

The Maximum Setup Time and Setup Cost of Achieving Just-in-Time System

Fu C. Chyr^{1*} & Shan Y. Huang²

¹ Department of International Business, Chang Jung Christian University, Tainan, Taiwan

² Department of International Trade, Overseas Chinese University, Taichung, Taiwan

* Fu C. Chyr, E-mail: chyr@mail.cjcu.edu.tw

Abstract

The primary topic of operation management has turned to setup cost reduction because of the success of Just-in-Time (JIT) system. Setup cost is treated as a policy variable that can be reduced. A few papers prove that setup cost reduction will increase the number of setups and approach to JIT. However, those papers do not discuss the maximum setup time allowed that will successfully achieve to JIT. The Wagner-Whitin (WW) algorithm is known to produce optimal lot size for T-period dynamic lot-sizing problems. This paper develops an extension of the WW algorithm to establish a recursive model and find the sufficient and necessary conditions of yielding JIT. Furthermore, the limited maximum setup time that will yield JIT system is discussed. The maximum setup time of achieving JIT can be easily computed and understood in practice. The formula and table of the setup time allowed are obtained to act as a goal of reducing setup time in JIT system.

Keywords

JIT, setup cost reduction, setup time, recursive model

1. Introduction

Due to the success of JIT system, setup cost reduction becomes a powerful concept and tool in operation management (Porteus, 1985; Kim, 1990; Cavinato, 1991; Mekler, 1993; Chyr, 2005; Chang & Chyr, 2010). Setup cost is treated as a policy variable that can be decreased. A few papers study the application of setup time reduction (Esrock, 1985), this paper extends that of the maximum setup time allowed that will successfully achieve to JIT. The approach of setup time reduction can be useful for practitioners and academics. The results of maximum setup time of achieving JIT can be extended to the multi-level dynamic lot-sizing problem in the future studies.

The past papers devoted to obtain the optimal solution of the Dynamic Lot-Sizing (DLS) problem and ignore the importance of setup reduction. This paper considers a T period production planning problem in which a sequence of known demands D_1, D_2, \dots, D_T must be satisfied. The total costs of production in period t include setup costs S_t and holding costs. The cost of carrying a unit of inventory into period t is I_t . An optimal policy is a production plan that satisfies demands at minimum setup and holding costs. In WW algorithm setup and unit holding costs are parameters which may differ from period to period (1958) while the manufacturing cost is independent of the amount produced in each period and constant overtime. No backorders are allowed, lead time is zero, and its objective is to minimize the sum of holding and setup costs for all periods in the planning horizon. The WW algorithm does not treat the setup costs as a variable. It devotes to solve the minimum total costs when the setup costs in each period are known. Since the computational complexity of the multi-level lot-sizing problems, Dellaert and Jeunet use a hybrid genetic algorithm to find the heuristic solutions (2000). Both of them focus on obtaining the optimal solution and ignore the benefit of setup reduction.

Operations Management has turned to the popular concepts of Just-in-Time (JIT) and Zero Inventories (ZI). The goals of JIT aim to reduce lot-size and result in ZI that can decrease total costs of DLS problem. The concept of setup cost reduction is widely applied to the production system. The consequence of setup cost reduction and smaller lot-sizes is significantly decreasing inventory. In sum, the setup cost reduction increases overall production efficiency. We devote to reduce setup costs all the way down to its lower limit. Many companies can benefit from lowering inventory levels. Nonetheless, few papers can define and compute the lower limit of the setup cost. The setup cost reduction becomes an abstract concept. This paper tries to transform the presentation of setup cost into the setup time. In a world where the setup time is becoming the competitive weapon, companies cannot maintain excessive inventories.

This paper develops a new recursive algorithm revised from the WW model to find the necessary and sufficient conditions of achieving JIT. It should be considered as an extension of the WW (1958) model wherein costs and demand are dynamic but deterministic. Wagner and Whitin obtain optimal solutions with a shortest route, dynamic programming algorithm under the assumption that no carrying cost is incurred unless inventories are carried from one period to another. We reconstruct the recursive relation existed in WW to clearly realize the utilization of setup cost reduction and easily compute the optimal solution.

