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The joint influence of quality assurance and postponement on a hybrid multi-item manufacturing-delivery decision-making

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A B S T R A C T

The present research explores the collective influence of quality assurance and postponement on a hybrid multiproduct replenishing-delivery decision-making. Assume the required multiproduct has a standard (common) component, and our replenishing-delivery model has incorporated a two-phase postponement strategy. The first phase makes all standard components and hires an external supplier to partially provide the required parts to cut short the needed uptime. In contrast, the second phase fabricates the finished multiproduct in sequence. To ensure the desired merchandise quality, we apply a quality-assurance action to the in-house processes to screen and remove scrap items and rework the repairable defects in both stages. Upon completing each merchandise, these products are transported to the customer in n fixed-quantity shipment in fixed-time intervals. We employ math modeling and formulating approaches to gain the overall supply-chain operating expenses comprising subcontracting, fabricating, stock holding, transportation, and customer holding costs. By minimizing system operating expenses, this research determines the optimal replenishing-delivery policy. Lastly, we give a numerical example to demonstrate our study's applicability and usefulness/capability for facilitating managerial decision-making.

1. Introduction

This work examines the collective influence of quality assurance and postponement on a hybrid multiproduct replenishing-delivery decision-making. To make an optimal replenishment-delivery decision in today's exceedingly competitive and turbulent global marketplaces, the management must continuously focus on simultaneously meeting clients' requirements for various types of high-quality goods and fast order-response time, with minimum fabricating-inventory-shipment expenses. For planning a multi-item fabrication with standard, and intermediate parts, a two-phase postponement strategy may assist in smoothening production efforts relating to preparing needed materials and easing setup and labor arrangements. The first phase focuses on making all standard parts required for fabricating multiple end products in the second phase. Such a postponement strategy can often shorten fabrication uptime and overall expenses. Fixson (2007) conducted a study focusing on commonality and modularity by surveying over 160 articles in 36 management and engineering journals for 35 years. The researcher concentrated on each study's subject (including organizations, products, fabricating processes, and innovations), methodology, and effect. The study found that many past studies' subjects focused on products, the cost dominated the impact and significantly different methods used by the past studies. The researcher believed that future studies still have great opportunities to contribute to the present-day supply-chain players incorporating modularity and commonality. Van Kampen and Van Donk (2014) investigated the impact of implementing a postponement discipline to deal with the increasing variety

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of goods and uncertain demands in the food-processing industry. The researchers examined various characteristics that affect the operating performance when implementing the postponement. They developed a simulation model using a dairy firm's data as a case study and found that implementing postponement substantially improved operational performance. It significantly enhances fabrication timing through restricted lot sizes and cyclical planning of fabricating settings. The study gave other considerations on maximizing the benefits of implementing the postponement and what other things will lower its benefits. Bolaños and Barbalho (2021) studied the complexity and lead times prototype to estimate/shorten the cycle time of the new product development (NPD). Replacing the conventional planning approaches, the researchers proposed regression models to investigate the potential complexity and prototype lead time projection for NPD processes. By first identifying and understanding the NPD relevant complex parameters and behaviors, the researcher then developed the variables validation procedures to collect the values of the variables enabling the study to design complexity issues. At last, the researchers showed their scheme's applicability with company data. They found an error rate of four percent compared to the existing literature to demonstrate the comparative impact of their model regarding complexity and lead time prototype on the improvement of new product development projects. Recent studies (Minguella-Canela ey al., 2017; Chiu et al., 2020; Dargaud & Jacques, 2020; Meistering & Stadtler, 2020; Chiu et al., 2021; Okfalisa et al., 2021; Chiu et al., 2022a; Lin et al., 2022a) investigated the influences of various multiproduct/postponement features on fabrication planning and management of different supply chains and multiproduct systems.

To satisfy clients' timely requirements in a multiproduct fabricating schedule incorporating postponement, partially subcontracting the required batch size could be an efficient strategy to cut down the uptime for the standard/common parts mass production in stage one. De Boer et al. (2006) explored a satisficing outsourcing model to offer practical guidance facilitating the early stages of outsourcing decision making. The researchers used two empirical logistics tasks outsourcing cases to compare/analyze the satisficing and rationality viewpoints compared to the existing literature. Based on the resulting satisfying principles, the study developed a conceptual model with helpful explanations to assist in managerial decision making. Hofer (2015) conducted a customer survey of Brazil's 3rd logistics provider to study the performance and dynamics of the inter-organizational joint-dependence and asymmetry-dependence relationships in logistics outsourcing. The survey results exposed that customers of 3rd-party logistics providers in high joint-dependence level relationships significantly influence their outsourcing performance and degree of information exchange. The study also found that customers of 3rd-party logistics providers with different degrees of asymmetry-dependence relationships may enhance/reduce the impact of mutual dependence. Anderson and McKenzie (2022) conducted an experiment associating consulting, outsourcing, training, and insourcing to improve small firms' business practices/skills needed in marketing and finance. The study focused on expanding the small firms' boundary by introducing professional marketing/finance insourcing workers or subcontracting these functions. The study experimented randomly in Nigeria to investigate the effects of relevant business practices, resulting in subcontracting and insourcing significantly impacting business practices improvement rather than training and cost less than business consulting. Other studies (Momme et al., 2000; Novak & Stern, 2008; Westphal & Sohal, 2016; Lin et al., 2021b; Chiu et al., 2022b; Dong et al., 2022; Ranasinghe et al., 2022; Suharmono et al., 2022) investigated different subcontracting strategies' effects on the optimal planning, operational controls, and management of various supply-chain systems and fabricating processes/ procedures.

In current global marketplaces, customers' orders request various goods, fast responses, and high quality. Hence, the management of production units must screen the random defects, take consequent quality-assurance actions, plan an efficient and client-anticipation transportation schedule, and minimize the overall operating costs. Past literature focused on various aspects of product-shipping, and quality assurances tasks are surveyed as follows. Guiffrida and Nagi (2006) explored the strategies for enhancing supply-chain shipment performance relating to cost characterizations. The study evaluated a serial supply-chain delivery window, developed models considering each stage in supply-chain financial measurement's variability and established a standard to justify the needed capital investment for delivery performance improvement. Mustafa et al. (2014) conducted a performance study of a parallel Kanban-based multi-stage high-mix products' fabrication-rework system. The study separated high- and low-runner items with Kanban and base stock systems, where the Kanban systems incorporated loading rule, rework entering discipline, and the model driver. The performance indexes included measurements of flow times, average utilization and work-in-process, and total output. The research methodologies comprised simulations, ANOVA analysis, response surface, and regression equations. Various rework policies are adopted to compare and select one that enhances the performance. Dhahri et al. (2022) studied a single-manufacturer multi-retailers unreliable fabrication-shipment integrated system. The manufactured goods are stored in a warehouse to supply retailers of different locations and demands. The study proposed a model to derive the optimal joint fabrication and shipping policy that minimized the total costs comprising stock holding, backlogging, and transportation. The researchers first used a hedging point discipline and a state-dependent economic lot sizing to control the fabrication and transportation policies. Then, they employed a simulation technique to optimize such a stochastic control model and verified the research results by sensitivity analysis. Secondly, the study expanded to incorporate the product-shipping priority rules into their model and compared the changes/performances in the optimal policies using the simulation method. Adak and Mahapatra (2022) examined a two-echelon producers-retailers supply-chain system with inspection of product quality and reworked faulty goods. Producers shipped only the perfect-quality goods to the retailers to meet customers' demands. Both producers and retailers consider probabilistic deterioration. The researchers built optimization models considering fabricating rate and unit cost, screening, and rework under both fuzzy and crispy environments. The study offered managerial insights into the influence of system parameters on the optimal solution.

Other literature (Goyal and Nebebe, 2000; Maddah and Jaber, 2008; Giri and Maiti, 2012; Uthayakumar and Tharani, 2017; Bachtiar et al., 2021; Euchi et al., 2021; Kakran et al., 2021; Shadrina et al., 2021; Tyagi et al., 2021; Velasco-Parra et al., 2021; Baig et al., 2022; Balázs et al., 2022; Kaviyarasu et al., 2022; Mohammadipour ey al., 2022; Mukhsin et al., 2022; Prajapati et al., 2022; Snow et al., 2022) considered the impact of diverse finished goods' shipping strategies, various manufacturing processes' imperfection, and their consequent actions on production and supply-chain systems' planning, operations, management, and optimization. Because limited past literature explored the collective influence of quality assurance and postponement on a hybrid multiproduct replenishing-delivery decision-making, this study aims to fill this gap.

2. The proposed problem

This study explores the collected influence of quality assurance and postponement on a hybrid multiproduct replenishing-delivery decision-making. We first use nomenclature to define all relevant notations below, and the problem statement follows.

