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Two-stage assembly system with imperfect items for a coordinated two-level integrated supply chain under carbon emission constraints

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SUMMARY

This paper may provide an alternative to the problem of a two-stage assembly system with imperfect processes in a single manufacturer-retailer and two-level integrated supply chain. A mathematical model is developed based on the following scenarios: (a) the manufacturer and the retailer are in different countries where the exchange rate is uncertain; (b) the fixed and variable carbon emission costs are incorporated into current environmental issues; (c) shortage is allowed, and the unsatisfied demand is completely backlogged. In the light of these concerns, our model is to determine the production run time, the shortage time period and defective rate of manual stage. The optimal solutions are computed by our proposed algorithm. Finally, a numerical example and sensitivity analysis are carried out to illustrate the model.

KEY WORDS: *carbon emissions; inventory; shortage; two-level integrated supply chain; two-stage assembly system.*

1. INTRODUCTION

During the last several decades, there has been a rapid growth of globalisation of industry, and the expansion of manufacturing has been a key driver of economic growth, enabled by the changes in geopolitical relations due to the development of global supply chains. Multinational enterprises and many other companies are expanding global sourcing of raw materials, equipment, intermediate items and finished items, in conjunction with global manufacturing and marketing. Oum and Park [1] have noted that due to the development of economic and market globalisation, managing the material flow from raw materials to retailers has emerged as a critical aspect of rapid internationalisation. However, both above-mentioned manufacturers and retailers often strive to diminish the shipping cost of commodities. The mode choice of manufacturers could have a considerable impact on the amount of CO2 emitted for the transportation of items. In the past, most manufacturers managed domestic supply chains and abided by regulatory mandates or faced the risk of being penalised. With the widespread concern over global warming, many countries have committed themselves to reducing carbon emissions by setting emissions targets. In the recent years, many airlines have also begun striving to reduce carbon emissions generated in the course of air transportation. According to a research report [2] on “CO2 emissions from fuel combustion” published in 2016 by the International Energy Agency, between 1990 and 2014, CO2 emissions from international transport rapidly grew. Chao [3] proposed a framework for assessing carbon emissions in different phases of flight during air cargo transportation and estimated increases in transportation costs for the airline.

For the reasons mentioned above, some enterprises focused on improving the supply chain efficiency by optimising freight transportation and reducing greenhouse gas emissions and air pollution. Some studies [4, 5] also noted that a relatively smaller amount of generated CO2 can also enhance brand reputation and sales appeal. Sgouridis et al. [6] pointed out five economic policies for reducing the CO2 emissions of commercial aviation including: (1) technological efficiency improvements, (2) operational efficiency improvements, (3) use of alternative fuels, (4) demand shift and (5) carbon pricing. As recommended by Srivastava [7] the way of cutting carbon emissions includes the use of environmentally friendly raw materials and green packaging as well as efficient energy in manufacturing, distribution and storage processes. In a practical example, Walmart mandated the upstream supplier (manufacturer) to reduce carbon emissions and released the time framework for emission reduction targets. Some literatures also considered this issue in their research. Memaria et al. [8] provide a logistic model for JIT distribution by taking different carbon emission constraints into account. Piecyk and McKinnon [9] pointed out the baseline trends in logistics and supply chain management and associated environmental effects up to 2020. Aksoy et al. [10] proposed a framework for a fuel consumption and CO2 emission calculation model by taking vehicle technical specifications, vehicle load and transportation distance into account. McKinnon [11] proposed the discrepancy results between the waterborne freight and air cargo in accumulating CO2 emission. Next, McKinnon and Piecyk [12] proposed a method for estimating CO2 emission from road freight transport in different ways, due to the accumulation of carbon dioxide from road haulage in the UK. If the passengers travel abroad, they should avoid air transportation for reducing the CO2 emissions. An increasing number of recent publications and empirical studies have evidenced the negative environmental influences of CO2 emission in green supply chain [13-21]. However, with regard to the present CO2 emission, there have been numerous studies in the literature dealing with the impacts of different emission sources on transportation. In fact, as opposed to the previous studies, there has been relatively little research conducted on the effect of CO2 emission on manufacturing. Taking into account “CO2 emissions” and “green supply chain” in the earlier paragraph of this section, we can consider CO2 emissions from the manufacturing industries. Rework has gathered great importance in green supply chain, since it can reduce production cost and environmental problems. Actually, in recent years, new research studies have tackled the issue of CO2 emissions in the manufacturing industry mostly focussing on economically developed regions and countries, such as North America, Japan and Europe. Approximately 35% of CO2 emission originated in China which is at the top of the world’s greenhouse CO2-emitting countries. Therefore, CO2 emissions in China's manufacturing industry should receive more attention and be comprehensively studied. Chang and Lahr [22] explored CO2 emissions in China's manufacturing industry using the structural decomposition method. Xu and Lin [23] confirmed the effect of industry’s CO2 emission on different regional levels and proposed a policy to mitigate CO2 emissions in the manufacturing industry.

On the other hand, in practical terms, the manufacturing process in imperfect production facilities usually causes defective items. Seminal work on a multi-stage production system with the rework of defective items was carried out by Chakraborty and Rao [24]. Sarker et al. [25] indicated two issues that need to be discussed in a multi-stage production system which is reworking defectives: whether we can assess the specific situation (a) within the same cycle, and (b) after N cycles. Cárdenas-Barrón [26] further corrected the mathematical expressions presented by Sarker et al. [31]. The findings of Pearn et al. [27] referred to a two-stage production system with the imperfect process of the capital investment which has been carried out. Chang and Ouyang [28] employed an arithmetic-geometric mean inequality method to determine the optimal production lot size and backorder level in the above production system, whereas most of the literature on imperfect process deals only with the demotic manufacturers. This paper aims to discuss the application of an international supply chain.

2. PROBLEM DESCRIPTION

Recently, with a rapidly growing consumer electronics in China, Taiwan's semiconductor supply chain has found itself at a crucial juncture. Taiwanese companies play a critical role in all three main stages in the production system: design, foundry (or manufacture), and assembly and testing. Consumer electronics with a steadier demand go to the market in a supply chain: via coastal distribution centres and large drop-ship orders to retail partners in China. End products travel via smaller regional distribution centres located closer to demand inland in China. Since many retailers in China accept cash-on-delivery payments, they will consider the fluctuation of exchange rate in the integrated supply chain. The purpose of the research presented in this paper is to examine the carbon dioxide (CO2) emissions policy in logistics within the two-stage model proposed by Pearn et al. [27]. The problem was composed of a manufacturer in Taiwan and a retailer in China with finished products flowing from a plant to DCs (International airport) and from there to the retailers. For this reason, most of the manufacturing industries are involved in automatic-manual (two-stage) assembly system such as aerospace industry, precise industry, consumer electronics, TFT-LCD, light electric vehicle industry, cell phone, and green energy industry, etc.

