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A hybrid delayed differentiation multiproduct EPQ model with scrap and end-products multi-shipment policy

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A B S T R A C T

The present work intends to optimize a hybrid delayed differentiation multiproduct economic production quantity-EPQ model with the scrap and end-products multi-shipment policy. Since the requirements of multi-goods have a standard part in common, our fabrication planning adopts a two-phase delayed differentiation strategy to make the standard components first and produce the finished multi-goods in the second phase. Implementing a partial subcontracting option (with the additional expense) for the standard parts helps us to expedite the required uptime in the first phase. A screening process identifies the faulty items that need to be removed to ensure the in-house production quality. A multi-shipment plan delivers the finished lot of end-products to clients in fixed time intervals. This study optimizes the overall operating expenses of this intra-supply chain system, including fabrication, delivery, and client stock holding, through our proposed modeling, formulation, and optimization procedure. In addition, this study gives a numerical demonstration of the obtained results' applicability and usefulness to managerial decision-making.

1. Introduction

Today's trend of market demands asks for high quality and various merchandise in a timely manner. Hence, the production planner/managers must simultaneously meet the client's expectations and minimize the expenditures of in-house fabrication-inventory-shipping activities. In addition, the management often examines the possibility of making all standard parts first and assembling/ producing customized finished goods in the 2nd phase of the fabrication process to plan an efficient various-goods fabrication in single manufacturing equipment. Weber (2008) studied a problem relating to the delayed differentiation of multi-attribute products (including horizontal and vertical attributes). The study proposed a two-stage model to study the market's acceptable price for top-quality end goods in the 1st stage and observe customer behavior concerning quality-degrade and horizontal differentiation on the goods in the 2nd stage. The researcher first explored a two-product nonconvex problem and extended it to optimize the vertical differentiation product line rather than horizontal differentiation. The result showed it is difficult to obtain the optimal investment/price and quality solution concerning both vertical and horizontal attributes, given different customer preferences/characteristics and demand patterns. It also indicated the firms facing a non-monotonic delayed differentiation development cost. Nugroho (2013) determined strategies of price and postponement for two substitutable products with commonality to enhance competition and maximize profit under uncertain demand. The researcher-built models to explore product substitutability influence to profit and appropriateness to various competition conditions. The study also examined the impact of uncertain markets on strategic decisions. As a result, the study showed the proposed price and postponement strategies are appropriate for highly customized goods, and it helps enhance product development and design

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fabrication processes. Al-Hakimi et al. (2022) studied the connection between supply chain flexibility and postponement under dissimilar environmental uncertainty levels. The researchers surveyed 260+ manufacturing firms in Yemen to test their proposed research scheme and exposed the significant influence of postponement on supply chain flexibility, especially when the environmental uncertainty level is lower. Some valuable insights from the research results can assist the management of manufacturing firms in establishing long-term partnerships within the supply chain parties. Additional studies (Anupindi and Jiang, 2008; Bruneel et al., 2014; Chiu et al., 2020a,b; Ojstersek et al., 2020; Ackermann et al., 2021; Chiu et al., 2021; Chowmali and Sukto, 2021; Chiu et al., 2022; Prataviera et al., 2022; Sung et al., 2022; Wofuru-Nyenke & Briggs, 2022) examined different features of postponement effect on the management/ planning of multi-item production and supply-chain systems.

The production postponement strategy may smoothen the fabricating plan (by making the required common parts first), ease the management efforts concerning labor arrangement and materials preparation, and save production time/expenses in some cases. Subcontracting a portion of the common-parts lot effectively shortens the lengthy uptime of making all the required common parts. Bardhan et al. (2007) built a conceptual scheme to explore the performance influences of information technology (IT) applications, strategy, and outsourcing business processes/production in United States manufacturing firms. The researchers empirically validated their model with cross-sectional US manufacturing firms' survey data. The study found that IT applications are a significantly practical approach to enable outsourcing business processes/ production. Firms with low-cost outsourcing policies are more likely to outsource their business support processes than those with competency-focused subcontracting policies. Both competency- and low-cost-based policies have the same influence on production processes outsourcing. The study also revealed that investing in IT applications and making firm-level outsourcing policies facilitate outsourcing business processes, improving firm performance. Görg et al. (2015) studied the relationship between outsourcing foreign services/materials inputs and internet usage. The researchers conducted an empirical study using Ireland's firm-level data, particularly regarding import purchases and internet-related offshoring outsourcers/suppliers. They verified their results with various existing econometric methods and exposed that using the internet for subcontracting increased foreign services by three to four percent. Gómez et al. (2022) studied the implementation of e-business by Spanish manufacturing firms. The researchers mainly considered the primary firm's features of technological cooperation and fabrication outsourcing to build a scheme with organization, technology, and environment. Then, they tested the proposed model on Spanish manufacturing firms over the 2002 to 2014 period and revealed that (1) technological cooperation between suppliers and clients and (2) outsourcing production firms both have a positive influence on Business-to-Business and Supplier-to-Business adoption. Other studies (Brusoni et al., 2001; Ni et al., 2009; Skowronski and Benton, 2018; Prajapati et al., 2020; Chołodowicz and Orłowski, 2021; Kulembayeva et al., 2022; Suharmono et al., 2022) examined dissimilar subcontracting policies' impact on operations and management of supply chains and manufacturing systems.

Since current market demands trend turns to timely responses and high-quality goods. To meet the client's expectations, the manufacturers must simultaneously focus on screening scraps, complying with the order due times, and minimizing overall operating expenditures. Surveys of past studies on product quality and shipping schedules are as follows. Khouja (2003) considered the potential product-quality issues in a two-stage supply-chain system's material flow. The study built the relevant supply-chain models with formulation and assumption that the number of defective items rises with increased fabrication batch sizes. Then, the researcher resolved the problem and showed that the quality issues significantly reduced batch sizes. The study derived the closed-form optimal batch sizes for the deterministic demand problem, and the study demonstrated its models numerically for the stochastic demand problem. The research result also exposed the producer's just-in-time fabrication is more beneficial than the client side's just-in-time delivery. Golmakani and Moakedi (2012) proposed an inspection scheme with a search algorithm for a repairable multi-component system to optimally schedule inspection that minimizes overall system operating expenses. Each component in the system has a chance of deteriorating, and once it occurs, a minimal repair is applied immediately with extra cost. The purpose of finding the optimal inspection is to find the potential component failure in advance, preventing the system malfunction and minimizing the total expected operating expenses. The researchers demonstrate their proposed scheme with an example. Seçkin and Seçkin (2022) proposed a feature extraction approach to detect fabric defects accurately. The proposed intertwined frame vector takes the image from the window with centering gravity as the feature aiming to replace conventional human-eye examination. It applies a classification algorithm to detect the defect. The researchers used the AITEX dataset to validate their approach's performance, resulting in 55% more speedy and 1.8% more accuracy. Nampinyo et al. (2022) studied the influence of rapid delivery, top management, and accidental management on the growth of sustainable logistics using Thai logistic firms as the case. The researchers collected over 450 survey data from logistics firms' employees to analyze/explore the relationship among rapid delivery, top and accidental management, and growth of sustainable logistics. The results showed quick delivery has the most influence on the growth of sustainable logistics, and also top and accidental management has a positive influence on the growth of sustainable logistics. Other studies (Goyal, 2000; Alamri and Balkhi, 2007; Öztürk et al., 2015; Pourmohammadi et al., 2020; Barata, 2021; Velasco-Parra et al., 2021; Yusriski et al., 2021; Berahhou et al., 2022; Jaroenwanit et al., 2022; Kulkarni et al., 2022; Rachih et al., 2022) examined the influence of different fabricating imperfect-quality issues & consequent actions and diverse end-items shipping schedules on the controlling and operations management of various manufacturing and supply-chain systems. Few earlier studies have examined the individual/combined influence of delayed differentiation and subcontracting strategies, scraps, and end-products multi-shipment policy on the multiproduct EPQ-based replenishing-shipping decisions; we would like to bridge this gap.