2.1. Nomenclature

Definitions of stage one's notations in making standard parts:

Q_0 = lot size (in-house),
λ_0 = annual requirements,
π_0 = a proportion of required standard parts supplied by an outsider source,
$K_{\pi 0}$ = setup cost (subcontracting),
$C_{\pi 0}$ = subcontracting unit cost,
K_0 = setup cost (in-house making),
$\beta_{1,0}$ = relating variable between $K_{\pi 0}$ and K_0,
C_0 = in-house unit cost,
$\beta_{2,0}$ = relating variable between $C_{\pi 0}$ and C_0,
$h_{1,0}$ = unit holding cost,
i_0 = relating ratio of $h_{1,i}$ and C_i (e.g., $h_{1,i} = C_i\, i_0$, for $i = 0, 1, 2, \ldots, L$),
$t_{1,0}$ = uptime in stage 1 of our study,
$P_{1,0}$ = stage 1's annual fabricating rate,
x_0 = random proportion of faulty items,
$d_{1,0}$ = random faulty common parts' fabricating rate ($d_{1,0} = P_{1,0}x_0$),
$\theta_{1,0}$ = scrap proportion of faulty items,
$C_{S,0}$ = unit disposal cost,
$P_{2,0}$ = reworking rate,
$C_{R,0}$ = rework cost per product,
$h_{2,0}$ = holding cost per reworked item,
$\theta_{2,0}$ = scrap proportion of the reworked faulty items,
$d_{2,0}$ = scrap items' fabricating rate in rework time ($d_{2,0} = P_{2,0}\theta_{2,0}$),
φ_0 = stage 1's total scrap rate,
γ = common part's completion rate compared to the end-product,
S_0 = setup time,
$h_{4,0}$ = safety items' unit holding cost,
$H_{1,0}$ = inventory level when stage 1's uptime ends,
$t_{2,0}$ = needed rework time for faulty common parts,
$H_{2,0}$ = inventory level when rework time completes,
t_0^* = summation of $t^*_{1,0}$ and $t^*_{2,0}$,
$t_{3,0}$ = standard parts' depleting time,
$H_{3,0}$ = stock level when external supplies are received.

Stage two's notations in fabricating each finished item i (where $i = 1, 2, \ldots, L$),

L = number of finished goods,
T_π = cycle time,
λ_i = annual requirement,
Q_i = lot size,
K_i = setup cost,
$P_{1,i}$ = annual production rate,
$t_{1,i}$ = uptime,
S_i = setup time,
C_i = unit cost,
x_i = random proportion of faulty end product i,

$d_{1,i}$ = random faulty items' fabricating rate ($d_{1,i} = x_i P_{1,i}$),,
$\theta_{1,i}$ = scrap proportion of faulty items,
$h_{1,i}$ = unit holding cost,
$H_{1,i}$ = level of inventory when finished item i's uptime ends,
$P_{2,i}$ = annual rework rate,
$t_{2,i}$ = rework time,
t_i^* = sum of optimal rework time and uptime,
$C_{R,i}$ = unit rework cost,
$h_{2,i}$ = holding cost per reworked item,
$H_{2,i}$ = level of stock when end product i's rework ends,
$I_d(t)_i$ = level of faulty stocks at time t,
$\theta_{2,i}$ = scrap proportion of the reworked faulty items,
$d_{2,i}$ = scrap items' fabricating rate in rework time ($d_{2,i} = P_{2,i}\theta_{2,i}$),
$C_{S,i}$ = unit disposal cost,
φ_i = total scrap rate,
$I_S(t)_i$ = scrap stock level at time t,
$h_{4,i}$ = safety items' unit holding cost,
$I(t)_i$ = inventory level at time t,
$t_{3,i}$ = end products' transportation time,
n = equal-size transporting frequency,
$t_{n,i}$ = time-interval of transportations,
$K_{D,i}$ = fixed transporting cost,
D_i = fixed quantity per transportation,
$h_{3,i}$ = customer's unit holding cost,
I_i = left over goods when $t_{n,i}$ ends,
$C_{D,i}$ = unit transporting cost,
$I_c(t)_i$ = customer stock level at time t,
$TC(T_\pi, n)$ = total system cost per cycle,
$E[TC(T_\pi, n)]$ = expected total system cost per cycle,
$E[T_\pi]$ = the expected rotation cycle time,
$E[TCU(T_\pi, n)]$ = the expected annualized system cost.

2.2. Problem statement

This work explores a hybrid multiproduct replenishing-delivery decision featuring quality assurance and postponement. The multiple products have a standard part in common.

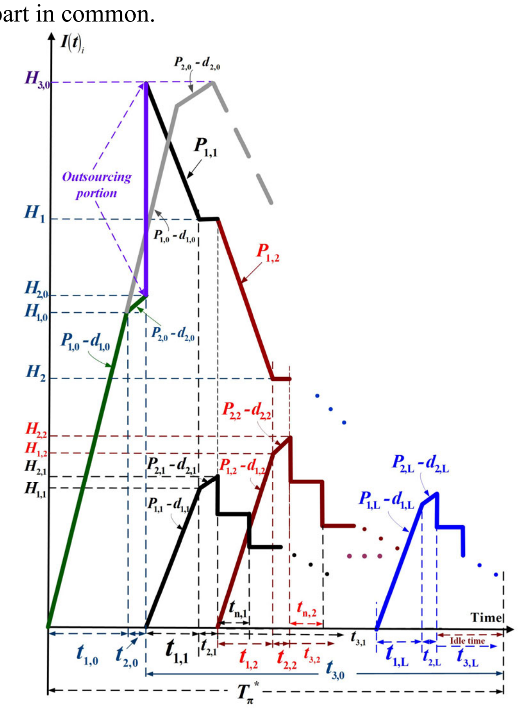

Fig. 1. Stock level in our hybrid multiproduct replenishing-delivery model featuring quality assurance and postponement as compared with the same system without outsourcer policy (in grey)

This study employs a postponement policy to make the required standard parts first (in phase 1). It fabricates the finished multiproduct in phase 2, aiming to simplify the production plan and reduce the operating expenses. We assume the standard part's completion rate γ is constant. If $\gamma = 0.5$ (i.e., it is 50% completion), then $P_{1,0}$ and $P_{1,i}$ are twice as much as their ordinary rates without applying postponement (i.e., in a multi-item single-stage system). This study uses actions for quality assurance to remove scraps and rework random repairable faulty items in both stages. Besides, an external supplier is hired to provide a π_0 proportion of standard parts to cut stage 1's uptime short. Fig. 1 depicts the stock status of the proposed problem. Fig. 1 illustrates that when uptime ends, the standard parts' level arrives at $H_{1,0}$. Then it reaches $H_{2,0}$ when the rework time ends. Finally, after receipt of the outsourced parts, its stock level piles up to $H_{3,0}$. In stage 2, each product i's uptime ends, its related stock level arrives at $H_{1,i}$; then, when its rework time end, the stock level reaches $H_{2,i}$. Since no stock-out situations are allowed, we must have the following: $P_{1,i} - d_{1,i} - \lambda_i > 0$ and $P_{1,0} - d_{1,0} > 0$.

Fig. 2 exhibits the standard parts' stock status during stage 2. Observing Figs. 1 and 2, we find the following formulas relating to the depletion of the standard parts in stage 2:

$$H_1 = H_{3,0} - Q_1 \tag{1}$$

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

$$H_L = H_{(L-1)} - Q_L = 0 \tag{3}$$

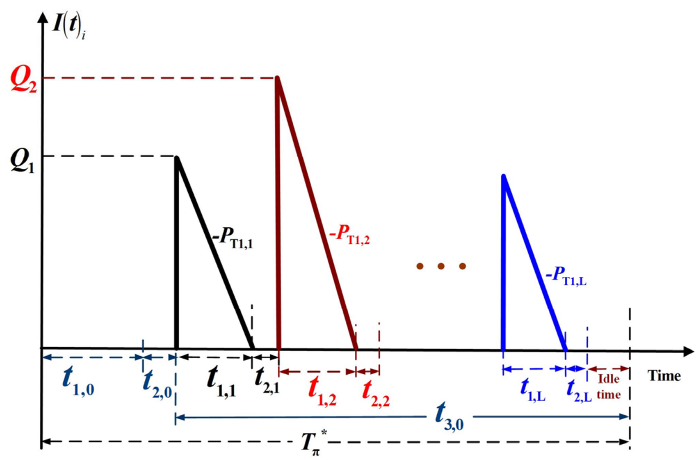

Fig. 2. The standard parts' stock status during stage 2

Fig. 3 and Fig. 4 display our model's stock levels of faulty and scrap items. Observing Fig. 3, we find when $t_{1,0}$ or $t_{1,i}$ end, the maximum faulty stock levels are ($d_{1,0}\,t_{1,0}$) or ($d_{1,i}\,t_{1,i}$). Then, upon removal of the scrap portion, the faulty items start to deplete to 0 when rework time ends. By observing Fig. 4, one finds the maximal level of scraps are $[d_{1,0}(\theta_{1,0})t_{1,0} + d_{2,0}\,t_{2,0}]$ or $[d_{1,i}(\theta_{1,i})t_{1,i} + d_{2,i}\,t_{2,i}]$ in each stage, when the rework time ends.