We formulated the two-stage production system to minimise the cost, while the production run time and defective rates in manual stages are decisive variables in a single vendor-retailer two-level green supply chain (one manufacturer and one retailer). The existence and uniqueness of the optimal solutions for the decision variables are proven. A simple algorithm is also developed for finding the optimal solutions. Finally, the numerical example, consisting of in-depth interviews from the company, is presented.

The remaining sections of this paper are organised as follows:

I. In Section 3, the notation and assumptions adopted in this paper are presented.

II. In Section 4, we developed a mathematical inventory model for a two-stage assembly system with imperfect processes and carbon emission constraints in a single manufacturer-retailer and two-level integrated supply chain.

III. In Section 5, a numerical example and sensitivity analysis are provided to illustrate the features of the proposed model.

IV. Finally, the conclusions and suggestions for future research are given in Section 6.

3. NOTATION AND ASSUMPTIONS

3.1. NOTATION

In this paper, we proposed the following system parameters and decision variables.

SYSTEM PARAMETERS

P_i	the production rate of stage *i* in units per unit time, where *i=1, 2*;
d	the demand rate in units per unit time;
c_{pl}	the procurement and labour cost per unit;
s	the shortage cost in units per unit time;
h_i	the holding cost for an intermediate item per unit time;
h_f	the holding cost for a finished item per unit time;
r_i	the rework cost for a defective intermediate item;
r_f	the rework cost for a defective finished item;
n_1	the number of defective intermediate items;
n_2	the number of defective finished items;
θ_1	the percentage of defective intermediate items;
K_v	the fixed transportation cost;
L_v	the variable transportation cost per item;
F_v	the fixed emission cost for production, warehousing and distribution costs;
C_v	the variable emission cost per item for production, warehousing and distribution costs;
δ	the screening cost per unit;
η	the long-term exchange rate;
θ_{02}	the initial percentage of defective finished items;
a	the loading of capital investment in the process quality improvement;
t_2	the production run time when backorder is replenished;

t_4	the time period when intermediate items inventory exhaust;
t_5	the time period when finished items inventory exhaust;
T	the length of cycle time;
H_0	the maximum backorder level;
H_1	the maximum inventory level of intermediate items;
H_2	the maximum inventory level of finished items.

DECISIVE VARIABLES

t_1	the period of shortage;
t_3	the production run time at stage 1;
θ_2	the percentage of defective finished items.

3.2. ASSUMPTIONS

In addition, the following assumptions are used in the development of the model:

(1) The production cycle repeats infinitely.

(2) From Figure 1, the production system is divided into automatic stage (Stage 1; raw materials to intermediate items) and manual stage (Stage 2; intermediate items to finished items).

(3) The production rates of the two stages meet the condition $P_1 > P_2 > d$.

(4) The rework time of defective items is disregarded.

(5) The shipping costs include transportation cost and emission cost on warehousing and distribution, and they can be categorised into fixed and variable costs. The variable cost depends on the amount of transport.

(6) Based on Wahab et al. [29], a long-term exchange rate is $\eta = e^{\left(\zeta+\sigma^2/4\lambda\right)}$ in the international supply chain, where σ is the uncertain volatility, λ is mean-reversion rate, and ζ is long-term average level.

(7) Assuming the quality target of automatic stage (Stage 1) is already accepted due to the standard equipment maintenance but the manual stage (Stage 2) still needs to improve by investing the training education, fixture, mould, tool, etc. Therefore, the percentage of defective finished items is a decisive variable of yield target.

While considerable attention was previously attributed to research issues related to minimising environmental impact, the literature on issues of a two-stage production system in a single vendor-retailer two-level green supply chain has emerged rather slowly and in a more scattered way. Recently, more and more international companies have been changing their practices in order to reduce the environmental impact of their activities. Little research has been done on the two-level integrated green supply chain. We will provide a more elaborated theoretical background in the next section.

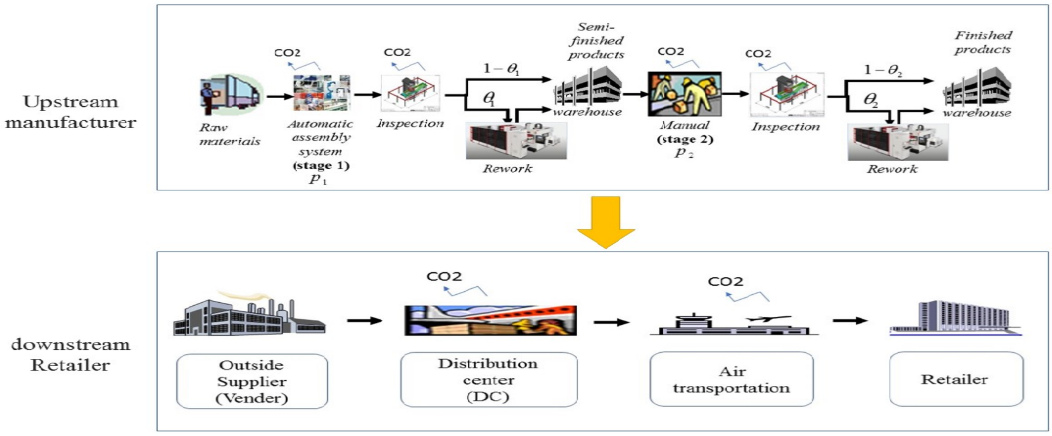

Fig. 1 *Two-stage production system with imperfect processes in two-level integrated supply chain*

4. MATHEMATICAL FORMULATION

Under the notation and assumptions in the previous section, the models are formulated for the cost minimisation problem of the manufacturer and the retailer. The total cost per unit time consists of eight elements: setup cost, holding cost, shortage cost, rework costs, production cost, screening cost, shipping cost, and investment cost. This research may be vital in laying the groundwork for understanding how to determine the optimal production run time, the shortage time period, and percentage of defective finished products such that the total cost per unit time in the two-level green supply chain is minimum. Below is Figure 2 which shows the graphic representation of the inventory.