This paper also extends the work of Porteus (1985), Billington (1987) and Zangwill (1987) by analyzing the effects of setup cost reduction on lot-size and total cost. Since one fundamental reason for holding inventory is setup costs, it is logical to concentrate on this aspect of the inventory model. Whereas Zangwill discusses setup cost reduction, not setup time reduction. Thus, we minimize total relevant costs, consisting of setup, holding and setup reduction. The setup time reduction based on the WW model also is discussed in this paper.

Before developing new model, let us review a few papers in setup cost reduction by highlighting the importance of JIT concept. For instance, Porteus and Chyr (1990) have done extensive research in setup cost reduction. They use an Economic Ordering Quantity (EOQ) model to study the effects of reduced setup costs. They assert that a single optimal setup cost should be found and maintained throughout a given planning horizon. They also address that the setup cost reduction will decrease lot size and total cost.

Billington (1987) extends the work of Porteus to the Economic Production Quantity (EPQ) model by balancing holding cost, setup cost and capital investment. He discusses two different setup cost reduction functions of investment: a decreasing exponential function that gives rise to a convex total cost and a declining linear function that leads to a concave total cost. Besides, he allows a technological nonzero lower limit to setup cost. In his model, He assumes constant demand for a single item in a single-stage manufacturing over an infinite horizon. He treats the investment as a sunk cost and does not include it in the cost function being minimized. This results in a slightly lower optimal setup cost. The maximal setup time limited is not yet discussed in Billington's research. Kim (1990) extends Billington's research to other standard setup reduction functions and analyzes by mathematical approach. Diaby (2000) extends their investigation to multi-product situation. Gallego and Moon (1995) show that for the Economic Lot Scheduling Problem (ELSP), setup times and costs can be reduced by an initial investment that is amortized over time. For most recent literatures on the ELSP, refer to Moon et al. (2002) who applied the genetic algorithm to the ELSP.

Spence and Porteus (1987) discuss the value of setup time reduction in the implementation of the JIT and Zero Inventory strategies. They also discuss how setup time reduction increases a factory's

effective capacity and how to use this capacity to either reduce lot sizes (i.e., perform more setups) or reduce overtime. Esrock (1985) gives an exhaustive list of the positive influences of setup time reduction on manufacturing operations. Cavinato (1991) stresses the importance of setup reduction in increasing a company's competitive edge. He notes the ripple effect is tremendous: less storage, less time between production runs, less time customers wait for their goods, more produce-to-order, and less produce-to-stock, easier ability to customize goods for customers, and in some instances it is possible to be paid by customers before payment must be made to suppliers. Hahn, Bragg and Shin (1988) examine the operating characteristics of setup when used as a decision variable in a capacity-constrained environment. Their study states that setup time reduction is a key way to increase effective capacity based on descriptive statements. This paper proves that setup time reduction can move towards JIT by mathematical approach.

Moreover, we consider Zangwill's advanced work on the dynamic lot-size model. He uses the WW model to analyze setup cost reduction in DLS problem. Zangwill obtains that changing demands and costs invalidate the EOQ formulation. Specifically, decreasing setup cost in the WW model may not have the same result as in an EOQ model. Furthermore, in Zangwill's analysis of the effects of setup cost reduction, increasing setup cost reduction will increase the number of setups and decrease total costs where all setup costs are reduced by constant r , but the setup costs are dynamic in that they may differ from period to period, both before and after any setup reduction. He develops an algorithm to calculate the minimal cost when the setup costs are reduced by r . This algorithm identifies in which periods to produce, since, with varying production and inventory costs, it is not enough to determine in how many periods to produce without specifying which periods. However, he does not mention the maximum setup cost and setup time allowed to execute JIT.

Meanwhile, Freeland et al. (1990) look at the WW model and provide guidelines for setup reduction programs. Their objective is not to reduce setup cost as much as possible, but only until they have achieved zero inventory. Zangwill also presents a procedure by increasing the number of facilities and dropping inventory. His goal is not to obtain an optimal production schedule; instead, it is to identify those facilities best suited for JIT. He uses an algorithm that incrementally reduces setup costs in an effort to obtain ZI. He emphasizes the ratio of setup cost to incremental holding costs, as opposed to simply setup cost. The discussion of maximum setup time allowed is still excluded.