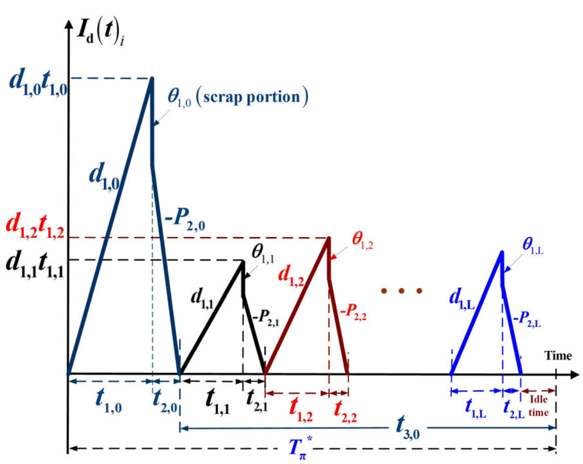

Fig. 3. The proposed model's faulty items stock level

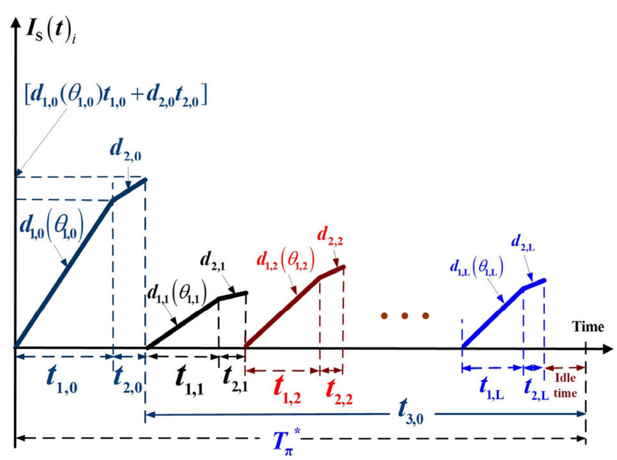

Fig. 4. Our model's scrap items stock level

2.3. Formulations

According to the model assumption and illustrations of Figs. (1), (3), and (4), one has the following relating formulas relating to stage 2 in each finished item *i*'s production for i = 1, 2, …, *L*:

$$T_{\pi} = t_{1,i} + t_{2,i} + t_{3,i} \tag{4}$$

$$t_{1,i} = \frac{Q_i}{P_{1,i}} = \frac{H_{1,i}}{P_{1,i} - d_{1,i}} \tag{5}$$

$$Q_i = \frac{\lambda_i T_{\pi}}{1 - \varphi_i x_i} \tag{6}$$

$$t_{2,i} = \frac{x_i Q_i \left(1 - \theta_{1,i}\right)}{P_{2,i}} = \frac{H_{2,i} - H_{1,i}}{P_{2,i} - d_{2,i}} \tag{7}$$

$$\varphi_i = \theta_{1,i} + \left(1 - \theta_{1,i}\right)\theta_{2,i} \tag{8}$$

$$t_{3,i} = T_{\pi} - \left(t_{1,i} + t_{2,i}\right) \tag{9}$$

$$H_{1,i} = t_{1,i}\left(P_{1,i} - d_{1,i}\right) \tag{10}$$

$$H_{2,i} = t_{2,i}\left(P_{2,i} - d_{2,i}\right) + H_{1,i} \tag{11}$$

Then, based on the model assumption and illustrations of Figs. (1), (3), and (4), one finds the following outsourcing consequent extra expenses and formulas relating to stage 1 in making the standard parts:

$$C_{\pi 0} = \left(1 + \beta_{2,0}\right) C_0 \tag{12}$$

$$K_{\pi 0} = \left(1 + \beta_{1,0}\right) K_0 \tag{13}$$

$$H_{3,0} = \sum_{i=1}^{L} \frac{\lambda_i T_{\pi}}{1 - \varphi_i x_i} = \sum_{i=1}^{L} Q_i \tag{14}$$

$$T_{\pi} = t_{1,0} + t_{2,0} + t_{3,0} \tag{15}$$

$$\lambda_0 = \frac{\sum_{i=1}^{L} Q_i}{T_{\pi}} \tag{16}$$

$$\pi_0 \left(\sum_{i=1}^{L} Q_i\right) = H_{3,0} - H_{2,0} \tag{17}$$

$$Q_0 = \frac{H_{2,0}}{1 - \varphi_0 x_0} \tag{18}$$

$$t_{1,0} = \frac{Q_0}{P_{1,0}} = \frac{H_{1,0}}{P_{1,0} - d_{1,0}} \tag{19}$$

$$t_{2,0} = \frac{x_0 Q_0 \left(1 - \theta_{1,0}\right)}{P_{2,0}} = \frac{H_{2,0} - H_{1,0}}{P_{2,0} - d_{2,0}} \tag{20}$$

$$\varphi_0 = \theta_{1,0} + \left(1 - \theta_{1,0}\right)\theta_{2,0} \tag{21}$$

$$t_{3,0} = T_{\pi} - \left(t_{1,0} + t_{2,0}\right) \tag{22}$$

$$H_{1,0} = \left(P_{1,0} - d_{1,0}\right) t_{1,0} \tag{23}$$

$$H_{2,0} = \left(\sum_{i=1}^{L} Q_i\right)\left(1 - \pi_0\right) \tag{24}$$

$$H_{2,0} = \left(P_{2,0} - d_{2,0}\right) t_{2,0} + H_{1,0} \tag{25}$$

Fig. 5 illustrates product i's stock levels during transporting time and n equal-size shipments are transported to the customer in $t_{3,i}$, and the total inventories are as follows:

$$\left(\frac{1}{n^2}\right)\left(\sum_{i=1}^{n-1} i\right)\left(t_{3,i}\right)H_{2,i}=\left(\frac{1}{n^2}\right)\left(t_{3,i}\right)H_{2,i}\left[\frac{n(n-1)}{2}\right]=\left(\frac{n-1}{2n}\right)\left(t_{3,i}\right)H_{2,i} \tag{26}$$

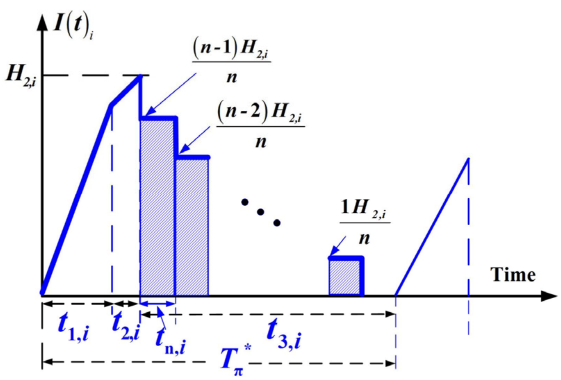

Fig. 5. End product i's stock levels during transporting time

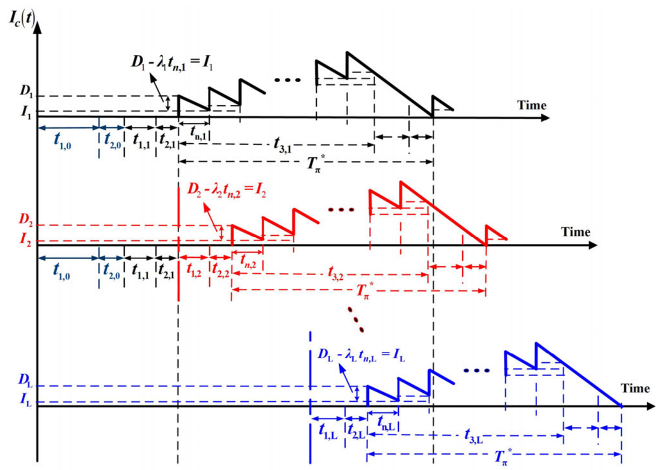

Fig. 6. End product i's stock level on customer's side

Fig. 6 displays the end product i's stock level on customer's side, and the following are total stocks on customer side for each product i:

$$\left[\frac{nI_i\left(t_{1,i}+t_{2,i}\right)}{2}+\frac{n\left(D_i-I_i\right)t_{n,i}}{2}+\frac{n\left(n+1\right)}{2}I_i t_{n,i}\right] \tag{27}$$

where

$$D_i=\frac{H_{2,i}}{n} \tag{28}$$

$$I_i=D_i-\lambda_i\left(t_{n,i}\right) \tag{29}$$

$$t_{n,i}=\frac{t_{3,i}}{n} \tag{30}$$

2.4. Analyzing and optimizing cost-function

$TC(T_\pi, n)$ comprise both stages' costs concerning the following: subcontracting setup and variable; (ii) in-house setup and variable; (iii) end products' transportation; and (iv) inventory holding in producing and customer sides.