In reference to Figure 2, the following results are obtained:

$$t_2 = \frac{dt_1}{P_2 - d} \tag{1}$$

$$t_4 = \frac{(P_1 - P_2)t_3}{P_2} \tag{2}$$

$$t_5 = \frac{H_2}{d} = \frac{(P_2 - d)(-t_2 + t_3 + t_4)}{d} = -t_1 + \frac{P_1(P_2 - d)t_3}{P_2 d} \tag{3}$$

and:

$$\begin{aligned} T &= t_1 + t_3 + t_4 + t_5 = \\ &= t_1 + t_3 + \frac{(P_1 - P_2)t_3}{P_2} - t_1 + \frac{P_1(P_2 - d)t_3}{P_2 d} = \frac{P_1 t_3}{P_2} + \frac{P_1(P_2 - d)t_3}{P_2 d} = \frac{P_1}{d} t_3 \end{aligned} \tag{4}$$

Note that since $t_5 > 0$, it follows:

$$t_1 < \hat{t}_1 = \frac{P_1(P_2 - d)}{P_2 d} t_3$$

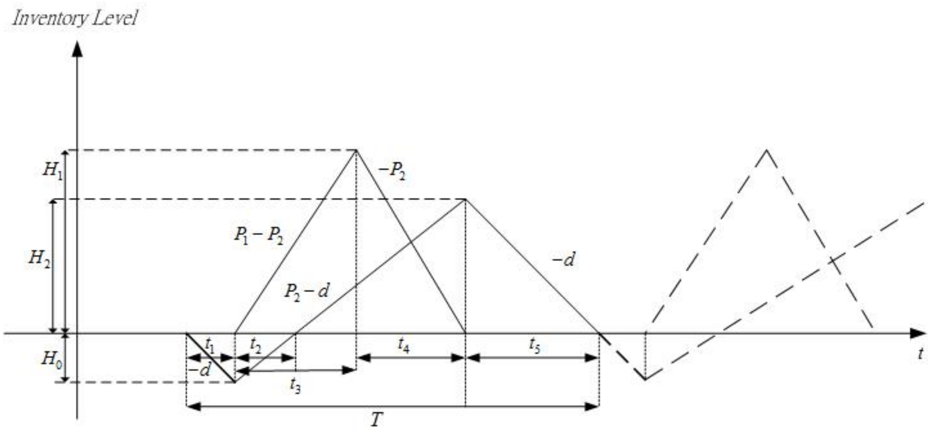

Fig. 2 *Inventory levels in the production process*

Then, we construct an inventory model that consists of the following eight elements:

1. Setup cost per cycle: K.
2. Holding cost per cycle (denoted by HC):

$$HC=\frac{h_i(P_1-P_2)t_3(t_3+t_4)}{2}+\frac{h_f d t_5(-t_2+t_3+t_4+t_5)}{2}=$$
$$=\frac{h_i P_1(P_1-P_2)t_3^{2}}{2P_2}+\frac{h_f(P_2-d)d\left(-\frac{P_2}{P_2-d}t_1+\frac{P_1}{d}t_3\right)^2}{2P_2} \tag{5}$$

3. Shortage cost per cycle (denoted by SC, i.e., the compensation fee for the customer):

$$SC=\frac{s(t_1+t_2)H_0}{2}=\frac{sP_2dt_1^{2}}{2(P_2-d)} \tag{6}$$

4. Rework cost per cycle (denoted by RC):

$$RC=r_i n_1+r_f n_2=\left(r_i\theta_1+r_f\theta_2\right)P_1t_3 \tag{7}$$

5. Production cost per cycle (denoted by PC):

$$PC=c_{pl}P_1t_3 \tag{8}$$

6. Screening cost per cycle (denoted by DC):

$$DC=\delta P_1t_3 \tag{9}$$

7. Shipping cost per cycle (denoted by EC):

$$EC=\left(\frac{1}{\eta}\right)\left\{F_v+K_v+\left(C_v+L_v\right)P_1t_3\right\} \tag{10}$$

8. Investment cost per cycle (denoted by IC):

$$IC=a\left(\theta_{02}-\theta_2\right)^2 \tag{11}$$

Therefore, the total cost per unit time $AC(t_1,t_3,\theta_2)$ is given by optimising t_1,t_3 and θ_2, i.e.:

$$
\begin{aligned}
AC(t_1,t_3,\theta_2) &= \frac{1}{T}\times\{K+HC+SC+RC+PC+DC+EC\} = \\
&= \frac{d}{P_1 t_3}\times\left\{K+\frac{h_i P_1(P_1-P_2)t_3^{2}}{2P_2}+\frac{h_f(P_2-d)d\left(-\frac{P_2}{P_2-d}t_1+\frac{P_1}{d}t_3\right)^{2}}{2P_2}+\right. \\
&\left.+\frac{sP_2 d t_1^{2}}{2(P_2-d)}+\left(r_i\theta_1+r_f\theta_2+c_{pl}+\delta+\frac{C_v+L_v}{\eta}\right)P_1 t_3+\frac{F_v+K_v}{\eta}+a(\theta_{02}-\theta_2)^{2}\right\}
\end{aligned}
\tag{12}
$$

In order to solve this nonlinear programming problem, we will derive the following first-order derivative of $AC(t_1,t_3,\theta_2)$:

$$
\frac{\partial AC(t_1,t_3,\theta_2)}{\partial t_1}=\frac{d\left[sP_2 d t_1+h_f(P_2 d t_1+P_1 d t_3-P_1 P_2 t_3)\right]}{P_1(P_2-d)t_3}
\tag{13}
$$

$$
\begin{aligned}
\frac{\partial AC(t_1,t_3,\theta_2)}{\partial t_3} &= \frac{1}{T}\left\{\frac{h_i P_1(P_1-P_2)t_3}{P_2}+\frac{h_f P_1(P_2-d)\left(-\frac{P_2}{P_2-d}t_1+\frac{P_1}{d}t_3\right)}{P_2}+\right. \\
&\left.+\left(r_i\theta_1+r_f\theta_2+c_{pl}+\delta+\frac{C_v+L_v}{\eta}\right)P_1-\frac{P_1}{d}\times AC(t_1,t_3,\theta_2)\right\}
\end{aligned}
\tag{14}
$$

and:

$$
\frac{\partial AC(t_1,t_3,\theta_2)}{\partial \theta_2}=\frac{d\left[r_f P_1 t_3-2a(\theta_{02}-\theta_2)\right]}{P_1 t_3}
\tag{15}
$$