2. Problem description, assumption and modeling

This study examines a hybrid multiproduct delayed differentiation two-stage economic production quantity (EPQ) model considering scraps and end-products multi-shipment policy. Stage one makes all standard (common) components required for producing the finished multiproduct in stage 2. First, the definition of our model's related parameters is given in subsection 2.1, and it follows the problem's description, assumption, and mathematical modeling.

2.1. Notation of our study

Stage 1's notation in fabricating standard components:

T_π = rotation cycle-time of our batch fabricating model,
λ_0 = standard part's annual requirements,
γ = standard part's completion rate compared with an end merchandise,
π_0 = subcontracting portion of the annual needed standard components,
$C_{\pi 0}$ = outsourcing cost per unit,
$K_{\pi 0}$ = outsourcing setup expense,
Q_0 = batch size of in-house fabrication,
C_0 = unit in-house production cost,
$\beta_{2,0}$ = connecting parameter of $C_{\pi 0}$ and C_0,
$h_{1,0}$ = inventory holding cost per unit,
i_0 = linking factor between C_i and $h_{1,i}$ (e.g., $h_{1,i} = C_i\, i_0$),
K_0 = in-house setup cost,
$\beta_{1,0}$ = connecting parameter of $K_{\pi 0}$ and K_0,
$P_{1,0}$ = annual production rate,
$t_{1,0}$ = the stage 1's uptime,
x_0 = random scrap proportion,
$d_{1,0}$ = random scraps' fabricating rate; $d_{1,0} = x_0 P_{1,0}$),
$C_{S,0}$ = unit disposal cost,
$H_{1,0}$ = inventory level when uptime ends,
$H_{2,0}$ = inventory level after receipt of subcontracting components,
S_0 = in-house setup time,
$h_{4,0}$ = holding cost per safety stock,
$t_{2,0}$ = depleting time of standard parts.

Stage 2's notation in fabricating each end/finished merchandise i (where $i = 1, 2, \ldots, L$),

n = delivering frequency,
λ_i = annual requirement of each finished merchandise,
L = the number of end products,
C_i = stage 2's unit cost,
K_i = stage 2's setup cost,
$h_{1,i}$ = stage 2's holding cost per item,
Q_i = batch size,
$t_{1,i}$ = uptime,
S_i = stage 2's setup time,
$P_{1,i}$ = annual producing rate,
x_i = random scrap proportion,
$d_{1,i}$ = production rate of random scraps ($d_{1,i} = P_{1,i}\, x_i$),,
$H_{1,i}$ = inventory level when uptime completes,
$I_d(t)_i$ = scrapped level at time t,
$C_{S,i}$ = unit disposal cost,
$I(t)_i$ = stock level at time t,
$I_S(t)_i$ = scrap stock level at time t,
$h_{4,i}$ = holding cost per safety item,
$C_{D,i}$ = unit delivering cost,
$h_{3,i}$ = customer end's holding cost per item,
$K_{D,i}$ = fixed delivering cost,
$t_{2,i}$ = finished merchandise's delivering time,
D_i = fixed delivering amount per shipment,
$t_{n,i}$ = fixed delivering time-interval,
I_i = amount of merchandise left when $t_{n,i}$ ends,

$I_c(t)_i$ = client stock level at time t,
$E[T_\pi]$ = expected cycle length,
$TC(T_\pi, n)$ = overall system costs per cycle,
$E[TC(T_\pi, n)]$ = expected overall system costs per cycle,
$E[TCU(T_\pi, n)]$ = the expected overall system costs per year.

2.2. Description, assumption, and mathematical modeling

The study builds a mathematical model to portray the proposed hybrid multiproduct delayed differentiation two-stage EPQ system with scrap and end-products multi-shipment policy. For the proposed delayed differentiation two-stage scheme, we plan to make standard components in stage 1 required for producing the L different finished merchandise in stage 2 (where $i = 1, 2, \ldots, L$). The common part's completion rate γ is assumed to be a known constant (compared with the end merchandise). For example, if $\gamma = 0.5$, then both $P_{1,i}$, and $P_{1,0}$ have double speeds of its single-stage fabricating system. Because stage 1's uptime is significantly prolonged, this study subcontracts a π_0 portion of the annual requirement of standard components to shorten uptime. Associating with stage 1's subcontracting strategy, there are different setup $K_{\pi0}$ and unit $C_{\pi0}$ expenses expressed as shown in Eq. (1) and Eq. (2).

$$K_{\pi0} = \left(1+\beta_{1,0}\right)K_0 \tag{1}$$

$$C_{\pi0} = \left(1+\beta_{2,0}\right)C_0 \tag{2}$$

Further, there exists a random scrap percentage x_0 and x_i in both stages. These scraps are identified and removed (with extra unit disposal expenses, $C_{S,0}$, and $C_{S,i}$) to ensure the anticipated quality. Fig. 1 shows our model's scheme and detailed stock status in a batch cycle at different time t, and Fig. 2 displays the scrap status at time t.

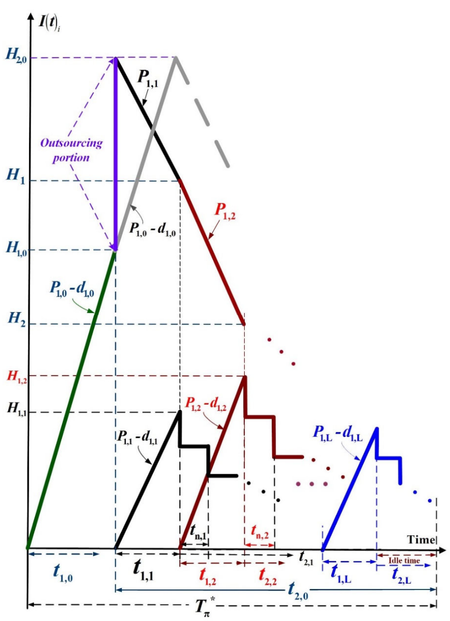

Fig. 1. The proposed model's scheme and detailed stock status in a batch cycle at different time t compared with the same system without subcontracting option (in grey)