$$\begin{aligned}
TC\left(T_\pi,n\right)&=K_0+K_{\pi0}+C_0Q_0+\pi_0\left(\sum_{i=1}^{L}Q_i\right)C_{\pi0}+\left(x_0Q_0\varphi_0\right)T_\pi h_{4,0}+x_0Q_0\left(1-\theta_{1,0}\right)C_{R,0}+\left(Q_0x_0\varphi_0\right)C_{S,0}\\
&+h_{1,0}\left[\frac{H_{1,0}t_{1,0}}{2}+\frac{H_{2,0}+H_{1,0}}{2}\left(t_{2,0}\right)+\frac{d_{1,0}t_{1,0}}{2}\left(t_{1,0}\right)+\sum_{i=1}^{L}\left[\frac{Q_i}{2}\left(t_{1,i}\right)+H_i\left(t_{1,i}+t_{2,i}\right)\right]\right]+h_{2,0}\left(\frac{d_{1,0}t_{1,0}\left(1-\theta_{1,0}\right)}{2}\right)\left(t_{2,0}\right)\\
&+\sum_{i=1}^{L}\left\{\begin{aligned}&K_i+Q_iC_i+\left(Q_ix_i\varphi_i\right)C_{S,i}+\left[Q_ix_i\left(1-\theta_{1,i}\right)\right]C_{R,i}+\left(x_i\varphi_iQ_i\right)T_\pi h_{4,i}+\left(\frac{d_{1,i}t_{1,i}\left(1-\theta_{1,i}\right)}{2}\right)\left(t_{2,i}\right)h_{2,i}\\
&+h_{1,i}\left[\frac{H_{1,i}t_{1,i}}{2}+\frac{H_{2,i}+H_{1,i}}{2}\left(t_{2,i}\right)+\left(\frac{n-1}{2n}\right)H_{2,i}\left(t_{3,i}\right)+\frac{d_{1,i}t_{1,i}}{2}\left(t_{1,i}\right)\right]+nK_{D,i}+Q_i\left(1-\varphi_ix_i\right)C_{D,i}\\
&+h_{3,i}\left[\frac{nI_i\left(t_{1,i}+t_{2,i}\right)}{2}+\frac{n\left(D_i-I_i\right)t_{n,i}}{2}+\frac{n\left(n+1\right)}{2}I_it_{n,i}\right]\end{aligned}\right\}
\end{aligned} \tag{31}$$

The expected annualized system expenses, $E[TCU(T_\pi, n)]$ can be obtained as following (details please see Appendix A):

$$
\begin{aligned}
E\left[TCU\left(T_\pi,n\right)\right] &= \frac{K_0\left(1+\beta_{1,0}\right)}{T_\pi} + \left(1+\beta_{2,0}\right)C_{\pi 0}\pi_0\lambda_0 + h_{4,0}\left(1-\pi_0\right)\lambda_0 E_{10}\varphi_0 T_\pi + C_0\left(1-\pi_0\right)\lambda_0 E_{00} \\
&+ h_{2,0}\frac{\left(1-\pi_0\right)^2\lambda_0^2 T_\pi\left[E_{10}\right]^2\left(1-\theta_{1,0}\right)^2}{2P_{2,0}} + \frac{K_0}{T_\pi} + C_{S,0}\left(1-\pi_0\right)\lambda_0\varphi_0 E_{10} + C_{R,0}\left(1-\theta_{1,0}\right)\left(1-\pi_0\right)\lambda_0 E_{10} \\
&+ h_{1,0}\left[\sum_{i=1}^{L}\left[\frac{\lambda_i^2\left(E_{0i}\right)^2 T_\pi}{2P_{1,i}}\right] + \frac{\left(1-\pi_0\right)^2\lambda_0^2\left(E_{00}\right)^2 E_{0P}T_\pi}{2} + \sum_{i=1}^{L}\left[\left(\lambda_i E_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_i E_{0i}T_\pi - \sum_{j=1}^{i}\lambda_j E_{0j}T_\pi\right)\right]\right] \\
&+ \sum_{i=1}^{L}\left\{\begin{aligned}&\frac{K_i}{T_\pi} + C_i\lambda_i E_{0i} + h_{4,i}\lambda_i\varphi_i E_{1i}T_\pi + C_{R,i}\left(1-\theta_{1,i}\right)\lambda_i + C_{S,i}E_{1i}\varphi_i\lambda_i + h_{1,i}\left(\frac{\lambda_i^2 T_\pi}{2}\right)E_{3i} + C_{D,i}\lambda_i \\ &+\frac{nK_{D,i}}{T_\pi} + h_{2,i}\frac{\lambda_i^2 T_\pi\left[E_{1i}\right]^2\left(1-\theta_{1,i}\right)^2}{2P_{2,i}} + \frac{\lambda_i^2\left(h_{3,i}-h_{1,i}\right)T_\pi}{2n}\left[\frac{1}{\lambda_i} - \left(E_{0i}E_{2i}\right)\right] + \frac{h_{3,i}\lambda_i^2 E_{0i}E_{2i}T_\pi}{2}\end{aligned}\right\}
\end{aligned}
\tag{32}
$$

Hessian Matrix Equations is applied to $E[TCU(T_\pi, n)]$ (Rardin, 1998):

$$
\left[T_\pi \quad n\right]\cdot\begin{pmatrix}\dfrac{\partial^2 E\left[TCU\left(T_\pi,\, n\right)\right]}{\partial T_\pi^{\,2}} & \dfrac{\partial^2 E\left[TCU\left(T_\pi,\, n\right)\right]}{\partial T_\pi \partial n} \\[2ex] \dfrac{\partial^2 E\left[TCU\left(T_\pi,\, n\right)\right]}{\partial T_\pi \partial n} & \dfrac{\partial^2 E\left[TCU\left(T_\pi,\, n\right)\right]}{\partial n^2}\end{pmatrix}\cdot\begin{bmatrix}T_\pi \\ n\end{bmatrix} = \left[\frac{2K_0}{T_\pi} + \frac{2\left(1+\beta_{1,0}\right)K_0}{T_\pi} + \sum_{i=1}^{L}\left\{\frac{2K_i}{T_\pi}\right\}\right] > 0
\tag{33}
$$

Since K_0, $(1 + \beta_{1,0})$, T_π, and K_i are all positive, Eq. (33) yields a positive result. We confirm that $E[TCU(T_\pi, n)]$ is strictly convex for all n and $T_\pi > 0$. Therefore, $E[TCU(T_\pi, n)]$ has the minimum. Apply $E[TCU(T_\pi, n)]$'s 1st and 2nd derivatives, we have:

$$
\begin{aligned}
\frac{\partial E\left[TCU\left(T_\pi,n\right)\right]}{\partial T_\pi} &= -\frac{K_0}{T_\pi^{\,2}} - \frac{K_0\left(1+\beta_{1,0}\right)}{T_\pi^{\,2}} + h_{2,0}\frac{\left(1-\pi_0\right)^2\left(1-\theta_{1,0}\right)^2\lambda_0^2\left[E_{10}\right]^2}{2P_{2,0}} + h_{4,0}\lambda_0 E_{10}\left(1-\pi_0\right)\varphi_0 \\
&+ h_{1,0}\left[+\sum_{i=1}^{L}\left[\frac{\lambda_i^2\left(E_{0i}\right)^2}{2P_{1,i}}\right]\frac{\left(E_{00}\right)^2 E_{0P}\left(1-\pi_0\right)^2\lambda_0^2}{2} + \sum_{i=1}^{L}\left[\left(\lambda_i E_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_i E_{0i}T_\pi - \sum_{j=1}^{i}\lambda_j E_{0j}\right)\right]\right] \\
&+ \sum_{i=1}^{L}\left\{\begin{aligned}&+h_{4,i}E_{1i}\lambda_i\varphi_i - \frac{nK_{D,i}}{T_\pi^{\,2}} - \frac{K_i}{T_\pi^{\,2}} + h_{2,i}\frac{\lambda_i^2\left[E_{1i}\right]^2\left(1-\theta_{1,i}\right)^2}{2P_{2,i}} + h_{1,i}\left(\frac{\lambda_i^2}{2}\right)E_{3i} \\ &+\frac{h_{3,i}\lambda_i^2 E_{0i}E_{2i}}{2} + \frac{\left(h_{3,i}-h_{1,i}\right)\lambda_i^2}{2n}\left[\frac{1}{\lambda_i} - \left(E_{0i}E_{2i}\right)\right]\end{aligned}\right\}
\end{aligned}
\tag{34}
$$

$$
\frac{\partial E\left[TCU\left(T_\pi,n\right)\right]}{\partial n} = \sum_{i=1}^{L}\left\{\frac{K_{D,i}}{T_\pi} - \frac{\lambda_i^2\left(h_{3,i}-h_{1,i}\right)T_\pi}{2n^2}\left[\frac{1}{\lambda_i} - \left(E_{0i}E_{2i}\right)\right]\right\}
\tag{35}
$$

By setting Eqs. (34) and (35) = 0, one can solve and simultaneously gain T_π* and n* as follows:

$$
T_\pi^{*} = \sqrt{\frac{2\left[\sum_{i=1}^{L}\left\{K_i + nK_{D,i}\right\} + \left(2+\beta_{1,0}\right)K_0\right]}{\begin{aligned}&h_{1,0}\left[\sum_{i=1}^{L}\left[\frac{\left(E_{0i}\right)^2\lambda_i^2}{P_{1,i}}\right] + \left(E_{00}\right)^2\left(1-\pi_0\right)^2\lambda_0^2 E_{0P} + 2\sum_{i=1}^{L}\left[\left(\lambda_i E_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_i E_{0i} - \sum_{j=1}^{i}\lambda_j E_{0j}\right)\right]\right] \\ &+2h_{4,0}\lambda_0\varphi_0\left(1-\pi_0\right)E_{10} + h_{2,0}\frac{\left(1-\pi_0\right)^2\left(E_{10}\right)^2\lambda_0^2\left(1-\theta_{1,0}\right)^2}{P_{2,0}} \\ &+\sum_{i=1}^{L}\left\{h_{1,i}\lambda_i^2 E_{3i} + h_{2,i}\frac{\lambda_i^2\left(E_{1i}\right)^2\left(1-\theta_{1,i}\right)^2}{P_{2,i}} + h_{3,i}E_{0i}E_{2i}\lambda_i^2 + 2h_{4,i}E_{1i}\lambda_i\varphi_i + \frac{\lambda_i^2}{n}\left(h_{3,i}-h_{1,i}\right)\left(\frac{1}{\lambda_i} - E_{0i}E_{2i}\right)\right\}\end{aligned}}}
\tag{36}
$$