Mekeler (1993) considers the investment of setup cost reduction and use an exponential setup reduction function to generate an optimal lot-sizing schedule. The maximum setup cost allowed to achieve JIT has not been discussed. Chyr (1990, 2005) presents the effects of non-stationary setup cost reduction to extend the result shown in Zangwill. Furthermore, this paper devotes to find the maximal setup cost and setup time of achieving JIT ignored in the past researches.

Due to the complexity of computation, Chang, Chyr and Yang (2010) adopt simulation to discuss the effects of reducing setup cost in the large-scale multi-level lot-sizing problem. This paper discusses the single level lot sizing problem to simplify the computation based on mathematical model without simulation.

2. A New Recursive Algorithm of the Wagner-Whitin Model

2.1 The Conventional Wagner-Whitin Model

We develop a new approach of the WW algorithm to find the sufficient and necessary conditions of achieving JIT. The WW model is a multi-period, lot-size problem with dynamic constant demand at each period. No backorders are allowed, lead time is zero, and its objective is to minimize the sum of

holding and setup costs for all periods in the planning horizon. This objective is constrained only by the production balance equation i.e., by

$$IQ_t + X_t - D_t = IQ_{t+1} \quad (1)$$

Where, in period t , IQ_t is the beginning inventory, X_t the lot-size, D_t the demand, and IQ_{t+1} the ending inventory. Let j denote the period of final setup in a production policy, h_t denote the unit holding cost for period $t-1$ through period t . The minimum total cost $F(T)$ of the original WW algorithm in period T can then be written as:

$$F(T) = \min. \left[\min_{1 \leq j < T} \left[S_j + \sum_{h=j}^{T-1} \sum_{k=h+1}^T h_h D_k + F(j-1) \right] \right. \\ \left. S_T + F(T-1) \right] \quad (2)$$

Where $F(0)=0$, $F(1)=S_1$. There are two important theorems which reduce the number of computation required. The formula (1) suggests considering programs where $IQ_t X_t = 0$ that nothing is produced for any period when inventory is brought into that period. The period $t-1$ has regeneration property. This can simply be interpreted as either a produce or carrying inventory policy. Second, all lot-sizes will satisfy demand for an integer number of periods. The WW algorithm exploits these two properties to reduce computation time. However, the formulation (2) can not obviously show the benefits of setup reduction.

2.2 A Revised Wagner-Whitin Model

We revise and present a new recursive relation between period $t-1$ and period t shown in the formulation (2) to find the benefit of setup reduction. Let $F(t, j)$ denote the total setup and holding costs at period t in which the final setup is performed in period j , where $j=1, 2, \dots, t$. Adopting the notation, the following recursive relation is existed.

$$F(t, j) = F(t-1, j) + D_t \sum_{k=t}^{j+1} h_k \quad (3)$$

Where $j=1, 2, \dots, t-1$. The $F(T)$ of the original WW algorithm in period T can be revised as:

$$F(T) = \min. \left[\min_{1 \leq j < T} \left[F(T, j) \right] \right. \\ \left. S_T + F(T-1) \right] = \min. \left[\begin{array}{l} F(T-1, j) + D_T \sum_{k=T}^{j+1} h_k \\ F(T-1) + S_T \end{array} \right] \quad (4)$$

The new recursive expression is simpler than traditional WW and more meaningful. We can find the necessary and sufficient conditions of executing JIT through the above expression.

3. The Necessary and Sufficient Conditions of Executing JIT

The JIT system can be defined as $X_t = D_t$ for each period t . No inventory is carried from period t to period $t+1$. It means that production policy of $X_t = D_t$ is the best. How can we achieve the goal through reducing setup cost?

[Theorem 1]

If $S_t \leq D_t h_t$ exists for $t=2, 3, \dots, T$, then the minimum total cost is $\sum_{t=1}^T S_t$.

Proof:

$$\because S_t \leq D_t h_t \leq D_t \sum_{k=t}^{j+1} h_k \quad \text{and} \quad F(T-1) \leq F(T-1, j),$$

$$\therefore F(t) = F(t-1) + S_t$$

$$\because F(0) = 0, \quad \therefore F(T) = \sum_1^T S_t$$

If the setup cost can be decreased to the above level, adopting production policy of $X_t = D_t$ in each period t can be achieved. Theorem 1 shows that the maximum setup cost S_t for each period t is not higher than $D_t h_t$, and then the reproduce policy can be adopted in each period t .