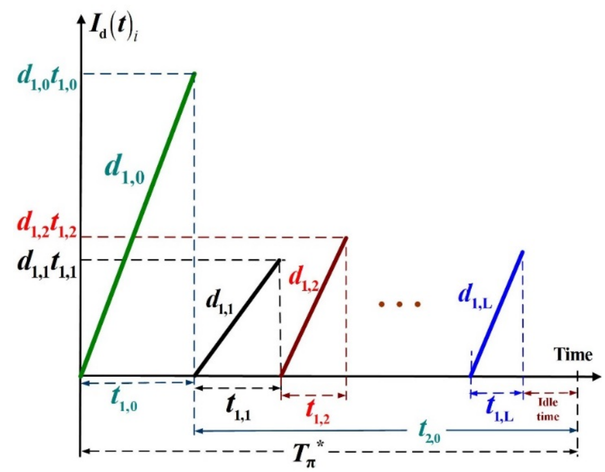

Fig. 2. The proposed model's scrap status at time t

By observing stage 1 in Fig. 1, the standard component's stock level surges to $H_{1,0}$ when uptime ends, reaches $H_{2,0}$, when the subcontracting parts arrive. In the 2nd stage, each end merchandise's stock reaching $H_{1,i}$ when its uptime ends. Because we do not allow stock-out condition, $P_{1,i} - d_{1,i} - \lambda_i > 0$ and $P_{1,0} - d_{1,0} > 0$ must hold. Observing both stages in Fig. 2, scrap level surges to ($d_{1,i}\, t_{1,i}$) and ($d_{1,0}\, t_{1,0}$). Fig. 3 illustrates the required standard components' stock status in making each merchandise i during stage 2. One can find the following relationships by observing stage 2 in Fig. 1 and Fig. 3:

$$H_1 = H_{2,0} - Q_1 \tag{3}$$

$$H_i = H_{(i-1)} - Q_i \;,\; for\ i = 2,\ 3,\ \ldots, L \tag{4}$$

$$H_L = 0 = H_{(L-1)} - Q_L \tag{5}$$

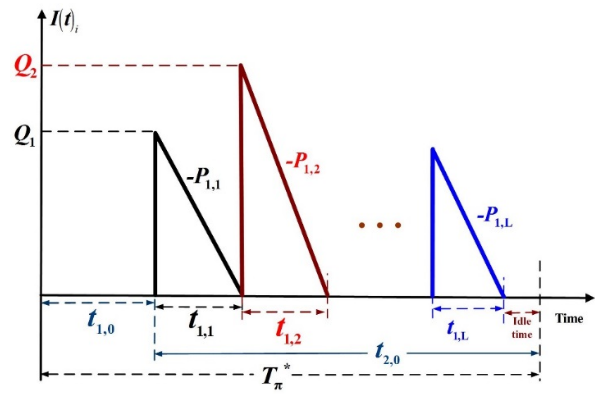

Fig. 3. The required standard components' stock status in making each merchandise *i*

2.3. Model formulation

The required standard components for making *L* finished merchandizing are expressed in Eq. (6), and by observing stage 1 in Fig. 1 and Fig. 2, one can find the following relationships:

$$H_{2,0} = \sum_{i=1}^{L} \frac{\lambda_i T_\pi}{1-x_i} = \sum_{i=1}^{L} Q_i \tag{6}$$

$$\lambda_0 = \frac{\sum_{i=1}^{L} Q_i}{T_\pi} \tag{7}$$

$$Q_0 = \frac{H_{1,0}}{1-x_0} \tag{8}$$

$$T_\pi = t_{1,0} + t_{2,0} \tag{9}$$

$$\pi_0 \left(\sum_{i=1}^{L} Q_i \right) = H_{2,0} - H_{1,0} \tag{10}$$

$$t_{1,0} = \frac{Q_0}{P_{1,0}} = \frac{H_{1,0}}{P_{1,0} - d_{1,0}} \tag{11}$$

$$t_{2,0} = T_\pi - t_{1,0} \tag{12}$$

$$H_{1,0} = (1-\pi_0)\left(\sum_{i=1}^{L} Q_i \right) = \left(P_{1,0} - d_{1,0}\right) t_{1,0} \tag{13}$$

Then, by observing stage 2 in Figs. 1 to 3, one finds the following relationships for $i = 1, 2, \ldots, L$:

$$Q_i = \frac{\lambda_i T_\pi}{1-x_i} \tag{14}$$

$$T_\pi = t_{1,i} + t_{2,i} \tag{15}$$

$$t_{1,i} = \frac{Q_i}{P_{1,i}} = \frac{H_{1,i}}{P_{1,i} - d_{1,i}} \tag{16}$$

$$H_{1,i} = t_{1,i}\left(P_{1,i} - d_{1,i}\right) \tag{17}$$

$$t_{2,i} = T_\pi - t_{1,i} \tag{18}$$

Fig. 4 exhibits each merchandise *i*'s stock level in delivering time and *n* equal-size shipments are distributed to the client in $t_{2,i}$, and the total stocks are as follows:

$$\left(\frac{1}{n^2}\right)\left(\sum_{i=1}^{n-1} i\right)\left(t_{2,i}\right)H_{1,i}=\left(\frac{1}{n^2}\right)\left(t_{2,i}\right)H_{1,i}\left[\frac{n(n-1)}{2}\right]=\left(\frac{n-1}{2n}\right)\left(t_{2,i}\right)H_{1,i} \tag{19}$$

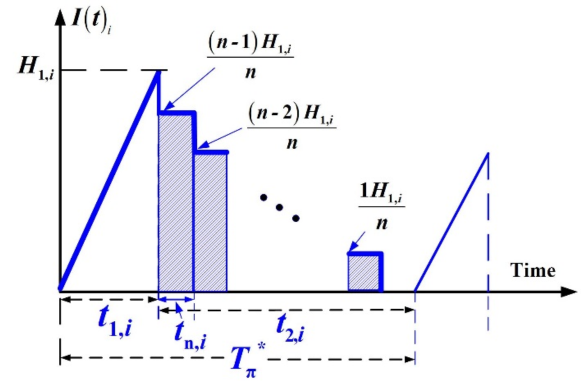

Fig. 4. Each merchandise i's stock level in delivering time $t_{2,i}$

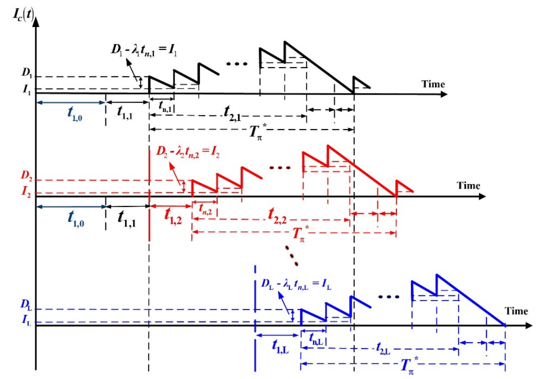

Fig. 5. Finished item i's stock level on the customer end

Fig. 5 demonstrates each merchandise i's stock level on the client's end, and the following are total stocks on the client side for each merchandise i:

$$\left[\frac{n(n+1)}{2}I_i t_{n,i}+\frac{n\left(D_i-I_i\right)t_{n,i}}{2}+\frac{nI_i\left(t_{1,i}\right)}{2}\right] \tag{20}$$

where

$$t_{n,i}=\frac{t_{2,i}}{n} \tag{21}$$

$$D_i=\frac{H_{1,i}}{n} \tag{22}$$

$$I_i=D_i-\lambda_i\left(t_{n,i}\right) \tag{23}$$

2.4. Cost analysis and optimal policy

The overall cycle's system cost, $TC(T_\pi, n)$, involves both stages' setup, variable, stock holding, delivery, and subcontracting cost, as follows:

$$\begin{aligned}TC\left(T_\pi,n\right)=&K_{\pi 0}+C_{\pi 0}\pi_0\left(\sum_{i=1}^{L}Q_i\right)+h_{1,0}\left[\frac{d_{1,0}t_{1,0}}{2}\left(t_{1,0}\right)+\frac{H_{1,0}t_{1,0}}{2}+\sum_{i=1}^{L}\left[\frac{Q_i}{2}\left(t_{1,i}\right)+H_i\left(t_{1,i}\right)\right]\right]+K_0+C_0Q_0+\left(Q_0x_0\right)C_{S,0}+h_{4,0}\left(x_0Q_0\right)T_\pi\\&+\sum_{i=1}^{L}\left\{\begin{array}{l}Q_iC_i+K_i+C_{S,i}\left(Q_ix_i\right)+h_{1,i}\left[\frac{H_{1,i}t_{1,i}}{2}+\left(\frac{n-1}{2n}\right)H_{1,i}\left(t_{2,i}\right)+\frac{d_{1,i}t_{1,i}}{2}\left(t_{1,i}\right)\right]+h_{4,i}\left(x_iQ_i\right)T_\pi\\+nK_{D,i}+C_{D,i}\left[Q_i\left(1-\varphi_i x_i\right)\right]+h_{3,i}\left[\frac{n\left(D_i-I_i\right)t_{n,i}}{2}+\frac{nI_i\left(t_{1,i}\right)}{2}+\frac{n\left(n+1\right)}{2}I_i t_{n,i}\right]\end{array}\right\}\end{aligned} \tag{24}$$

Therefore, one can further obtain the following expected overall system expense per year, $E[TCU(T_\pi, n)]$ (for details, see Appendix A):

$$\begin{aligned}E\left[TCU\left(T_\pi,n\right)\right]=&\frac{K_0\left(1+\beta_{1,0}\right)}{T_\pi}+\pi_0\lambda_0\left(1+\beta_{2,0}\right)C_{\pi 0}+h_{4,0}\lambda_0E_{10}\left(1-\pi_0\right)T+C_0\lambda_0E_{00\pi}\left(1-\pi_0\right)\\&+\frac{K_0}{T_\pi}+C_{S,0}\left(1-\pi_0\right)\lambda_0E_{10}+h_{1,0}\left[\begin{array}{l}\sum_{i=1}^{L}\left[\frac{\left(E_{0i}\right)^2\lambda_i^2T_\pi}{2P_{1,i}}\right]+\frac{\lambda_0^{\,2}\left(E_{00}\right)^2\left(1-\pi_0\right)^2E_{0P}T_\pi}{2}\\+\sum_{i=1}^{L}\left[\left(\lambda_iE_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_iE_{0i}T_\pi-\sum_{j=1}^{i}\lambda_jE_{0j}T_\pi\right)\right]\end{array}\right]\\&+\sum_{i=1}^{L}\left\{\begin{array}{l}C_i\lambda_iE_{0i}+\frac{K_i}{T_\pi}+\frac{nK_{D,i}}{T_\pi}+C_{D,i}\lambda_i+C_{S,i}E_{1i}\lambda_i+h_{1,i}\left(\frac{\lambda_i^2T_\pi}{2}\right)E_{3i}+h_{4,i}\lambda_iE_{1i}T_\pi\\+\frac{h_{3,i}\lambda_i^2E_{0i}E_{2i}T_\pi}{2}+\frac{\lambda_i^{\,2}\left(h_{3,i}-h_{1,i}\right)}{2n}\left[\frac{1}{\lambda_i}-\left(E_{0i}E_{2i}\right)\right]T_\pi\end{array}\right.\end{aligned} \tag{25}$$

By applying the Hessian Matrix equations to $E[TCU(T_\pi, n)]$ (Rardin, 1998):

$$[T_\pi \quad n]\cdot\begin{pmatrix}\dfrac{\partial^2 E\left[TCU(T_\pi,\, n)\right]}{\partial {T_\pi}^2} & \dfrac{\partial^2 E\left[TCU(T_\pi,\, n)\right]}{\partial T_\pi \partial n}\\ \dfrac{\partial^2 E\left[TCU(T_\pi,\, n)\right]}{\partial T_\pi \partial n} & \dfrac{\partial^2 E\left[TCU(T_\pi,\, n)\right]}{\partial n^2}\end{pmatrix}\cdot\begin{bmatrix}T_\pi\\ n\end{bmatrix}=\left[\frac{2(1+\beta_{1,0})K_0}{T_\pi}+\sum_{i=1}^{L}\left\{\frac{2K_i}{T_\pi}\right\}+\frac{2K_0}{T_\pi}\right]>0 \tag{26}$$

Eq. (26) results positive for all variables K_i, T_π, $(1 + \beta_{1,0})$, and K_0 are positive. Hence, $E[TCU(T_\pi, n)]$ is strictly convex for all values of n and $T_\pi > 0$. Apply the 1st and 2nd derivatives of $E[TCU(T_\pi, n)]$, one has the following:

$$\begin{aligned}\frac{\partial E\left[TCU(T_\pi,n)\right]}{\partial T_\pi} &= -\frac{K_0}{{T_\pi}^2}-\frac{K_0(1+\beta_{1,0})}{{T_\pi}^2}+h_{4,0}(1-\pi_0)\lambda_0 E_{10}\\ &+h_{1,0}\left[\sum_{i=1}^{L}\left[\frac{\lambda_i^2(E_{0i})^2}{2P_{1,i}}\right]+\frac{{\lambda_0}^2(E_{00})^2(1-\pi_0)^2E_{0P}}{2}+\sum_{i=1}^{L}\left[(\lambda_i E_{0i}E_{2i})\left(\sum_{i=1}^{L}\lambda_i E_{0i}T_\pi-\sum_{j=1}^{i}\lambda_j E_{0j}\right)\right]\right]\\ &+\sum_{i=1}^{L}\left\{-\frac{nK_{D,i}}{{T_\pi}^2}-\frac{K_i}{{T_\pi}^2}+h_{1,i}\left[\left(\frac{\lambda_i^2}{2}\right)E_{3i}\right]+\frac{h_{3,i}\lambda_i^2E_{0i}E_{2i}}{2}+h_{4,i}\lambda_i E_{1i}+\frac{(h_{3,i}-h_{1,i})\lambda_i^2}{2n}\left[\frac{1}{\lambda_i}-(E_{0i}E_{2i})\right]\right\}\end{aligned} \tag{27}$$

$$\frac{\partial E\left[TCU(T_\pi,n)\right]}{\partial n}=\sum_{i=1}^{L}\left\{\frac{K_{D,i}}{T_\pi}-\frac{\lambda_i^2(h_{3,i}-h_{1,i})T_\pi}{2n^2}\left[\frac{1}{\lambda_i}-(E_{0i}E_{2i})\right]\right\} \tag{28}$$