and

$$n^{*}=\sqrt{\frac{\sum_{i=1}^{L}\left\{\left(h_{3,i}-h_{1,i}\right)\left[\frac{1}{\lambda_i}-\left(E_{0i}E_{2i}\right)\right]\lambda_i^2\right\}\cdot\left[K_0\left(2+\beta_{1,0}\right)+\sum_{i=1}^{L}\left\{K_i\right\}\right]}{\sum_{i=1}^{L}\left(2K_{Di}\right)\sum_{i=1}^{L}\left\{\begin{array}{l} h_{2,0}\left(\frac{\left(1-\pi_0\right)^2\left(1-\theta_{1,0}\right)^2\lambda_0^2}{P_{2,0}}\right)\left(E_{10}\right)^2+2h_{4,0}\lambda_0\varphi_0\left(1-\pi_0\right)E_{10} \\ +h_{1,0}\left[\sum_{i=1}^{L}\left[\frac{\left(E_{0i}\right)^2\lambda_i^2}{P_{1,i}}\right]+E_{0P}\left(E_{00}\right)^2\left(1-\pi_0\right)^2\lambda_0^2+2\sum_{i=1}^{L}\left[\left(\lambda_i E_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\left(E_{0i}\lambda_i\right)-\sum_{j=1}^{i}\left(E_{0j}\lambda_j\right)\right)\right]\right] \\ +\sum_{i=1}^{L}\left\{h_{1,i}\left[\lambda_i^2E_{3i}\right]+h_{3,i}\left(\lambda_i^2\right)E_{0i}E_{2i}+h_{2,i}\frac{\lambda_i^2\left(1-\theta_{1,i}\right)^2}{P_{2,i}}\left(E_{1i}\right)^2+2h_{4,i}E_{1i}\lambda_i\varphi_i\right\} \end{array}\right\}}} \tag{37}$$

2.5. Discussion on setup times and prerequisite condition

When planning the multiproduct fabrication, one must consider the overall setup times. Computation of $T_{\min}$ (Nahmias (2009)) as shown in Eq. (38) is needed. Select the maximum values of (T_π*, $T_{\min}$) as our resulting cycle time to ensure sufficient capacity.

$$T_{\min}=\frac{\sum_{i=0}^{L}\left(S_i\right)}{1-\left\{\sum_{i=1}^{L}\left[\frac{1}{P_{1,i}}+\frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}}\right]\frac{\lambda_i}{\left[1-\varphi_iE\left[x_i\right]\right]}+\left(\frac{1}{P_{1,0}}+\frac{E\left[x_0\right]\left(1-\theta_{1,0}\right)}{P_{2,0}}\right)\frac{\lambda_0\left(1-\pi_0\right)}{\left[1-\varphi_0E\left[x_0\right]\right]}\right\}} \tag{38}$$

Another prerequisite condition to ensure adequate capacity for making and reworking the common parts and finished goods (Nahmias, 2009):

$$\left[\sum_{i=1}^{L}\left(t_{1,i}+t_{2,i}\right)\right]+\left(t_{1,0}+t_{2,0}\right)<T_\pi \text{ or } \left[\sum_{i=1}^{L}Q_i\left(\frac{1}{P_{1,i}}+\frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}}\right)\right]+Q_0\left(\frac{1}{P_{1,0}}+\frac{E\left[x_0\right]\left(1-\theta_{1,0}\right)}{P_{2,0}}\right)<T_\pi \tag{39}$$

or

$$\left\{\left(\frac{1}{P_{1,0}}+\frac{E\left[x_0\right]\left(1-\theta_{1,0}\right)}{P_{2,0}}\right)\left(\frac{\lambda_0\left(1-\pi_0\right)}{\left[1-\varphi_0E\left[x_0\right]\right]}\right)+\sum_{i=1}^{L}\left[\frac{1}{P_{1,i}}+\frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}}\right]\left(\frac{\lambda_i}{\left[1-\varphi_iE\left[x_i\right]\right]}\right)\right\}<1 \tag{40}$$

3. Demonstration example

The following example explicitly shows our research results can solve the replenishing-delivery decision for our proposed model and explore various crucial system information. Tables 1, 2, and 3 display the assumed parameter values in both fabricating phases of this demonstration example. Conversely, its corresponding values in a single-stage scheme are given in Tables B-1 and B-2 (Appendix B).

Table 1

Parameter values assumption in the first fabricating phase

$C_{S,0}$	$P_{2,0}$	x_0	$h_{2,0}$	π_0	$\beta_{2,0}$	$P_{1,0}$	$\beta_{1,0}$	$h_{1,0}$	γ
$10	96000	0.025	$8	0.4	0.4	120000	-0.7	$8	0.5
i_0	C_0	$C_{R,0}$	$\theta_{2,0}$	K_0	δ	λ_0	φ_0	$\theta_{1,0}$	$h_{4,0}$
0.2	$40	$25	0.046	$8500	0.5	17406	9.0%	0.046	$8

Table 2

Parameter values assumption in the second fabricating phase (1 of 2)

Product i	$\theta_{2,i}$	x_i	$h_{3,i}$	$P_{1,i}$	$C_{D,i}$	$h_{4,i}$	$\theta_{1,i}$	i_i	K_i	$h_{1,i}$
1	0.046	0.025	$70	112258	$0.1	$8	0.046	0.2	$8500	$8
2	0.094	0.075	$75	116066	$0.2	$10	0.094	0.2	$9000	$10
3	0.146	0.125	$80	120000	$0.3	$12	0.146	0.2	$9500	$12
4	0.200	0.175	$85	124068	$0.4	$14	0.200	0.2	$10000	$14
5	0.258	0.225	$90	128276	$0.5	$16	0.258	0.2	$10500	$16

Table 3
Parameter values assumption in the second fabricating phase (2 of 2)

Product i	$C_{S,i}$	$h_{2,i}$	$K_{D,i}$	$P_{2,i}$	$C_{R,i}$	φ_i	λ_i	C_i
1	\$10	\$8	\$1800	89806	\$25	0.09	3000	\$40
2	\$15	\$10	\$1900	92852	\$30	0.18	3200	\$50
3	\$20	\$12	\$2000	96000	\$35	0.27	3400	\$60
4	\$25	\$14	\$2100	99254	\$40	0.36	3600	\$70
5	\$30	\$16	\$2200	102621	\$45	0.45	3800	\$80

To demonstrate the applicability of our results, one can first apply equations (37) and (36) and find the optimal operating policy for distribution frequency $n^* = 4$ and cycle length for replenishment $T_\pi^* = 0.5370$. Then, apply n^* and T_π^* to Eq. (32), the optimal system operating expense $E[TCU(T_\pi^*, n^*)] = \$2,299,407$, as illustrated in Fig. 7. It shows as n and T_π depart away and n seen that One notices that $E[TCU(T_\pi, n)]$ considerably rises as n and T_π differ from n^* and T_π^* (i.e., optimal point), $E[TCU(T_\pi, n)]$ knowingly surges.

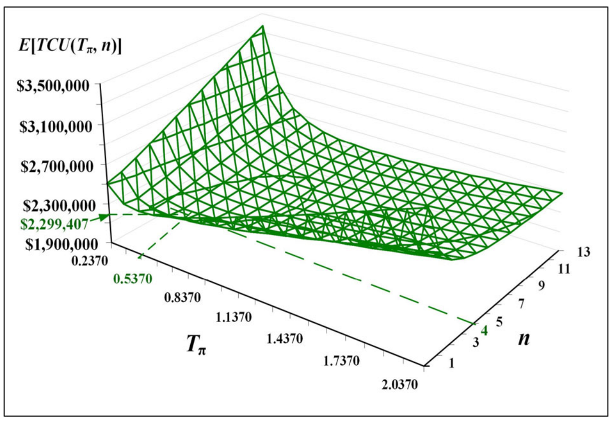

Fig. 7. $E[TCU(T_\pi^*, n^*)]$'s convexity and performance in relation to n and T_π

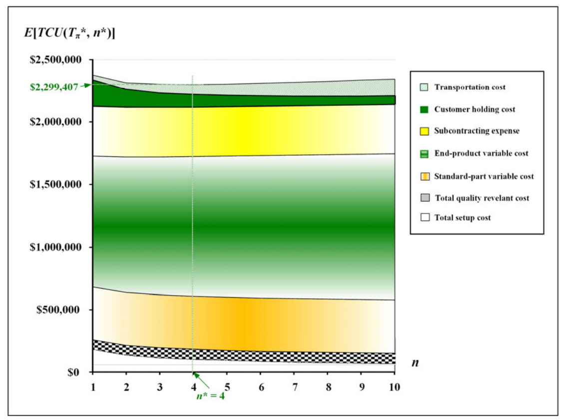

Fig. 8. $E[TCU(T_\pi^*, n^*)]$'s behavior regarding n

With our model, we can research $E[TCU(T_\pi^*, n^*)]$'s behavior regarding n (the transportation frequency of end products each cycle). Fig. 8 demonstrates each system expenditure of $E[TCU(T_\pi^*, n^*)]$ in detail. One discovers as n increases, end products' shipping quantity decreases, so the customer's holding cost drops knowingly; in contrast, the transporting expense and production unit's holding cost upsurge. Furthermore, this model allows us to examine the combined influence of the average scrap rate φ_i and faulty rate x_i on $E[TCU(T_\pi^*, n^*)]$ (see Fig. 8). It discovers that as the average scrap rate φ_i and faulty rate x_i rise, $E[TCU(T_\pi^*, n^*)]$ considerably surges. The average faulty rate influences $E[TCU(T_\pi^*, n^*)]$ more than the average scrap rate.