The necessary conditions for minimising $AC(t_1,t_3,\theta_2)$ are $\partial AC(t_1,t_3,\theta_2)/\partial t_1=0$, $\partial AC(t_1,t_3,\theta_2)/\partial t_3=0$ and $\partial AC(t_1,t_3,\theta_2)/\partial \theta_2=0$ simultaneously, which implies:

$$
t_1=\frac{h_f P_1(P_2-d)}{P_2 d(s+h_f)}t_3<\hat{t}_1
\tag{16}
$$

$$
\begin{aligned}
&h_i(P_1-P_2)t_3+h_f(P_2-d)\left(-\frac{P_2}{P_2-d}t_1+\frac{P_1}{d}t_3\right)+ \\
&+P_2\left(r_i\theta_1+r_f\theta_2+c_{pl}+\delta+\frac{C_v+L_v}{\eta}\right)-\frac{P_2}{d}\times AC(t_1,t_3,\theta_2)=0
\end{aligned}
\tag{17}
$$

$$
\theta_2=\theta_{02}-\frac{r_f P_1}{2a}t_3
\tag{18}
$$

It is discernible from Eq. (16) and Eq. (18) that both t_1 and θ_2 are the functions of t_3. By substituting t_1 and θ_2 given by Eqs. (16) and (18) into Eq. (17), it is obtained:

$$Bt_3 + P_2\left(r_i\theta_1 + r_f\theta_{02} + c_{pl} + \delta + \frac{C_v + L_v}{\eta} \right) - \frac{P_2}{d} \times AC(t_1, t_3, \theta_2) = 0 \tag{19}$$

where:

$$B = h_i\left(P_1 - P_2\right) + \frac{h_f s P_1\left(P_2 - d\right)}{d\left(s + h_f\right)} - \frac{r_f^{\,2} P_1 P_2}{2a} \tag{20}$$

Now, the left-hand side of Eq. (19) is denoted as $\psi(t_3)$. Taking the first-order derivative of $\psi(t_3)$ with respect to t_3, we obtain $d\psi(t_3)/dt_3 = B$. Since $\psi(0) = -\infty$, the following results are obtained:

THEOREM 1. *FOR ANY GIVEN* $t_3 \geq 0$

(a) *if* $B > 0$, *then the existence and uniqueness of the solution* $(t_1^*, t_3^*, \theta_2^*)$ *that minimises* $AC(t_1, t_3, \theta_2)$ *in* $t_3 \in (0, \infty)$.

(b) *if* $B \leq 0$, *then the optimal value of* t_3 *is obtained as* $t_3^* \to 0$ *.The production system should not be opened.*

Proof.

(a) Because $\psi(0) = -\infty$ and $\psi(t_3)$ is strictly increasing in the interval $t_3 \in (0, \infty)$, from the Intermediate Value Theorem, we can find a unique solution $t_3^* \in (0, \infty)$ such that $\psi(t_3^*) = 0$. By substituting t_3^* into Eqs. (16) and (18), the corresponding t_1^* and θ_2^* can be determined. Furthermore, in order to examine the second-order sufficient conditions for a minimum value, we first obtain the Hessian matrix ***H*** as follows:

$$\boldsymbol{H} = \begin{bmatrix} \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_1^{\,2}} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_1 \partial t_3} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_1 \partial \theta_2} \\ \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_3 \partial t_1} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_3^{\,2}} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial t_3 \partial \theta_2} \\ \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial \theta_2 \partial t_1} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial \theta_2 \partial t_3} & \dfrac{\partial^2 AC(t_1,t_3,\theta_2)}{\partial \theta_2^{\,2}} \end{bmatrix}$$

Then we proceed by evaluating the principal minor determinants of ***H*** at the stationary point $(t_1^*, t_3^*, \theta_2^*)$. The first, second and third principal minor determinant of ***H*** are calculated as follows:

$$\left|H_{11}\right| = \frac{P_2 d^2\left(s + h_f\right)}{P_1\left(P_2 - d\right)t_3^*} > 0$$

$$\left|H_{22}\right| = \frac{d}{P_1 t_3^*}\left[\frac{h_i P_1\left(P_1 - P_2\right)}{P_2} + \frac{h_f P_1^{\,2}\left(P_2 - d\right)}{P_2 d}\right] > 0$$

and:

$$\left|H_{33}\right| = \frac{2ad\theta_2^*}{P_1 t_3^*} > 0$$

According to the above results, it is clear that the Hessian matrix $\boldsymbol{H}$ is a positive definite. Hence, the existence and uniqueness of the solution $(t_1^*, t_3^*, \theta_2^*)$ that minimises $AC(t_1, t_3, \theta_2)$ in $t_3 \in (0, \infty)$. This completes the proof of (a).

(b) Because $\psi(0) = -\infty$ and $\psi(t_3)$ is strictly decreasing in the interval $t_3 \in (0, \infty)$, then:

$$\frac{\partial AC(t_1, t_3, \theta_2)}{\partial t_3} = \frac{P_1 \psi(t_3)}{P_2 T} < 0$$

It implies that a large value of t_3 causes a lower value of $AC(t_1, t_3, \theta_2)$. Hence, the optimal solution $t_3^* \to 0$. The production system should not be opened. This completes the proof of (b).

The computations of optimal solutions and steps required in the production system are not complicated. We developed a simple algorithm for finding the optimal shortage period, production run time of Stage 1, and the percentage of defective finished products. The procedure of our proposed algorithm is presented in Figure 3.

