16,500	8,429	15,000	15,750	16,718	12,077	0	0	0	0	12,750	105,938
Normal OT production of temporary workers		6,536	11,500	6,321	11,250	11,813	9,664	3,623	0	0	0	0	9,563	70,269
Holiday OT production of permanent workers		0	0	0	9,679	12,000	0	0	0	0	0	0	3,107	24,786
Holiday OT production of temporary workers		0	0	0	7,259	9,000	0	0	0	0	0	0	2,330	18,589
Subcontracted unit		0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL PRODUCTION		136,000	148,000	146,000	148,188	158,813	140,000	82,000	38,000	45,000	81,000	105,000	117,000	1,357,000
Demand		136,000	148,000	146,000	147,000	168,000	140,000	82,000	38,000	45,000	81,000	105,000	117,000	1,357,000
Ending inventory	0.00	0	0	0	1,187	0	0	0	0	0	0	0	0	1,187
Summary of Costs		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Permanent workers salary		3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	3,300,000	39,600,000
OT wages of Permanent workers		479,266	907,500	463,571	1,534,763	1,746,258	919,501	664,231	0	0	0	0	939,107	7,644,208
Temporary workers wages		1,863,000	1,610,000	2,025,000	1,620,000	1,701,000	1,488,333	550,800	259,200	0	648,000	1,404,000	1,377,000	14,600,235
OT wages of Temporary workers		352,939	621,000	341,317	1,138,143	1,255,875	521,836	195,644	0	0	0	0	584,161	5,132,946
Hiring cost of temporary workers		120,000	137,576	222,424	120,000	120,000	0	0	0	0	228,571	244,156	127,273	1,320,000
Inventory holding cost		0	0	0	237,500	0	0	0	0	0	0	0	0	237,500
Subcontracting cost		0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL COST		6,115,204	6,622,076	6,352,313	7,942,405	8,153,125	6,229,501	4,710,677	3,559,200	3,300,000	4,176,571	4,948,156	6,417,541	68,316,958

period is less costly than subcontracting in May. This is due to the fact that the overtime schedules during workdays and holidays reach their maximum limits in May. With this situation, the production quantity cannot be increased unless (costly) subcontracting is allowed. Thus, producing additional units in April and carrying them over to May can avoid utilizing subcontracting.

Based on the optimal aggregate production plan with an objective to minimize the total cost, the optimal policy for adjusting production rates for Thai industries is recommended and presented in Table 3. To increase the production rate, the first priority is to hire temporary workers, the second priority is to apply overtime work during workdays, and the last priority is to apply overtime work during holidays. The undertime may be applied during low-demand periods to reduce production rate and avoid unnecessary inventory.

This optimal policy is different from the current normal practice of Thai industries that is also presented in Table 3. Thai industries firstly apply overtime work during workdays, and then during holidays, and finally use temporary workers since applying overtime work is the most convenient (but costly) method. Moreover, they never allow undertime, which results in carrying unnecessary inventory. The normal practice of Thai industries is different from the optimal policy since Thai industries do not explicitly consider costs related to APP and do not try to minimize the total cost. Therefore, the proposed spreadsheet APP model is very useful for Thai industries.

Step 4. Implement and revise the aggregate production plan

Since the optimal aggregate production plan is satisfactory, it is immediately implemented in the company. After one month, the aggregate production plan is regenerated using a rolling horizon concept. We need to add forecasted demand, number of workdays, and number of holidays that can apply overtime of the last period to the spreadsheet APP model and update forecasted demands of other periods. The inventory at the beginning of the first period, target inventory at the end of the last period, and number of workers hired during last three months are also updated. Updating the input data before regenerating the optimal aggregate production plan takes less than 10 minutes, and it takes less than one minute of computation time by the spreadsheet solver to obtain the optimal solution using a 500 MHz, Pentium III PC. The company currently takes about one day for manually generating an acceptable (but not optimal) aggregate production plan. Therefore, the company can save significant time of a planner in using the spreadsheet APP model instead of manually generating the aggregate production plan.

Discussion and conclusions

This paper proposes a four-step guideline for developing the optimal aggregate production plan for industries. A general APP model is developed based on real situations and requirements of industries. A case study is presented to demonstrate how to develop the optimal aggregate production plan using the proposed guideline.

The proposed APP model and the obtained optimal aggregate production plan are useful for most industries since they supply useful information and recommend appropriate actions. They recommend the optimal number of temporary workers to be hired at the beginning of each period, the optimal number of temporary workers to be laid off at the end of each period, and the number of temporary workers that should be available in each period. These pieces of information are useful for managing human resources of the company. They also recommend the optimal number of overtime man-hours of permanent and temporary workers during workdays and holidays, inventory level, number of subcontracting units, and number of undertime man-hours for some periods. Related cost elements and the total cost are presented for financial consideration by top management.

Table 3. Comparison of the optimal policy and current normal practice of APP in Thai industries.

	Optimal policy	Current normal practice
1. Priority to adjust production rates	1st priority: Hire temporary workers 2nd priority: Apply OT during workdays 3rd priority: Apply OT during holidays	1st priority: Apply OT during workdays 2nd priority: Apply OT during holidays 3rd priority: Hire temporary workers
2. Application of undertime	Undertime may be applied during low-demand periods	Never allow undertime
3. Cost consideration	Explicitly consider costs related to APP and optimize them	Not consider costs related to APP

The normal practice for adjusting production rates adopted by most industries is different from the recommended aggregate production plan. The industries tend to firstly select an alternative that is the most convenient to manage (such as applying overtime) although it is more costly than other alternatives (such as hiring temporary workers). This normal practice occurs since firstly, the industries do not explicitly consider costs or try to minimize the total cost when they develop the aggregate production plan. Secondly, they lack well-qualified engineers in production planning section to develop a workable APP model. Therefore, the proposed guideline to develop the optimal aggregate production plan using the spreadsheet APP model should be able to help them reduce production costs and increase competitive advantages.

The proposed general APP model is applicable for a wide range of industries in which the production quantity per period can be adjusted by changing the number of workstations and number of workers, and by applying overtime. However, the proposed APP model is not applicable for the process industries since the number of workstations and number of workers cannot be changed. In such cases, the production quantity per period can be adjusted by changing the number of working days and applying overtime. A new APP model can be constructed with different set of constraints to handle the process industries. It is recommended that further studies be conducted to develop APP models to match specific requirements of the process industries and others. Appropriate methods for disaggregating the aggregate plan into the master production plan should also be further developed based on situations and requirements of industries.

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