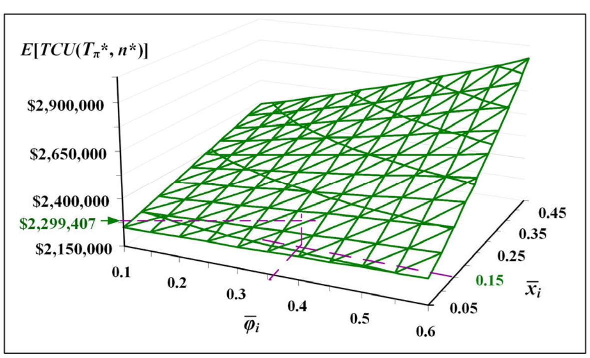

Fig. 9. The performance of $E[TCU(T_\pi^*, n^*)]$ regarding the average scrap rate φ_i and faulty rate x_i

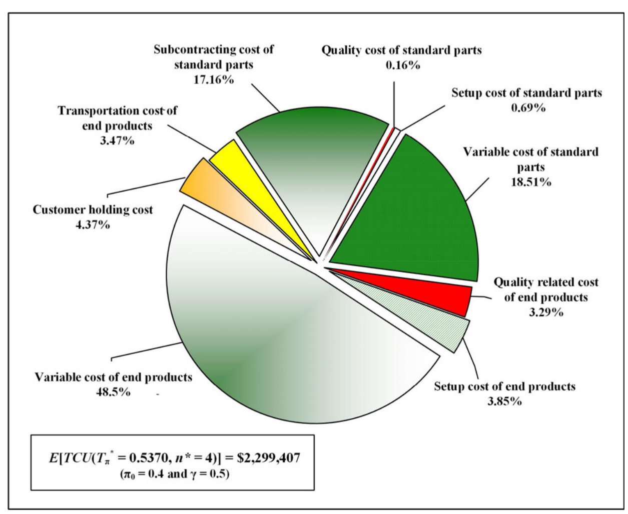

Fig. 10. $E[TCU(T_\pi^*, n^*)]$'s expenditure contributors in detail

We further detail $E[TCU(T_\pi^*, n^*)]$'s expenditure contributors, as depicted in Fig. 10. It exposes all expenditures contributing to $E[TCU(T_\pi^*, n^*)]$, and the significant contributors consist of the following (summed up to 84.17%):

(1) The variable end products' making costs 48.50%;
(2) The variable standard parts' fabricating cost 18.51; and
(3) The standard parts' subcontracting expense of 17.16%.

Other costs include customer's holding charge of 4.37%, end products' setup cost of 3.85%; transportation expense of 3.47%; end products' quality relevant cost of 3.29; and in-house standard parts' cost relating to the setup of 0.69% and quality of 0.16%. We are also curious how the collective effect of the average faulty rate x_i and scrap rate φ_i on the optimal cycle time T_π^*. Fig. 11 shows the analytical results of the behavior of T_π^* regarding the average faulty rate x_i and scrap rate φ_i. It uncovers that as the average scrap rate φ_i and faulty rate x_i increase, T_π^* decreases significantly, especially when both rates are higher.

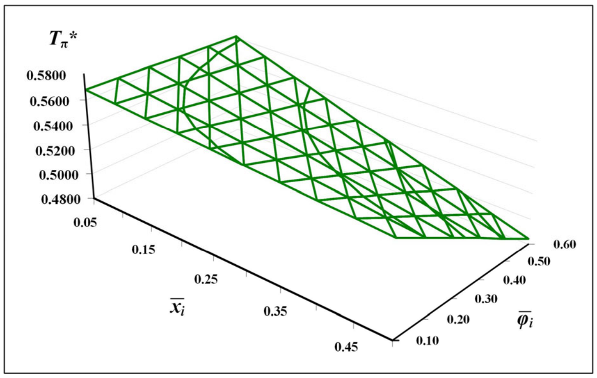

Fig. 11. The behavior of T_π^* regarding the average faulty rate x_i and scrap rate φ_i

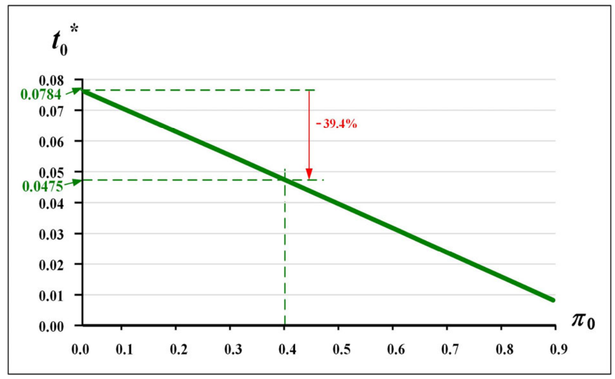

Fig. 12. The behavior of t_0^* regarding π_0

Our study assumes outsourcing π_0 proportion of needed standard parts reduces the required in-house fabricating time. We are curious how π_0 impacts the optimal system uptime and rework time t_0^*. The behavior of t_0^* regarding π_0 has been extensively examined, and Fig. 12 demonstrates its effect. One discovers that as π_0 increases, t_0^* drastically declines. For our assumption π_0 at 0.4, t_0^* significantly declines 39.4%, i.e., from 0.0784 to 0.0475 (year). Table C-1 illustrates the investigative outcomes of various crucial fabricating-time-related parameters impacted by π_0 (See Appendix C). Furthermore, one may wonder how this π_0's impact of a 39.4% drop in t_0^* is equivalent to how much scale of system utilization. Fig. 13 exhibits the further research outcome of the utilization's behavior regarding π_0. As π_0 rises, utilization t_0^* radically drops. For our assumption π_0 at 0.4 (with γ at 0.5), the utilization declines 19.56% (from 0.3012 to 0.2423; refer to Table C-1).

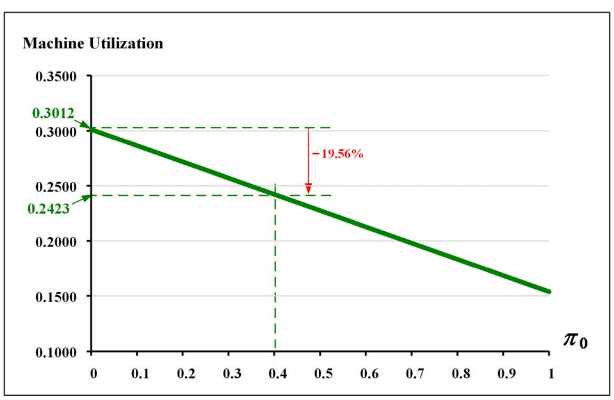

Fig. 13. The research outcome of utilization's behavior regarding π_0

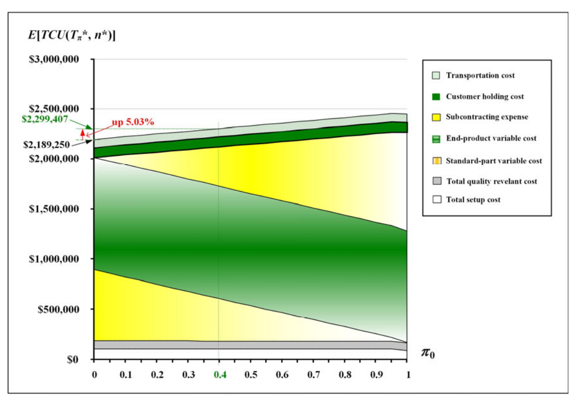

Fig. 14. $E[TCU(T_\pi^*, n^*)]$'s behavior regarding π_0

Moreover, we also wonder how this π_0's influence of a 19.56% decline in utilization will cost us. Fig. 14 demonstrates the advanced exploration outcome of $E[TCU(T_\pi^*, n^*)]$'s behavior regarding π_0. As π_0 increases, subcontracting standard parts' expense increases drastically, which is much more influential than the decline in in-house variable cost, so $E[TCU(T_\pi^*, n^*)]$ surges considerably. For our assumption π_0 at 0.4 (with γ at 0.5), a 19.56% drop in utilization has made that $E[TCU(T_\pi^*, n^*)]$ upsurges a 5.03% (from \$2,189,250 to \$2,299,407). Table C-2 discloses the explorative results of various crucial fabricating-expense- related parameters impacted by π_0 (See Appendix C). Our example considers δ (the relationship of the standard part's value and its related completing rate γ) linear. For instance, if γ at 0.5, we think the value of each standard part is one-half of its end product. However, this linear connection may not apply to many tangible goods in diverse industries. To cope with the possible nonlinear δ relationship, we conduct advanced exploration of the following nonlinear cases: (1) δ is $\gamma^{1/3}$ (where the value of the standard part is higher) and (2) γ^3 (when its value is lower), then observing how these different δ relationships influence the optimal cycle length T_π* (see Fig. 15). As γ rises, T_π* declines knowingly. For $\delta = \gamma^3$, the optimal cycle length T_π* is longer than $\delta = \gamma^1$ and $\delta = \gamma^{1/3}$.