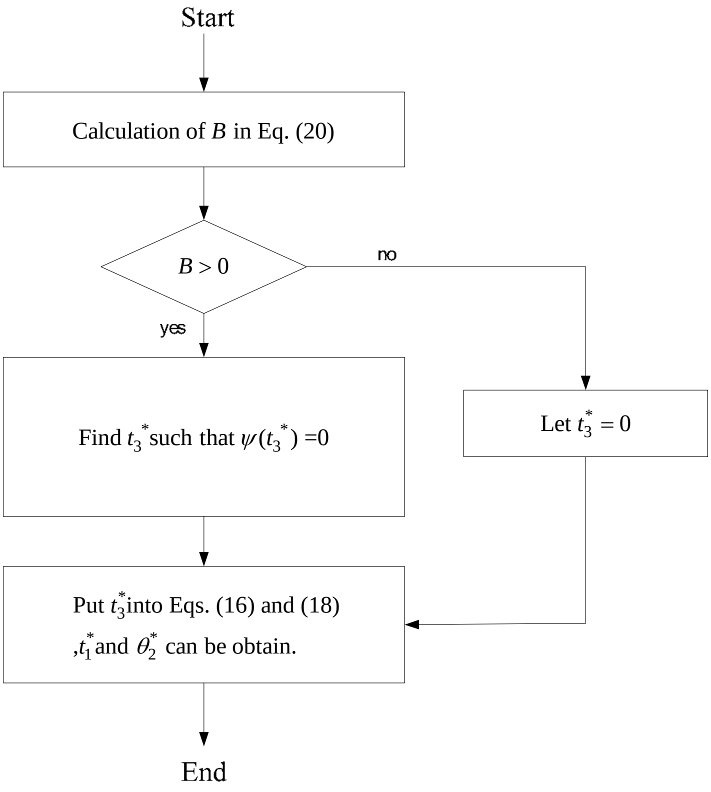

Fig. 3 *The procedure of proposed algorithm*

5. NUMERICAL EXAMPLE AND SENSITIVITY ANALYSIS

Taiwan is the top market for semiconductor manufacturing equipment and is also a home of the largest EMS (electronic manufacturing services). With the annual sales exceeding *$71* billion in 2015, the semiconductor industry is the major component of Taiwan's vital electronics sector, which accounts for about *40%* of exports. This model is considered as the international two-level integrated supply chain, where the manufacturer (vendor) produces electronics items in Taiwan and exports them to China (retailer). However, the effects of the exchange rate variability on semiconductor exports should not be overlooked, especially for China. Let us consider now an example of a real manufacturing company from Taiwan. The following parameters for the analysed manufacturing company consisted of utilising the data collected during 40 in-depth interviews averaging 2 hours each. The results are presented in Table 1.

Table 1 *Parameters of interviews conducted for the manufacturing company*

$K = \$100/\text{per cycle}$	$P_1 = 600/\text{unit time}$	$P_2 =$	$d = 400/\text{unit time}$
$h_i = \$0.1/\text{unit/unit time}$	$h_f = \$0.2/\text{unit/unit time}$	$s = 0.5/\text{unit/unit time}$	$c_{pl} = \$10/\text{unit}$
$r_i = \$0.1/\text{unit}$	$r_f = \$0.2/\text{unit}$	$\theta_1 = 0.1$	$\theta_{02} = 0.2$
$K_v = 100$	$L_v = \quad /\text{unit}$	$F_v =$	$C_v = \quad /\text{unit}$
$\delta = \$0.05/\text{unit}$	$a =$		

In addition, consider the following parameter in Dixit and Pindyck [30]: the values of $\zeta = 1.5241$, $\sigma = 0.0448$, and $\lambda = 0.8950$. When we calculated the optimal production run time by using the algorithm, the following results were obtained: $t_1^* = 0.22584$, $t_3^* = 2.63474$, $\theta_2^* = 0.16838$, $T^* = 3.95211$, and $AC(t_1^*, t_3^*, \theta_2^*) = 5061.57$.

Three-dimensional graphs of $AC(t_1, t_3 | \theta_2^* = 0.16838)$ are shown in Figure 4. Then, 10 values of $(\theta_2, AC(\theta_2 | t_1^*, t_3^*))$ are plotted in Figure 5. Based on Figures 4-5, we can prove that $AC(t_1^*, t_3^*, \theta_2^*)$ is the global minimum.