[Theorem 2]

If the minimum total cost is $\sum_{t=1}^T S_t$, then $S_t \leq D_t h_t$ exists for $t=2, 3, \dots, T$.

Proof:

If $S_t > D_t h_t$ exists at any period t , then $F(t-1) + S_t$ may not be the minimum. Therefore,

$F(T-1, j) + D_T \sum_{k=T}^{j+1} h_k$ may be the minimum. This will result in the minimum total cost is not

$$\sum_{t=1}^T S_t.$$

Theorem 1 and theorem 2 show that reducing the setup cost S_t in each period t to the level of $D_t h_t$ will achieve the JIT system. This result addresses the goal of decreasing the setup cost is a good policy. However, the maximum amount of setup cost permitted is not easily understood in a practical production system. We will try to transform it into the setup time which can be easily understood in real production system.

4. The Maximum Setup Time Limited in JIT System

To formulate the maximum setup time permitted in the JIT system, we use the following notations:

- 1) TS_t : the setup time at period t ,
- 2) TT : the daily production time in minutes,
- 3) TO : the processing time of producing one unit product,
- 4) Q : the daily production quantity,
- 5) N_t : the ratio of D_t/Q at period t ,
- 6) I_t : the unit carrying rate from period $t-1$ to period t ,
- 7) V : the value-added rate of one unit product,
- 8) P : the unit price.

Using the above notations, the setup cost S_t can be formulated as:

$$S_t = \frac{TS_t}{TT} \times Q \times P \times V = \frac{TS_t}{TT} \times \frac{TT}{TO} \times P \times V = \frac{TS_t}{TO} \times P \times V \quad (5)$$

The formulation (5) mentioned above shows the relation between the setup cost S_t and the setup time TS_t in period t .

The holding cost $D_t h_t$ can be formulated as

$$D_t h_t = D_t \times P \times I_t \quad (6)$$

To achieve JIT, the formulation $S_t \leq D_t h_t$ should be satisfied. We can develop the following formulation to show the relation between TS_t and the other factors.

$$TS_t \leq D_t \times TO \times \frac{I_t}{V} \quad (7)$$

Since the processing time of producing one unit product, TO , is dependent on the product item, we can not obtain practical information about the maximum setup time, TS_t . Let N be $\frac{D_t}{Q}$. We obtain

$$D_t \times TO \times \frac{I_t}{V} = N \times Q \times TO \times \frac{I_t}{V} = N_t \times TT \times \frac{I_t}{V}$$

The formulation $TS_t \leq D_t \times TO \times \frac{I_t}{V}$, can be revised as

$$TS_t \leq N_t \times TT \times \frac{I_t}{V} \quad (8)$$

Using the above notations, we have successfully transformed the setup cost S_t at period t into the setup time TS_t . The setup time, TS_t , is decided by the factors of $N_t (=D_t/Q)$, TT , V and I_t . The results are as follows.

- 1) Increasing the ratio of $D_t/Q (=N_t)$ will yield a higher TS_t permitted.
- 2) The higher daily working time will result in a higher TS_t permitted.
- 3) The higher I_t will increase TS_t permitted.
- 4) The lower value-added ratio, V , will permit a higher TS_t .

The maximum setup time permitted to achieve JIT, TS_t , can be computed as the formulation mentioned above. Since the value of N , TT , V and I_t can be easily collected, so the setup time permitted, TS_t , can be obviously obtained. This result addresses that the setup time at period t is reduced to the TS_t level shown in Table 1, the goal of JIT can be completed. Let the daily working minutes TT be 1440. The value-added ratio V is 0.5. The setup time affected by the value of N_t and I_t are computed as Table 1.

Table 1. The Maximum Setup Time TS_t (Minutes) Permitted to Achieve JIT

$TT=1440, V=0.5$				$TT=480, V=0.5$		
$N_t \backslash I_t$	0.01	0.02	0.03	0.01	0.02	0.03
0.25	7.2	14.4	21.6	2.4	4.8	7.2
0.5	14.4	28.8	43.2	4.8	9.6	14.4
0.75	21.6	43.2	64.8	7.2	14.4	21.6
1	28.8	57.6	86.4	9.6	19.2	28.8
2	57.6	115	172.8	19.2	38.4	57.6
3	86.4	172	259.2	28.8	57.6	86.4

Table 1 is plotted as the following figure. The relation between TS_t and D_t/Q is obviously shown in the Figure 1. The higher carrying rate and demand will significantly increase the setup time required in JIT system.