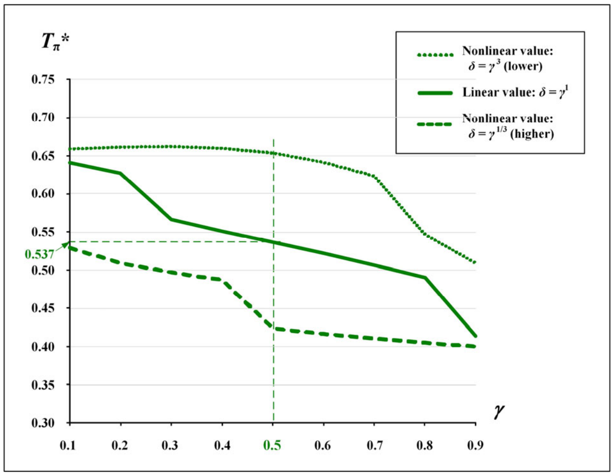

Fig. 15. T_π*'s behavior regarding dissimilar relationship δ in terms of γ rates

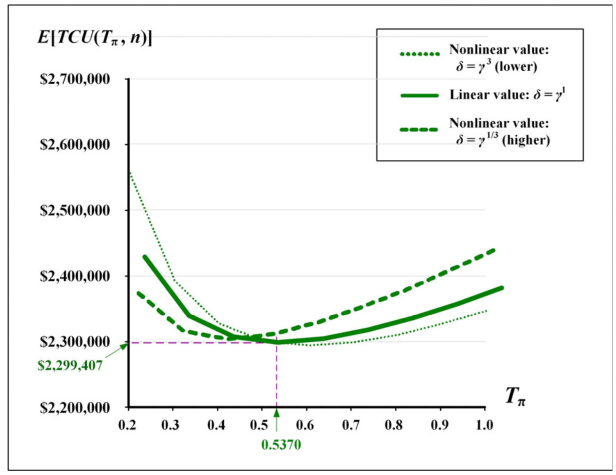

Fig. 16. $E[TCU(T_\pi, n)]$'s behavior and convexity regarding diverse relationship δ relating to γ

This study further explores $E[TCU(T_\pi, n)]$'s behavior and convexity regarding diverse relationship δ relating to γ (the outcome is illustrated in Fig. 16). It reconfirms that for our linear assumption and $\gamma = 0.5$, $E[TCU(T_\pi^* = 0.5370, n^* = 4)] = \$2,299,407$.

4. Conclusions

In today's markets, client merchandise demands have an apparent upward trend for various types of goods, high quality, and shorter lead times. Recent manufacturers must plan and work hard to meet the client's expectations. This research aims to assist present-day manufacturing managers in exploring and better understanding the collective influence of quality assurance and postponement on a hybrid multiproduct replenishing-delivery decision-making. We employ math modeling and formulations to interpret the studied two-phase production problem accurately and gain the problem's expected operations expenses. Furthermore, this research derives the best manufacturing cycle-time and equal-size transporting frequency by applying the optimization methodology (refer to Section 2). Lastly, a numerical illustration helps depict the following uses of our study's results to assist in facilitating manager's decisions (Section 3):

(1) $E[TCU(T_\pi^*, n^*)]$'s behavior in relation to n and T_π (Fig. 7) and the behavior of various sensitive expenses in $E[TCU(T_\pi^*, n^*)]$ regarding n (Fig. 8);
(2) $E[TCU(T_\pi^*, n^*)]$'s and T_π*'s behavior regarding the average scrap rate φ_i and faulty rate x_i (Fig. 9 & Fig. 11) and $E[TCU(T_\pi^*, n^*)]$'s expenditure contributors in detail (Fig. 10);
(3) Behavior of t_0^*, utilization, and $E[TCU(T_\pi^*, n^*)]$ regarding π_0 (Figs. 12-14);
(4) T_π*'s behavior regarding diverse relationship δ in terms of γ rates (Fig. 15);
(5) $E[TCU(T_\pi, n)]$'s behavior regarding diverse relationship δ relating to γ (Fig. 16).

The influence of stochastic client requirements on the best operating policy is worth future investigation.

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Appendix - A

The detailed derivations of obtaining $E[TCU(T_\pi, n)]$ (Eq. (32)) are listed below:

$E[TCU(T_\pi, n)]$ is gained after the following steps: (1) apply $E[x_0]$ and $E[x_i]$ to deal with the faulty items' randomness, and (2) substitute Eqs. (1) to (30) in Eq. (31) and calculate $E[TC(T_\pi, n)]/E[T_\pi]$. Thus, we gain the following with extra derivations:

$$
\begin{aligned}
E\left[TCU\left(T_\pi,n\right)\right] = {} & \frac{K_0}{T_\pi} + \frac{\left(1+\beta_{1,0}\right)K_0}{T_\pi} + \left(1+\beta_{2,0}\right)C_{\pi 0}\pi_0\lambda_0 + h_{4,0}\frac{\left(1-\pi_0\right)\lambda_0 E\left[x_0\right]\varphi_0 T_\pi}{1-\varphi_0 E\left[x_0\right]} + h_{2,0}\frac{\left(1-\pi_0\right)^2\lambda_0^2 T_\pi E\left[x_0\right]^2\left(1-\theta_{1,0}\right)^2}{2P_{2,0}\left(1-\varphi_0 E\left[x_0\right]\right)^2} \\
& + C_{S,0}\frac{\left(1-\pi_0\right)\lambda_0 E\left[x_0\right]\varphi_0}{1-\varphi_0 E\left[x_0\right]} + C_{R,0}E\left[x_0\right]\left(1-\theta_{1,0}\right)\frac{\left(1-\pi_0\right)\lambda_0}{1-\varphi_0 E\left[x_0\right]} + C_0\frac{\left(1-\pi_0\right)\lambda_0}{1-\varphi_0 E\left[x_0\right]} \\
& + h_{1,0}\left[\begin{aligned}
& \frac{E\left[x_0\right]\left(1-\theta_{1,0}\right)\left(1-\pi_0\right)^2\lambda_0^2 T_\pi\left(2-E\left[x_0\right]-\varphi_0 E\left[x_0\right]\right)}{2P_{2,0}\left(1-\varphi_0 E\left[x_0\right]\right)^2} + \frac{\lambda_0^{\,2}\left(1-\pi_0\right)^2 T_\pi}{2P_{1,0}\left(1-\varphi_0 E\left[x_0\right]\right)^2} + \sum_{i=1}^{L}\left[\frac{\lambda_i^2 T_\pi}{2P_{1,i}\left(1-\varphi_i E\left[x_i\right]\right)^2}\right] \\
& + \sum_{i=1}^{L}\left[\left(\frac{\lambda_i\left[E\left[x_i\right]\left(1-\theta_{1,i}\right)\right]}{P_{2,i}\left(1-\varphi_i E\left[x_i\right]\right)} + \frac{\lambda_i}{P_{1,i}\left(1-\varphi_i E\left[x_i\right]\right)}\right)\left(\sum_{i=1}^{L}\frac{\lambda_i T_\pi}{1-\varphi_i E\left[x_i\right]} - \sum_{j=1}^{i}\frac{\lambda_j T_\pi}{1-\varphi_j E\left[x_j\right]}\right)\right]
\end{aligned}\right] \\
& + \sum_{i=1}^{L}\left\{\begin{aligned}
& C_{R,i}\left[E\left[x_i\right]\left(\frac{\lambda_i}{1-\varphi_i E\left[x_i\right]}\right)\left(1-\theta_{1,i}\right)\right] + C_i\left(\frac{\lambda_i}{1-\varphi_i E\left[x_i\right]}\right) + h_{4,i}\left(\frac{E\left[x_i\right]\lambda_i\varphi_i}{1-\varphi_i E\left[x_i\right]}\right)T_\pi + \frac{nK_{D,i}}{T_\pi} + \frac{K_i}{T_\pi} + C_{S,i}\left(\frac{E\left[x_i\right]\varphi_i\lambda_i}{1-\varphi_i E\left[x_i\right]}\right) \\
& + h_{2,i}\left(\frac{\lambda_i^2 E\left[x_i\right]^2\left(1-\theta_{1,i}\right)^2 T_\pi}{2P_{2,i}\left(1-\varphi_i E\left[x_i\right]\right)^2}\right) + C_{D,i}\lambda_i + h_{1,i}\left[\left(\frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)\left(1-E\left[x_i\right]\right)}{P_{2,i}\left(1-\varphi_i E\left[x_i\right]\right)^2} + \frac{1}{\lambda_i} + \frac{E\left[x_i\right]\varphi_i}{P_{1,i}\left(1-\varphi_i E\left[x_i\right]\right)^2}\right)\left(\frac{\lambda_i^2 T_\pi}{2}\right)\right] \\
& + \left[-\frac{1}{P_{1,i}\left(1-\varphi_i E\left[x_i\right]\right)} + \frac{1}{\lambda_i} - \frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}\left(1-\varphi_i 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{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}\left(1-\varphi_i E\left[x_i\right]\right)} + \frac{1}{P_{1,i}\left(1-\varphi_i E\left[x_i\right]\right)}\right)\frac{h_{3,i}\left(\lambda_i^2 T_\pi\right)}{2}
\end{aligned}\right\}
\end{aligned}
\tag{A-1}
$$