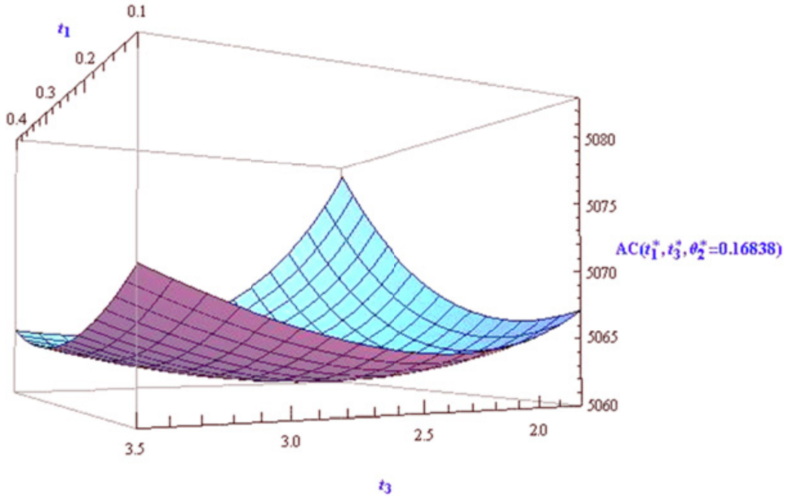

Fig. 4 *Three-dimensional graphs of* $AC(t_1, t_3 | \theta_2^* = 0.16838)$

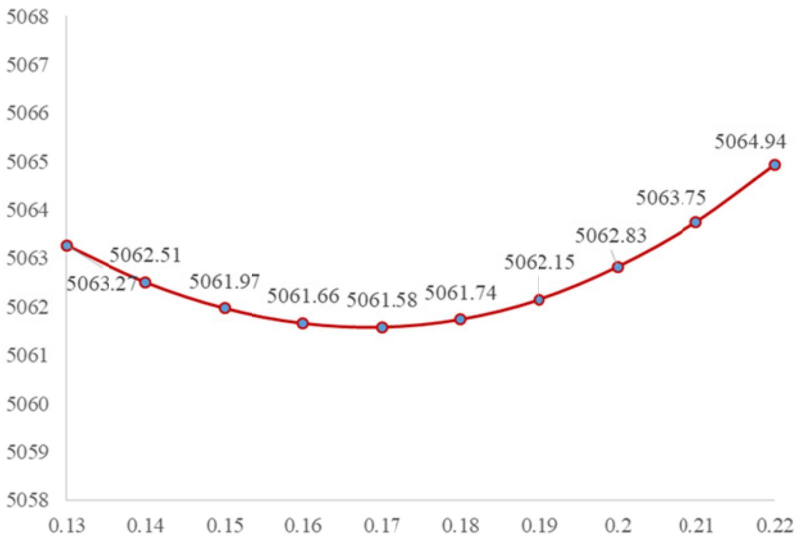

Fig. 5 *Graphical representation of* $AC(\theta_2 | t_1^*, t_3^*)$

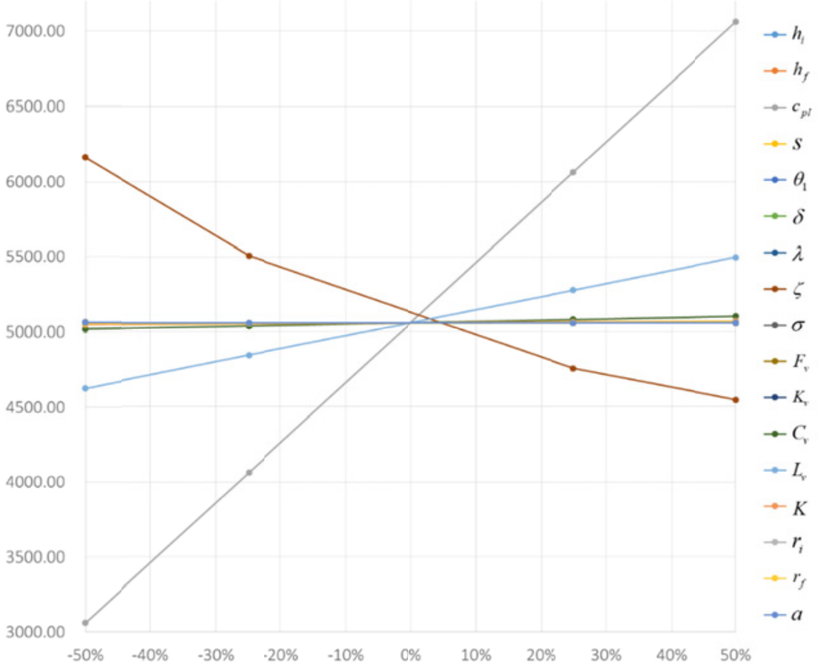

Fig. 6 *Total cost per unit time with optimal solutions vs. parameters change*

Furthermore, this numerical example is considered in order to study the effects of changes in the system parameters h_i, h_f, c_{pl}, s, θ_1, δ, λ, ζ, σ, F_v, K_v, C_v, L_v, K, r_i, r_f, and a on the optimal values of $t_1^*, t_3^*, \theta_2^*, T^*$, and $AC(t_1^*, t_3^*, \theta_2^*)$. The sensitivity analysis is performed by changing each of the major parameters by *+50%*, *+25%*, *−25%*, and *−50%*, taking one parameter at a time and keeping the remaining parameters unchanged. The results are shown in Table 2 and Figure 6.

Table 2 *Effect of changes in various parameters of the inventory model*

Parameter	*% change*	*Optimal Solutions*				
		t_1^*	t_3^*	θ_2^*	T^*	$AC(t_1^*,t_3^*,\theta_2^*)$
h_i	50%	0.20920	2.44062	0.17071	3.66092	5066.64
	25%	0.21704	2.53212	0.16962	3.79817	5064.16
	-25%	0.23580	2.75095	0.16699	4.12643	5058.88
	-50%	0.24720	2.88404	0.16539	4.32605	5056.07
h_f	50%	0.26819	2.38389	0.17139	3.57584	5068.28
	25%	0.24917	2.49166	0.17010	3.73749	5065.23
	-25%	0.19627	2.83506	0.16598	4.25260	5057.07
	-50%	0.15694	3.13875	0.16234	4.70813	5051.34
c_{pl}	50%	0.22584	2.63474	0.16838	3.95211	7061.57
	25%	0.22584	2.63474	0.16838	3.95211	6061.57
	-25%	0.22584	2.63474	0.16838	3.95211	4061.57
	-50%	0.22584	2.63474	0.16838	3.95211	3061.57
s	50%	0.16052	2.54162	0.16950	3.81243	5063.91
	25%	0.18763	2.57991	0.16904	3.86986	5062.93
	-25%	0.28382	2.71991	0.16736	4.07986	5059.58
	-50%	0.38274	2.87052	0.16555	4.30578	5056.34
θ_1	50%	0.22584	2.63474	0.16838	3.95211	5063.57
	25%	0.22584	2.63474	0.16838	3.95211	5062.57
	-25%	0.22584	2.63474	0.16838	3.95211	5060.57
	-50%	0.22584	2.63474	0.16838	3.95211	5059.57
δ	50%	0.22584	2.63474	0.16838	3.95211	5071.57
	25%	0.22584	2.63474	0.16838	3.95211	5066.57
	-25%	0.22584	2.63474	0.16838	3.95211	5056.57
	-50%	0.22584	2.63474	0.16838	3.95211	5051.57
λ	50%	0.22584	2.63479	0.16838	3.95219	5061.75
	25%	0.22584	2.63477	0.16838	3.95216	5061.68
	-25%	0.22583	2.63469	0.16838	3.95204	5061.39
	-50%	0.22582	2.63459	0.16839	3.95189	5061.03
ζ	50%	0.21309	2.48599	0.17017	3.72899	4547.16
	25%	0.21835	2.54741	0.16943	3.82112	4755.97
	-25%	0.23637	2.75759	0.16691	4.13639	5508.78
	-50%	0.25098	2.92813	0.16486	4.39220	6163.18
σ	50%	0.22582	2.63455	0.16839	3.95183	5060.90
	25%	0.22583	2.63466	0.16838	3.95199	5061.27
	-25%	0.22584	2.63481	0.16838	3.95221	5061.81
	-50%	0.22585	2.63486	0.16838	3.95229	5061.98

Table 2 *Effect of changes in various parameters of the inventory model (Continued)*