Setting formulas (27) and (28) = 0 and solving them simultaneously, one derives T_π* and n* as follows:

$$T_\pi^*=\sqrt{\frac{2\left[K_0(2+\beta_{1,0})+\sum_{i=1}^{L}\{K_i+nK_{D,i}\}\right]}{\begin{gathered}h_{1,0}\left[2(\lambda_i E_{0i}E_{2i})\sum_{i=1}^{L}\left[\left(\sum_{i=1}^{L}\lambda_i E_{0i}-\sum_{j=1}^{i}\lambda_j E_{0j}\right)\right]+\lambda_0^2E_{0P}(E_{00})^2(1-\pi_0)^2+\sum_{i=1}^{L}\left[\frac{\lambda_i^2(E_{0i})^2}{P_{1,i}}\right]\right]\\ +\sum_{i=1}^{L}\left\{\frac{\lambda_i^2(h_{3,i}-h_{1,i})}{n}\left(\frac{1}{\lambda_i}-E_{0i}E_{2i}\right)+h_{3,i}\lambda_i^2E_{0i}E_{2i}+h_{1,i}\lambda_i^2E_{3i}+2h_{4,i}\lambda_i E_{1i}\right\}+2\lambda_0 E_{10}h_{4,0}(1-\pi_0)\end{gathered}}} \tag{29}$$

and

$$n^*=\sqrt{\frac{\left[(2+\beta_{1,0})K_0+\sum_{i=1}^{L}\{K_i\}\right]\cdot\sum_{i=1}^{L}\left\{(h_{3,i}-h_{1,i})\lambda_i^2\left[\frac{1}{\lambda_i}-(E_{0i}E_{2i})\right]\right\}}{\sum_{i=1}^{L}(2K_{Di})\sum_{i=1}^{L}\left\{\begin{gathered}h_{1,0}\left[2\sum_{i=1}^{L}\left[\left(\sum_{i=1}^{L}(E_{0i}\lambda_i)-\sum_{j=1}^{i}(E_{0j}\lambda_j)\right)(\lambda_i E_{0i}E_{2i})\right]+(E_{00})^2\lambda_0^2(1-\pi_0)^2E_{0P}+\sum_{i=1}^{L}\left[\frac{\lambda_i^2(E_{0i})^2}{P_{1,i}}\right]\right]\\ +2h_{4,0}(1-\pi_0)\lambda_0 E_{10}+\sum_{i=1}^{L}\left\{2h_{4,i}\lambda_i E_{1i}+h_{1,i}\left[\lambda_i^2E_{3i}\right]+h_{3,i}(\lambda_i^2)E_{0i}E_{2i}\right\}\end{gathered}\right.}} \tag{30}$$

2.5. Comments on prerequisite conditions and setup times

The prerequisite conditions for this multiproduct fabricating plan must ensure adequate capacity in a cycle for both stages (Nahmias, 2009).

$$\left[\sum_{i=1}^{L}(t_{1,i}+t_{2,i})+(t_{1,0}+t_{2,0})\right]<T_\pi \text{ or } \left[\sum_{i=1}^{L}Q_i\left(\frac{1}{P_{1,i}}\right)+Q_0\left(\frac{1}{P_{1,0}}\right)\right]<T_\pi \tag{31}$$

or

$$\left\{\sum_{i=1}^{L}\frac{\lambda_i}{P_{1,i}\left[1-E[x_i]\right]}+\frac{\lambda_0(1-\pi_0)}{P_{1,0}\left[1-E[x_0]\right]}\right\}<1 \tag{32}$$

Furthermore, one must ensure adequate cycle length to accommodate setup times for both stages; as Nahmias (2009) pointed out, the following parameter: $T_{\min}$. That is, choosing the max (T_π*, $T_{\min}$) as the optimal operating cycle length.

$$T_{\min} = \frac{\sum_{i=0}^{L}(S_i)}{1-\left\{\left(\frac{1}{P_{1,0}}\right)\frac{\lambda_0(1-\pi_0)}{\left[1-E[x_0]\right]}+\sum_{i=1}^{L}\left(\frac{1}{P_{1,i}}\right)\frac{\lambda_i}{\left[1-E[x_i]\right]}\right\}} \tag{33}$$

3. Illustrative example

An illustrative example demonstrates how our proposed research scheme and model resolve the specific hybrid delayed-differentiation multiproduct EPQ system featuring scraps and finished goods' multi-shipment plan. Our assumed values for the proposed two-stage system's parameters are shown in Table 1 and Table 2. In comparison, Table B-1 (Appendix B) gives the corresponding parameter values of the single-stage fabricating scheme.

Table 1
Assumed values of the stage-1 parameters in this illustrative example

$C_{S,0}$	λ_0	γ	$P_{1,0}$	$h_{4,0}$	C_0	$h_{1,0}$
$10	17406	0.5	120000	$8	$40	$8
i_0	x_0	δ	π_0	$\beta_{2,0}$	K_0	$\beta_{1,0}$
0.2	2.5%	0.5	0.4	0.4	$8500	-0.7

Table 2
Assumed values of the stage-2 parameters in this illustrative example

Product *i*	x_i	$C_{D,i}$	$C_{S,i}$	$P_{1,i}$	$h_{1,i}$	$K_{D,i}$	λ_i	$h_{4,i}$	K_i	$h_{3,i}$	C_i	i_i
1	2.5%	$0.1	$10	112258	$8	$1800	3000	$8	$8500	$70	$40	0.2
2	7.5%	$0.2	$15	116066	$10	$1900	3200	$10	$9000	$75	$50	0.2
3	12.5%	$0.3	$20	120000	$12	$2000	3400	$12	$9500	$80	$60	0.2
4	17.5%	$0.4	$25	124068	$14	$2100	3600	$14	$10000	$85	$70	0.2
5	22.5%	$0.5	$30	128276	$16	$2200	3800	$16	$10500	$90	$80	0.2

First, we show how to obtain the optimization results for the shipping frequency and rotation fabricating length in a replenishing cycle. By calculation of equations (30) and (29), one finds $n^* = 4$ and $T_\pi^* = 0.5227$. Then, applying these optimal values to Eq. (25), one gains $E[TCU(T_\pi^*, n^*)]$ = $2,388,554. Fig. 5 shows $E[TCU(T_\pi, n)]$'s convexity and behavior relating to n and T_π. As n and T_π deviate from the optimal points, $E[TCU(T_\pi, n)]$ knowingly surges.

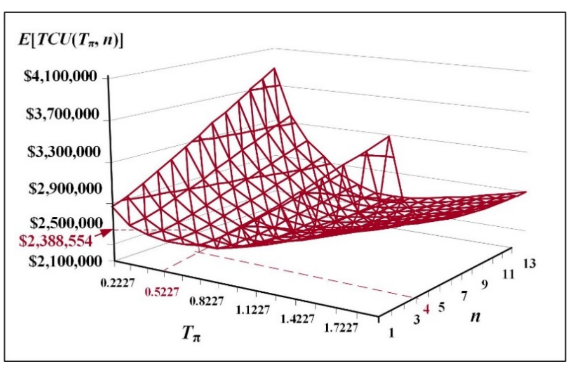

Fig. 6. $E[TCU(T_\pi^*, n^*)]$'s convexity and behavior relating to n and T_π

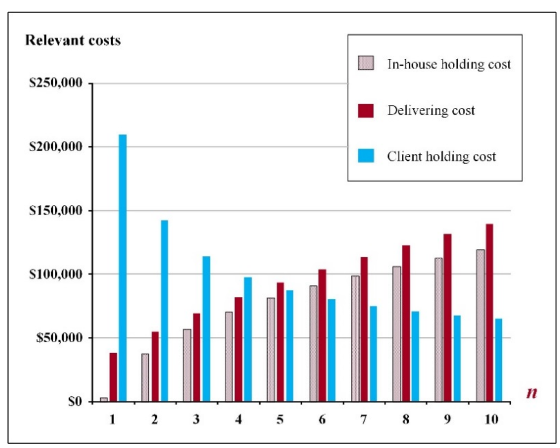

Fig. 7. Various sensitive expenses relating to n

We can now explore crucial managerial decision-related information with the proposed model and research result. For instance, the analyses of expenses of in-house holding, end products' delivery, and client side's stock holding concerning different delivery frequencies in a cycle become possible (see Figure 7). As n increases, the number of end products per shipment drop, so the client's holding cost decreases significantly, and both delivery and in-house holding expenditure rise. We can also study the impact of scraps produced in the fabricating processes in both stages on $E[TCU(T_\pi^*, n^*)]$. As the mean scrap rate increases, the optimal expected annualized system cost $E[TCU(T_\pi^*, n^*)]$ sensitively rises. When mean scrap rate at 15%, as we assumed, we confirm $E[TCU(T_\pi^*, n^*)]$ = $2,388,554 (Fig. 8).