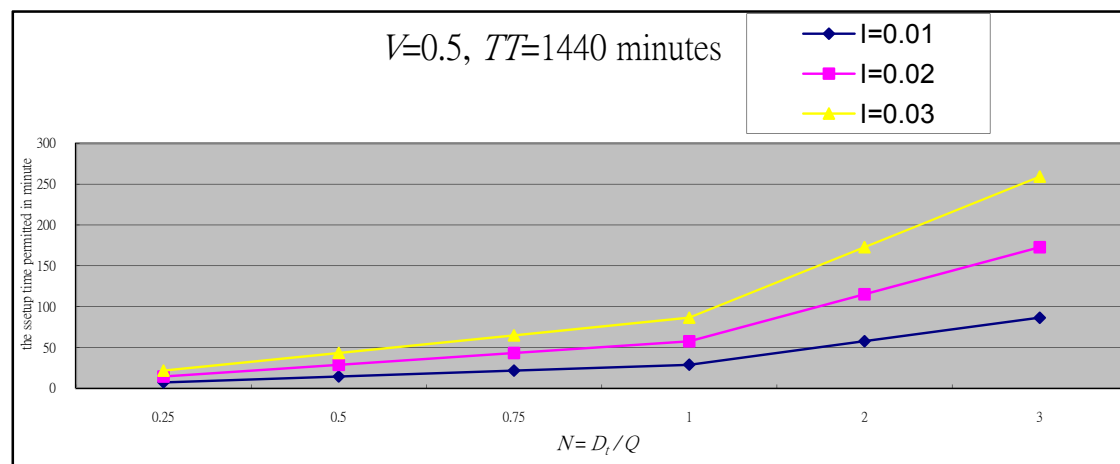


Figure 1. The Relation between TS_t and D_t/Q

Hall (1983) mentions that the carrying rate per month is approximate 0.03. Under the conditions with $T=1440$ and $V=0.5$, if the demand D_t is equal to the production quantity Q per day, then the setup time permitted is 86.4 minutes. As shown in Table 1 if the demand D_t is equal to $0.5*Q$, then the setup time permitted is 43.2 minutes. The setup time shown in Table 1 can be achieved in recent technology. We use the formulation and Table1 to obtain the following results.

1) If the factors of V , TT , I_b , D_b , Q and N_t are known, then we must try to decrease the setup time to the level shown in the formulation.

2) The higher values of TT , I_b , D_b , Q and N_t increase the setup time limited to achieve JIT.

All of the permitted setup time mentioned above in JIT system is the goal of the recent technology. Using the concept of setup time permitted is clear and useful than that of setup cost.

5. Conclusions

This paper finds the maximum setup cost and setup time to prove the success of JIT system. The WW algorithm, which solves the dynamic lot-size problem, discusses the minimum total cost and ignores setup cost reduction. By treating setup cost to be variable in the WW algorithm as well as by revising the recursive relation between adjacent periods, the maximum setup cost allowed in JIT system is obtained. Our goal is to find minimum total cost as before, but in addition, we emphasize how much to reduce in setup cost reduction in order to take reproducing policies in each period.

By reconstructing the WW model, we develop the necessary and sufficient conditions of reaching JIT system. The results show that reducing setup cost to the level of $D_t h_t$ at each period t will result in JIT. These theorems offer useful insights into the effects of setup cost reduction in conventional models.

Since the setup cost is hard to be realized for production manager, we provide the concept of setup time to explain JIT. Considering the factors of $N_t (=D_t/Q)$, TT , V and I , the results show that reducing setup

time to the level of $N_t \times TT \times \frac{I_t}{V}$ at each period t will reach JIT. In JIT system, the maximum setup

time should not be higher than $N_t \times TT \times \frac{I_t}{V}$. This obviously addresses the goal of setup time

reduction at each period. The maximum setup time allowed in JIT is computed as Table1. The value in Table 1 is feasible to be achieved in recent technology.

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