Parameter	%change	Optimal Solutions				
		t_1^*	t_3^*	θ_2^*	T^*	$AC(t_1^*,t_3^*,\theta_2^*)$
F_v	50%	0.22768	2.65629	0.16812	3.98444	5062.09
	25%	0.22676	2.64554	0.16825	3.96831	5061.83
	-25%	0.22491	2.62390	0.16851	3.93585	5061.31
	-50%	0.22397	2.61301	0.16864	3.91952	5061.05
K_v	50%	0.23540	2.74627	0.16705	4.11941	5064.27
	25%	0.23066	2.69108	0.16771	4.03663	5062.94
	-25%	0.22090	2.57717	0.16907	3.86575	5060.18
	-50%	0.21585	2.51828	0.16978	3.77742	5058.76
C_v	50%	0.22584	2.63474	0.16838	3.95211	5105.11
	25%	0.22584	2.63474	0.16838	3.95211	5083.34
	-25%	0.22584	2.63474	0.16838	3.95211	5039.80
	-50%	0.22584	2.63474	0.16838	3.95211	5018.03
L_v	50%	0.22584	2.63474	0.16838	3.95211	5496.96
	25%	0.22584	2.63474	0.16838	3.95211	5279.27
	-25%	0.22584	2.63474	0.16838	3.95211	4843.88
	-50%	0.22584	2.63474	0.16838	3.95211	4626.18
K	50%	0.26694	3.11426	0.16263	4.67140	5073.17
	25%	0.24724	2.88449	0.16539	4.32673	5067.61
	-25%	0.20218	2.35870	0.17170	3.53806	5054.90
	-50%	0.17535	2.04575	0.17545	3.06863	5047.33
r_i	50%	0.22584	2.63474	0.16838	3.95211	5063.57
	25%	0.22584	2.63474	0.16838	3.95211	5062.57
	-25%	0.22584	2.63474	0.16838	3.95211	5060.57
	-50%	0.22584	2.63474	0.16838	3.95211	5059.57
r_f	50%	0.23166	2.70265	0.15135	4.05398	5067.97
	25%	0.22840	2.66466	0.16003	3.99699	5064.86
	-25%	0.22390	2.61216	0.17649	3.91824	5058.12
	-50%	0.22255	2.59638	0.18442	3.89456	5054.51
a	50%	0.22436	2.61748	0.17906	3.92622	5061.99
	25%	0.22494	2.62435	0.17481	3.93652	5061.83
	-25%	0.22734	2.65235	0.15756	3.97853	5061.15
	-50%	0.23046	2.68865	0.13547	4.03297	5060.30

In view of Table 2 and Figure 6, the following results are obtained:

A. When the values of parameters c_{pl}, θ_1, δ, C_v, L_v, and r_i increase, the optimal solution (t_1^*,t_3^*,θ_2^*) is not changed but the minimum total cost per unit time $AC(t_1^*,t_3^*,\theta_2^*)$ increases. It implies that if these parameters could be reduced effectively, the total cost per unit time could be improved.

B. When the values of parameters h_i and h_f increase, t_3^* and T^* decrease but θ_2^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase. It implies that the production run time is shortened for avoiding more holding costs of intermediate and finished items. Besides, it is getting more and more difficult to implement the capital investment in the process quality improvement.

C. When the values of parameter S increase, t_1^* , t_3^* and T^* decrease but θ_2^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase. It means that the allowable shortages are becoming increasingly worse.

D. Referring to the long-term exchange rate, when the values of parameters σ and ζ increase, t_1^* , t_3^* and T^* decrease but θ_2^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase. The uncertain volatility and long-term average level not only affect the production yield, but also reduce the opportunity of investment in the process quality improvement. As opposed to σ and ζ , λ (mean-reversion rate) is beneficial to expand the production and the investment.

E. When the values of parameters F_v, K_v, and K increase, t_1^* , t_3^*, T^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase but θ_2^* decreases. It implies that the production run time is lengthened for retarding the growth of these fixed costs.

F. With the increase in the value of parameter r_f , θ_2^* decreases but t_1^* , t_3^* , T^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase. It implies that if the rework cost of a finished item increases, the manufacturer should focus on the process quantity improvement for reducing the rework quantity and increase the production cycle time to retard the growth of the investment cost per unit.

G. With the increase in the value of parameter a, θ_2^* and $AC(t_1^*,t_3^*,\theta_2^*)$ increase. It implies that there is an upper bound of a such that the capital investment in the process quality improvement is invalid, i.e., $\theta_2^* = \theta_{02}$.

H. As evident from Figure 6, the slope of c_{pl} is the largest. In fact, the extent of influence on the total cost per unit time depends on the production rate and demand rate. Therefore, if the production rate and demand rate are large, the total cost per unit time will increase substantially when c_{pl} slightly increases.

6. CONCLUSION

In this paper, we study a two-stage (automatic-manual) assembly system with imperfect items in a single manufacturer-retailer and a two-level integrated supply chain (Taiwan-China), as well as considered the environment impact such as the effects of the uncertainty exchange rate and the carbon emission constraints. The key decision variables are the optimal production run time, shortage time period and defective rates for the manual stage such that the total cost per unit time is minimum. In addition, the results of the sensitivity analysis are provided for the manufacturer to do the decision-making in the production system. Such a production system may account in part for aerospace industry, precise industry, consumer electronics, TFT-LCD, light electric vehicle industry, cell phone, green energy industry, and so on.

7. REFERENCES

[1] T.H. Oum and J.H. Park, Multinational firms' location preference for regional distribution centers: focus on the Northeast Asian region, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 40, No. 2, pp. 101–121, 2004.

https://doi.org/10.1016/S1366-5545(03)00036-X

[2] OECD "CO2 emissions from fuel combustion highlights." *International Energy Agency*, pp. 1–156, 2016.

[3] C.C. Chao, Assessment of carbon emission costs for air cargo transportation, *Transportation Research Part D*, Vol. 33, pp. 186–195, 2014.

https://doi.org/10.1016/j.trd.2014.06.004

[4] W. Young, K. Hwang, S. McDonald and C.J. Oates, Sustainable consumption: green consumer behavior when purchasing products, *Sustainable Development*, Vol. 18, No. 1, pp. 20–31, 2010. https://doi.org/10.1002/sd.394

[5] J.K. Vanclay, J. Shortiss, S. Aulsebrook, A.M. Gillespie, B.C. Howell, R. Johanni, M.J. Maher, K.M. Mitchell, M.D. Stewart and J. Yates, Customer response to carbon labelling of groceries, *Journal of Consumer Policy*, Vol. 34, No.1, pp. 153–160, 2011.

https://doi.org/10.1007/s10603-010-9140-7

[6] S. Sgouridis, P.A. Bonnefoy and R.J. Hansman, Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation, *Transportation Research Part A*, Vol. 45, No. 10, pp. 1077–1091, 2011. https://doi.org/10.1016/j.tra.2010.03.019