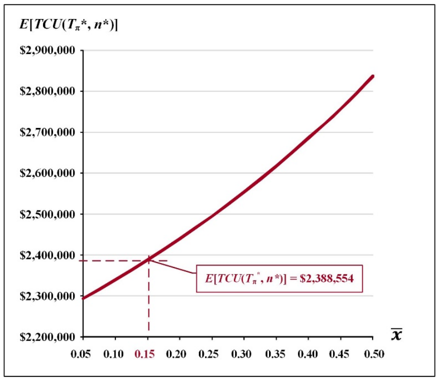

Fig. 8. $E[TCU(T_\pi^*, n^*)]$'s behavior relating to the mean scrap rate

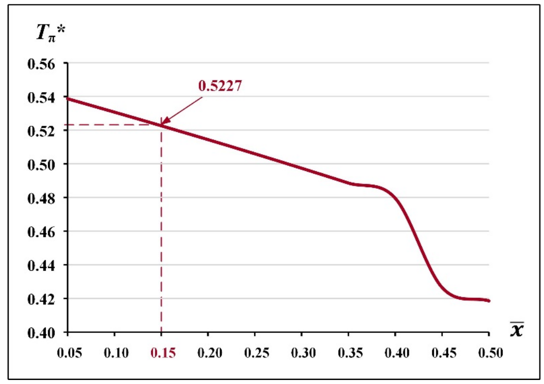

Fig. 9. T_π^*'s behavior relating to the mean scrap rate

As to the impact of mean scrap rate on the optimal batch cycle time T_π^*, a further analytical result is depicted in Figure 9. It exposes that as the mean scrap rate increases to 0.40, T_π^* declines mildly, and as the mean scrap rate goes beyond and over 0.4, T_π^* drops severely. The optimal $T_\pi^* = 0.5227$ as we assumed the mean scrap rate at 0.15. Fig> 10 exhibits the investigative result of the collective impact of the mean scrap rate and subcontracting portion π_0 on $E[TCU(T_\pi^*, n^*)]$. As the mean scrap rate and π_0 increase, the optimal expected annualized system cost $E[TCU(T_\pi^*, n^*)]$ knowingly surges. In our example's assumption, the mean scrap rate influences $E[TCU(T_\pi^*, n^*)]$ more than π_0.

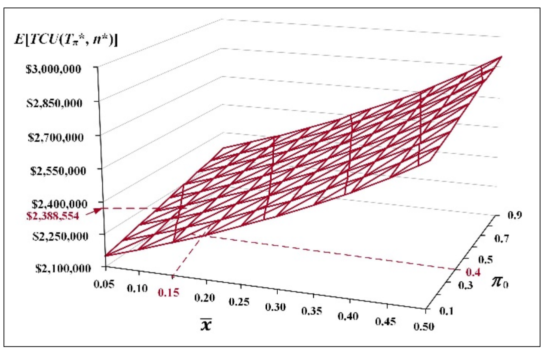

Fig. 10. $E[TCU(T_\pi^*, n^*)]$'s behavior relating to the mean scrap rate and π_0

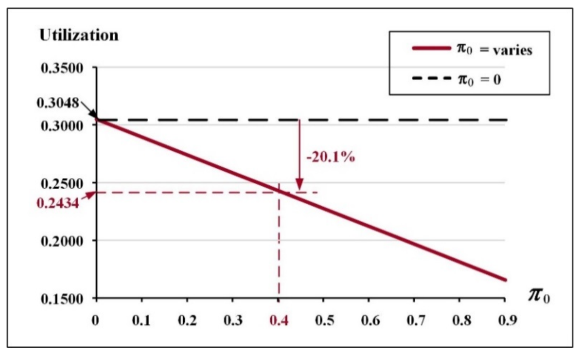

Fig. 11. The impact of subcontracting portion π_0 on the system's utilization

Table C-1 exposes further investigative outcomes of various critical production-system-relating variables influenced by π_0. The impact of subcontracting portion π_0 on the system's utilization is illustrated in Fig. 11. One notes as π_0 rises, the in-house production load relaxes, so utilization considerably drops. In the example, we assume $\pi_0 = 0.4$, and the utilization decreases a 20.1% (i.e., falling from 0.3048 to 0.2434). Fig. 12 explores the difference in $E[TCU(T_\pi^*, n^*)]$ for the studied problem with and without subcontracting. Fig. 11 indicates a 20.1% decline in utilization and Fig. 12 shows the price-pay is a 4.96% increase in the optimal expected annualized system cost $E[TCU(T_\pi^*, n^*)]$ (see Table C-1), i.e., surging from $2,275,764 (without subcontracting) to $$2,388,554 (with subcontracting $\pi_0 = 0.4$).

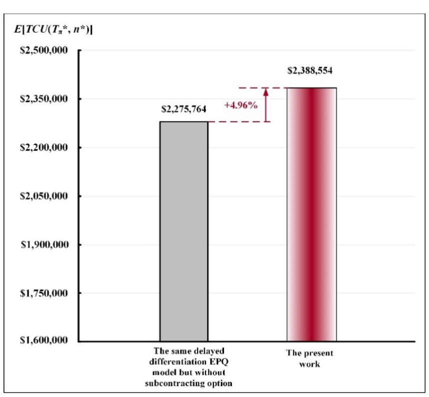

Fig. 12. The difference in $E[TCU(T_\pi^*, n^*)]$ for the system with and without subcontracting

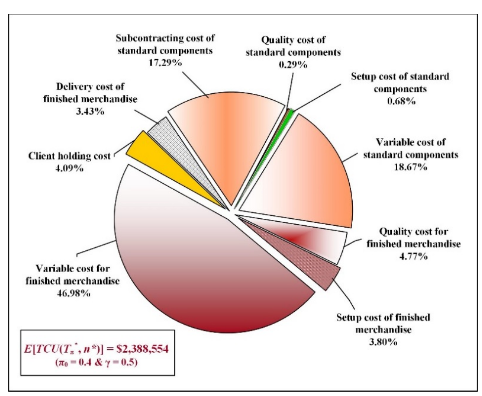

Fig. 13. Detailed expenses breakup of $E[TCU(T_\pi^*, n^*)]$

The proposed research model enables us to investigate the detailed expenses contributing to the expected annualized system cost $E[TCU(T_\pi^*, n^*)]$ (Figure 13). It exposes that the main contributors to $E[TCU(T_\pi^*, n^*)]$ are in the following order:

(1) the variable fabricating cost for finished merchandise: 46.98%;

(2) for our assumption $\pi_0 = 0.4$, the variable cost for standard components: 18.67%;

(3) the subcontracting cost for standard components: 17.29%; and

(4) other expenses include total quality cost: 5.06%, client's holding cost: 4.09%, finished products' delivery cost: 3.43, etc.