[7] S.K. Srivastava, Green supply chain management: a state-of-the-art literature review, *International Journal of Management Review*, Vol. 9, No. 1, pp. 53–80, 2007.

https://doi.org/10.1111/j.1468-2370.2007.00202.x

[8] A. Memaria, A.R.A. Rahim, N. Absic, R. Ahmad and A. Hassana, Carbon-capped distribution planning: A JIT perspective, *Computers & Industrial Engineering*, Vol. 97, pp. 111–127, 2016. https://doi.org/10.1016/j.cie.2016.04.015

[9] M.I. Piecyk and A.C. McKinnon, Forecasting the carbon footprint of road freight transport in 2020, *International Journal of Production Economics*, Vol. 128, No. 1, pp. 31–42, 2010. https://doi.org/10.1016/j.ijpe.2009.08.027

[10] A. Aksoy, İ. Küçükoğlu, S. Ene and N. Öztürk, Integrated emission and fuel consumption calculation model for green supply chain management, *Procedia - Social and Behavioral Sciences*, Vol. 109, pp. 1106–1109, 2014.

https://doi.org/10.1016/j.sbspro.2013.12.595

[11] A.C. McKinnon, CO2 emissions from freight transport: An analysis of UK data, Logistics Research Centre, Heriot-Watt University, 2007.

[12] A.C. McKinnon and M.I. Piecyk, Measurement of CO2 emissions from road freight transport: A review of UK experience, *Energy Policy*, Vol. 37, No. 10, pp. 3733–3742, 2009. https://doi.org/10.1016/j.enpol.2009.07.007

[13] P.R. Murphy, R.F. Poist and C.D. Braunschwieg, Green logistics: comparative views of environmental progressives, moderates, and conservatives, *Journal of Business Logistics*, Vol. 17, No. 1, pp. 191–212, 1996.

[14] Y.Y. Tseng, W.L. Yue and M.A.P. Taylor, The role of transportation in logistics chain, *Proceedings of the Eastern Asia Society for Transportation Studies*, Vol. 5, pp. 1657–1672, 2005.

[15] H. Aronsson and M.H. Brodin, The environmental impact of changing logistics structures, *The International Journal of Logistics Management*, Vol. 17, No. 3, pp. 394–415, 2006. https://doi.org/10.1108/09574090610717545

[16] C.H. Han, Strategies to reduce air pollution in shipping industry as expansive carbon measuring plan eyes distribution, *The Asian Journal of Shipping and Logistics*, Vol. 26, No. 1, pp. 7–30, 2010. https://doi.org/10.1016/S2092-5212(10)80009-4

[17] H.K. Chan, S. Yin and T.S. Felix, Chan, Implementing just-in-time philosophy to reverse logistics systems: a review, *International Journal of Production Research*, Vol. 48, No. 21, pp. 6293–6313, 2010. https://doi.org/10.1080/00207540903225213

[18] S. Elhedhli and R. Merrick, Green supply chain network design to reduce carbon emissions, *Transportation Research Part D: Transport and Environment*, Vol. 17, No. 5, pp. 370–379, 2012. https://doi.org/10.1016/j.trd.2012.02.002

[19] N. Arvidsson, J. Woxenius and C. Lammgård, Review of road hauliers' measures for increasing transport efficiency and sustainability in urban freight distribution, *Transport Reviews*, Vol. 33, No. 1, pp. 107–127, 2013.

https://doi.org/10.1080/01441647.2013.763866

[20] G.S. Kushwaha and N.K. Sharma, Green initiatives: a step towards sustainable development and firm's performance in the automobile industry, *Journal of Cleaner Production*, Vol. 121, pp. 116–129, 2016. https://doi.org/10.1016/j.jclepro.2015.07.072

[21] M.A. Alhaj, D. Svetinovic and A. Diabat, A carbon-sensitive two-echelon-inventory supply chain model with stochastic demand, Resources, *Conservation and Recycling*, Vol. 108, pp. 82–87, 2016. https://doi.org/10.1016/j.resconrec.2015.11.011

[22] N. Chang, and M.L. Lahr, Changes in China's production-source CO2 emissions: insights from structural decomposition analysis and linkage analysis, *Economic Systems Research*, Vol. 28, pp. 224–242, 2016.

https://doi.org/10.1080/09535314.2016.1172476

[23] R. Xu and B. Lin, Why are there large regional differences in CO2 emissions? Evidence from China's manufacturing industry, *Journal of Cleaner Production*, Vol. 140, pp. 1330–1343, 2017. https://doi.org/10.1016/j.jclepro.2016.10.019

[24] S. Chakraborty and N.V. Rao, EBQ for a multistage production system considering rework, *Opsearch*, Vol. 25, No. 2, pp. 75–88, 1988.

[25] B.R. Sarker, A.M.M. Jamal and S. Mondal, Optimal batch sizing in a multi-stage production system with rework consideration, *European Journal of Operational Research*, Vol. 184, No. 3, pp. 915–929, 2008.

https://doi.org/10.1016/j.ejor.2006.12.005

[26] L.E. Cárdenas-Barrón, On optimal batch sizing in a multi-stage production system with rework consideration, *European Journal of Operational Research*, Vol. 196, No. 3, pp. 1238–1244, 2009. https://doi.org/10.1016/j.ejor.2008.04.015

[27] W.L. Pearn, R.H. Su, M.W. Weng and C.H. Hsu, Optimal production run time for two-stage production system with imperfect processes and allowable shortages, *Central European Journal of Operational Research*, Vol. 19, No. 4, pp. 533–545, 2011.

https://doi.org/10.1007/s10100-010-0143-x

[28] C.T. Chang, and L.Y. Ouyang, An arithmetic-geometric mean inequality approach for determining the optimal production lot size with backlogging and imperfect rework process, *Journal of Applied Analysis and Computation*, Vol. 7, No. 1, pp. 224–235, 2017.

[29] M.I.M. Wahab, S.M.H. Mamun and P. Ongkunaruk, EOQ models for a coordinated two-level international supply chain considering imperfect items and environmental impact, *International Journal of Production Economics*, Vol. 134, No. 1, pp. 151–158, 2011.

https://doi.org/10.1016/j.ijpe.2011.06.008

[30] A.K. Dixit and R.S. Pindyck, *Investment Under Uncertainty*, Princeton University Press, Princeton, NJ, 1994.