Fig. 14 portrays the investigative outcome of the influence of γ (i.e., standard part's completing proportion) on the optimal uptime $t_{1,0}^*$. It discloses $t_{1,0}^*$ knowingly rises as γ increases. For our assumption $\gamma = 0.5$, $t_{1,0}^*$ upsurges to 0.0482 from zero.

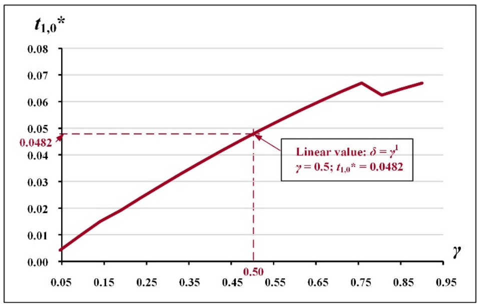

Fig. 14. The optimal standard component's uptime $t_{1,0}^*$ relating to γ

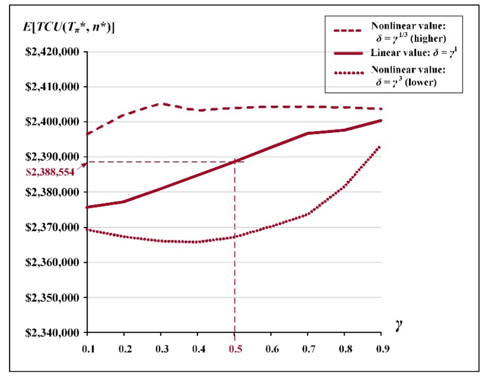

Fig. 15. $E[TCU(T_\pi^*, n^*)]$'s behavior concerning different relationship δ in terms of γ values

In the example, we assume a linear relationship δ for the commercial value of a standard component and its completing proportion γ. For instance, if $\gamma = 0.5$, we assume common part's value is half of its end merchandise's unit cost. However, this may not be true in certain kinds of industrial commodities. To address this issue, we would like to show that our research model is capable of exploring many different types of relationships (e.g., $\delta = \gamma^1$ (be a linear) and $\delta = \gamma^{1/3}$ (be a specific nonlinear)). Figure 15 demonstrates the behavior of optimal expected annualized system cost $E[TCU(T_\pi^*, n^*)]$ concerning the different types of relationship δ in terms of γ values.

4. Conclusions

The customer requirements have an evident trend of becoming varied, fast-response, and anticipated quality. Meeting these customers' growing expectations are today's fabrication managers' routine operations goals. This work intends to optimize a hybrid delayed differentiation multiproduct economic production quantity-EPQ model with the scrap and end-products multi-shipment policy to help management simultaneously achieve these targets. This study derives the optimal fabricating time and delivery frequency for a batch cycle by building a precise two-phase fabricating model to portray the studied system and aiming with formulation and optimization approaches (see sections 2 and 3). In section 4, this work gives a numerical demonstration of the obtained results' applicability and usefulness to managerial decision-making as follows:

(1) $E[TCU(T_\pi^*, n^*)]$'s convexity and behavior relating to n and T_π (see Fig. 6);
(2) Various sensitive expenses relating to n (Figure 7);
(3) The behavior of $E[TCU(T_\pi^*, n^*)]$ and T_π^* relating to the mean scrap rate (Figures 8 & 9);
(4) $E[TCU(T_\pi^*, n^*)]$'s behavior relating to the mean scrap rate and π_0 (Figure 10);
(5) Impact of subcontracting portion π_0 on utilization and $E[TCU(T_\pi^*, n^*)]$ (Figures 11 & 12);
(6) Detailed expenses breakup of $E[TCU(T_\pi^*, n^*)]$ (Figure 13);
(7) The optimal standard component's uptime $t_{1,0}^*$ relating to γ (Figure 14);
(8) $E[TCU(T_\pi^*, n^*)]$'s behavior concerning different relationship δ in terms of γ values (Figure 15).
Incorporating random annual end-products demands in the proposed problem is worth future study.

Appendix – A

One can obtain $E[TCU(T_\pi, n)]$ from Eq. (24) by completing the steps below: (A) apply the expected values $E[x_0]$ and $E[x_i]$ to deal with randomness of scrap rates, (B) substitute Eqs. (1-23) in Eq. (24), and (C) compute $E[TC(T_\pi, n)] / E[T_\pi]$. Eq. (A-1) shows the result of $E[TCU(T_\pi, n)]$.

$$E\left[TCU\left(T_\pi,n\right)\right]=\frac{\left(1+\beta_{1,0}\right)K_0}{T_\pi}+\left(1+\beta_{2,0}\right)C_{\pi 0}\pi_0\lambda_0+C_0\frac{\left(1-\pi_0\right)\lambda_0}{1-E\left[x_0\right]}+\frac{K_0}{T_\pi}+C_{S,0}\frac{\left(1-\pi_0\right)\lambda_0 E\left[x_0\right]}{1-E\left[x_0\right]}$$
$$+h_{4,0}\frac{\left(1-\pi_0\right)\lambda_0 E\left[x_0\right]T_\pi}{1-E\left[x_0\right]}+h_{1,0}\left[\begin{array}{l}\frac{\left(1-\pi_0\right)^2\lambda_0^{\,2}T_\pi}{2P_{1,0}\left(1-E\left[x_0\right]\right)^2}+\sum_{i=1}^{L}\left[\frac{\lambda_i^2T_\pi}{2P_{1,i}\left(1-E\left[x_i\right]\right)^2}\right]\\+\sum_{i=1}^{L}\left[\left(\sum_{i=1}^{L}\frac{\lambda_iT_\pi}{1-E\left[x_i\right]}-\sum_{j=1}^{i}\frac{\lambda_jT_\pi}{1-E\left[x_j\right]}\right)\left(\frac{\lambda_i}{P_{1,i}\left(1-E\left[x_i\right]\right)}\right)\right]\end{array}\right]$$
$$+\sum_{i=1}^{L}\left\{\begin{array}{l}C_i\left(\frac{\lambda_i}{1-E\left[x_i\right]}\right)+\frac{K_i}{T_\pi}+C_{S,i}\left(\frac{E\left[x_i\right]\lambda_i}{1-E\left[x_i\right]}\right)+\frac{nK_{D,i}}{T_\pi}+C_{D,i}\lambda_i+h_{1,i}\left(\frac{\lambda_i^2T_\pi}{2}\right)\left(\frac{1}{\lambda_i}+\frac{E\left[x_i\right]}{P_{1,i}\left(1-E\left[x_i\right]\right)^2}\right)\\+h_{4,i}\left(\frac{E\left[x_i\right]\lambda_i}{1-E\left[x_i\right]}\right)T_\pi+\frac{h_{3,i}\left(\lambda_i^2T_\pi\right)}{2}\left(\frac{1}{P_{1,i}\left(1-E\left[x_i\right]\right)}\right)+\left(\frac{\lambda_i^{\,2}\left(h_{3,i}-h_{1,i}\right)T_\pi}{2n}\right)\left[\frac{1}{\lambda_i}-\frac{1}{P_{1,i}\left(1-E\left[x_i\right]\right)}\right]\end{array}\right\} \tag{A-1}$$

Let E_{00}, E_{10}, E_{0i}, E_{1i}, E_{0j}, E_{0P}, E_{2i}, and E_{3i} represent the following:

$$E_{00}=\frac{1}{\left(1-E\left[x_0\right]\right)};\ E_{10}=\frac{E\left[x_0\right]}{\left(1-E\left[x_0\right]\right)};\ E_{0P}=\left[\frac{1}{P_{1,0}}\right];\ E_{0j}=\frac{1}{\left(1-E\left[x_j\right]\right)}\ \ for\ \ j=1,...,i \tag{A-2}$$

$$E_{0i}=\frac{1}{\left(1-E\left[x_i\right]\right)};\ E_{1i}=\frac{E\left[x_i\right]}{\left(1-E\left[x_i\right]\right)};\ E_{2i}=\left[\frac{1}{P_{1,i}}\right];\ E_{3i}=\left[\frac{1}{\lambda_i}+\frac{\left(E_{0i}\right)\left(E_{1i}\right)}{P_{1,i}}\right]\ \ for\ \ i=1,...,L. \tag{A-3}$$

Substitute Eqs. (A-2) and (A-3) in Eq. (A-1), one find $E[TCU(T_\pi, n)]$ as follows:

$$E\left[TCU\left(T_\pi,n\right)\right]=\frac{K_0\left(1+\beta_{1,0}\right)}{T_\pi}+\pi_0\lambda_0\left(1+\beta_{2,0}\right)C_{\pi 0}+h_{4,0}\lambda_0E_{10}\left(1-\pi_0\right)T+C_0\lambda_0E_{00\pi}\left(1-\pi_0\right)$$
$$+\frac{K_0}{T_\pi}+C_{S,0}\left(1-\pi_0\right)\lambda_0E_{10}+h_{1,0}\left[\begin{array}{l}\sum_{i=1}^{L}\left[\frac{\left(E_{0i}\right)^2\lambda_i^2T_\pi}{2P_{1,i}}\right]+\frac{\lambda_0^{\,2}\left(E_{00}\right)^2\left(1-\pi_0\right)^2E_{0P}T_\pi}{2}\\+\sum_{i=1}^{L}\left[\left(\lambda_iE_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_iE_{0i}T_\pi-\sum_{j=1}^{i}\lambda_jE_{0j}T_\pi\right)\right]\end{array}\right]$$
$$+\sum_{i=1}^{L}\left\{\begin{array}{l}C_i\lambda_iE_{0i}+\frac{K_i}{T_\pi}+\frac{nK_{D,i}}{T_\pi}+C_{D,i}\lambda_i+C_{S,i}E_{1i}\lambda_i+h_{1,i}\left(\frac{\lambda_i^2T_\pi}{2}\right)E_{3i}+h_{4,i}\lambda_iE_{1i}T_\pi\\+\frac{h_{3,i}\lambda_i^2E_{0i}E_{2i}T_\pi}{2}+\frac{\lambda_i^{\,2}\left(h_{3,i}-h_{1,i}\right)}{2n}\left[\frac{1}{\lambda_i}-\left(E_{0i}E_{2i}\right)\right]T_\pi\end{array}\right\} \tag{25}$$

Appendix – B

Table B-1
The corresponding variables' values as in a one-stage fabricating system

Product i	i_i	$C_{D,i}$	C_i	$K_{D,i}$	$h_{3,i}$	$P_{1,i}$	$h_{1,i}$	x_i	$C_{S,i}$	K_i	λ_i	$h_{4,i}$
1	0.2	$0.1	$80	$1800	$70	58000	$16	5%	$20	$17000	3000	$16
2	0.2	$0.2	$90	$1900	$75	59000	$18	10%	$25	$17500	3200	$18
3	0.2	$0.3	$100	$2000	$80	60000	$20	15%	$30	$18000	3400	$20
4	0.2	$0.4	$110	$2100	$85	61000	$22	20%	$35	$18500	3600	$22
5	0.2	$0.5	$120	$2200	$90	62000	$24	25%	$40	$19000	3800	$24

Appendix - C

Table C-1
Various critical production-system relating variables influenced by π_0

π_0	$t_{1,0}$* (A)	(A)% fall	Utilization (B)	(B) % fall	T_π*	n*	$E[TCU(T_\pi*, n*)]$ (C)	(C) % surge	Stage 1's Subcontracting expenditure (D)	(D) / (C) %
0.00	0.0784	-	0.3048	-	0.5102	4	$2,275,764	-	$0	0.00%
0.05	0.0756	-3.57%	0.2972	-2.49%	0.5178	4	$2,294,107	0.81%	$55,935	2.44%
0.10	0.0718	-8.42%	0.2895	-5.02%	0.5186	4	$2,307,513	1.40%	$106,938	4.63%
0.15	0.0679	-13.39%	0.2818	-7.55%	0.5194	4	$2,320,948	1.99%	$157,941	6.81%
0.20	0.0640	-18.37%	0.2741	-10.07%	0.5201	4	$2,334,411	2.58%	$208,944	8.95%
0.25	0.0601	-23.34%	0.2664	-12.60%	0.5208	4	$2,347,903	3.17%	$259,948	11.07%
0.30	0.0561	-28.44%	0.2587	-15.12%	0.5215	4	$2,361,425	3.76%	$310,952	13.17%
0.35	0.0522	-33.42%	0.2510	-17.65%	0.5221	4	$2,374,975	4.36%	$361,957	15.24%
0.40	**0.0482**	**-38.52%**	**0.2434**	**-20.14%**	**0.5227**	**4**	**$2,388,554**	**4.96%**	**$412,962**	**17.29%**
0.45	0.0442	-43.62%	0.2357	-22.67%	0.5232	4	$2,402,163	5.55%	$463,967	19.31%
0.50	0.0403	-48.60%	0.2280	-25.20%	0.5237	4	$2,415,800	6.15%	$514,973	21.32%
0.55	0.0363	-53.70%	0.2203	-27.72%	0.5242	4	$2,429,468	6.75%	$565,979	23.30%
0.60	0.0323	-58.80%	0.2126	-30.25%	0.5246	4	$2,443,164	7.36%	$616,986	25.25%
0.65	0.0282	-64.03%	0.2049	-32.78%	0.5250	4	$2,456,890	7.96%	$667,993	27.19%
0.70	0.0242	-69.13%	0.1972	-35.30%	0.5253	4	$2,470,646	8.56%	$719,000	29.10%
0.75	0.0202	-74.23%	0.1895	-37.83%	0.5256	4	$2,484,432	9.17%	$770,008	30.99%
0.80	0.0162	-79.34%	0.1819	-40.32%	0.5259	4	$2,498,247	9.78%	$821,016	32.86%
0.85	0.0121	-84.57%	0.1742	-42.85%	0.5261	4	$2,512,092	10.38%	$872,024	34.71%
0.90	0.0081	-89.67%	0.1665	-45.37%	0.5262	4	$2,525,967	10.99%	$923,033	36.54%
0.95	0.0040	-94.90%	0.1588	-47.90%	0.5264	4	$2,539,871	11.61%	$974,042	38.35%
1.00	0.0000	-100%	0.1511	-50.43%	0.5033	4	$2,537,296	11.49%	$1,025,275	40.41%

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