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

$$
\begin{aligned}
& E_{10} = \frac{E\left[x_0\right]}{\left(1-\varphi_0 E\left[x_0\right]\right)};\ E_{00} = \frac{1}{\left(1-\varphi_0 E\left[x_0\right]\right)};\ E_{0j} = \frac{1}{\left(1-\varphi_j E\left[x_j\right]\right)}\quad for\ \ j=1,\dots,i \\
& E_{1i} = \frac{E\left[x_i\right]}{\left(1-\varphi_i E\left[x_i\right]\right)};\ E_{0i} = \frac{1}{\left(1-\varphi_i E\left[x_i\right]\right)};\ E_{2i} = \left[\frac{1}{P_{1,i}} + \frac{E\left[x_i\right]\left(1-\theta_{1,i}\right)}{P_{2,i}}\right]\quad for\ \ i=1,\dots,L.
\end{aligned}
\tag{A-2}
$$

$$
E_{0P} = \left[\frac{\left(1-\theta_{1,0}\right)\left[2-E\left[x_0\right]\left(\varphi_0+1\right)\right]E\left[x_0\right]}{P_{2,0}} + \frac{1}{P_{1,0}}\right].
\tag{A-3}
$$

$$
E_{3i} = \left[\frac{\varphi_i\left(E_{0i}\right)\left(E_{1i}\right)}{P_{1,i}} + \frac{1}{\lambda_i} + \frac{\left(1-\theta_{1,i}\right)\left(E_{0i}\right)\left(E_{1i}\right)\left(1-E\left[x_i\right]\right)}{P_{2,i}}\right]\quad for\ \ i=1,\dots,L.
\tag{A-4}
$$

Substitute Eqs. (A-2), (A-3), and (A-4) in Eq. (A-1), $E[TCU(T_\pi, n)]$ becomes as follows:

$$\begin{aligned}
E\left[TCU\left(T_\pi,n\right)\right] &= \frac{K_0}{T_\pi} + \frac{K_0\left(1+\beta_{1,0}\right)}{T_\pi} + \left(1+\beta_{2,0}\right)C_{\pi 0}\pi_0\lambda_0 + h_{4,0}\left(1-\pi_0\right)\lambda_0 E_{10}\varphi_0 T_\pi + C_0\left(1-\pi_0\right)\lambda_0 E_{00} \\
&+ h_{2,0}\frac{\left(1-\pi_0\right)^2\lambda_0^2 T_\pi\left[E_{10}\right]^2\left(1-\theta_{1,0}\right)^2}{2P_{2,0}} + C_{S,0}\left(1-\pi_0\right)\lambda_0\varphi_0 E_{10} + C_{R,0}\left(1-\theta_{1,0}\right)\left(1-\pi_0\right)\lambda_0 E_{10} \\
&+ h_{1,0}\left[\sum_{i=1}^{L}\left[\frac{\left(E_{0i}\right)^2\lambda_i^2 T_\pi}{2P_{1,i}}\right] + \frac{\left(E_{00}\right)^2 E_{0P}\left(1-\pi_0\right)^2\lambda_0^{\,2}T_\pi}{2} + \sum_{i=1}^{L}\left[\left(\lambda_i E_{0i}E_{2i}\right)\left(\sum_{i=1}^{L}\lambda_i E_{0i}T_\pi - \sum_{j=1}^{i}\lambda_j E_{0j}T_\pi\right)\right]\right] \\
&+ \sum_{i=1}^{L}\left\{\begin{aligned}&\frac{nK_{D,i}}{T_\pi} + \frac{K_i}{T_\pi} + C_i\lambda_i E_{0i} + h_{4,i}\lambda_i\varphi_i E_{1i}T_\pi + h_{2,i}\frac{\lambda_i^2 T_\pi\left[E_{1i}\right]^2\left(1-\theta_{1,i}\right)^2}{2P_{2,i}} + C_{S,i}E_{1i}\varphi_i\lambda_i + C_{R,i}\left(1-\theta_{1,i}\right)\lambda_i \\ &+h_{1,i}\left[\left(\frac{\lambda_i^2 T_\pi}{2}\right)E_{3i}\right] + \frac{h_{3,i}E_{0i}E_{2i}\lambda_i^2 T_\pi}{2} + C_{D,i}\lambda_i + \frac{\lambda_i^2\left(h_{3,i}-h_{1,i}\right)T_\pi}{2n}\left[\frac{1}{\lambda_i} - \left(E_{0i}E_{2i}\right)\right]\end{aligned}\right\}
\end{aligned} \tag{A-5}$$

Appendix - B

Table B-1
Corresponding parameter values in a single-phase fabricating scheme (1 of 2)

Product i	$C_{D,i}$	$\theta_{1,i}$	$P_{1,i}$	φ_i	$h_{3,i}$	$h_{1,i}$	K_i	x_i	i_i	$C_{S,i}$
1	\$0.1	0.094	58000	0.18	\$70	\$16	\$17000	0.05	0.2	\$20
2	\$0.2	0.146	59000	0.27	\$75	\$18	\$17500	0.10	0.2	\$25
3	\$0.3	0.200	60000	0.36	\$80	\$20	\$18000	0.15	0.2	\$30
4	\$0.4	0.258	61000	0.45	\$85	\$22	\$18500	0.20	0.2	\$35
5	\$0.5	0.322	62000	0.54	\$90	\$24	\$19000	0.25	0.2	\$40

Table B-2
Corresponding parameter values in a single-stage fabricating scheme (2 of 2)

Product i	$K_{D,i}$	$h_{4,i}$	$C_{R,i}$	λ_i	$\theta_{2,i}$	C_i	$P_{2,i}$	$h_{2,i}$
1	\$1800	\$16	\$50	3000	0.094	\$80	46400	\$16
2	\$1900	\$18	\$55	3200	0.146	\$90	47200	\$18
3	\$2000	\$20	\$60	3400	0.200	\$100	48000	\$20
4	\$2100	\$22	\$65	3600	0.258	\$110	48800	\$22
5	\$2200	\$24	\$70	3800	0.322	\$120	49600	\$24

Appendix - C

Table C-1
Various crucial fabricating-time-related parameters impacted by π_0

π_0	T_π*	(A) t_0*	(A)% decline	(B) Utilization	(B) % decline	(C) Total uptime	(C) % drop	(D)Total Rework time	(D) % drop
0.00	0.5249	0.0784	-	30.12%	-	0.1521	-	0.00614	-
0.05	0.5326	0.0746	-4.86%	29.39%	-2.45%	0.1504	-1.07%	0.00609	-0.79%
0.10	0.5333	0.0707	-9.74%	28.65%	-4.89%	0.1468	-3.48%	0.00604	-1.59%
0.15	0.5340	0.0669	-14.64%	27.91%	-7.34%	0.1431	-5.90%	0.00599	-2.40%
0.20	0.5347	0.0630	-19.56%	27.18%	-9.78%	0.1394	-8.34%	0.00594	-3.22%
0.25	0.5354	0.0592	-24.50%	26.44%	-12.23%	0.1357	-10.79%	0.00589	-4.05%
0.30	0.5360	0.0553	-29.46%	25.70%	-14.68%	0.1319	-13.25%	0.00584	-4.89%
0.35	0.5365	0.0514	-34.43%	24.97%	-17.12%	0.1282	-15.72%	0.00579	-5.74%
0.40	**0.5370**	**0.0475**	**-39.41%**	**24.23%**	**-19.57%**	**0.1244**	**-18.20%**	**0.00573**	**-6.59%**
0.45	0.5375	0.0436	-44.41%	23.49%	-22.01%	0.1206	-20.69%	0.00568	-7.46%
0.50	0.5379	0.0396	-49.42%	22.76%	-24.46%	0.1168	-23.20%	0.00563	-8.33%
0.55	0.5383	0.0357	-54.45%	22.02%	-26.91%	0.1130	-25.71%	0.00557	-9.21%
0.60	0.5387	0.0318	-59.48%	21.28%	-29.35%	0.1091	-28.23%	0.00552	-10.10%
0.65	0.5390	0.0278	-64.53%	20.55%	-31.80%	0.1053	-30.77%	0.00546	-11.00%
0.70	0.5393	0.0238	-69.58%	19.81%	-34.25%	0.1014	-33.31%	0.00541	-11.91%
0.75	0.5395	0.0199	-74.64%	19.07%	-36.69%	0.0975	-35.85%	0.00535	-12.82%
0.80	0.5397	0.0159	-79.70%	18.33%	-39.14%	0.0937	-38.41%	0.00529	-13.74%
0.85	0.5399	0.0119	-84.77%	17.60%	-41.58%	0.0898	-40.97%	0.00524	-14.67%
0.90	0.5400	0.0080	-89.85%	16.86%	-44.03%	0.0859	-43.53%	0.00518	-15.60%
0.95	0.5400	0.0040	-94.92%	16.12%	-46.48%	0.0820	-46.10%	0.00512	-16.54%
1.00	0.5163	0.0000	-100%-	15.39%	-48.92%	0.0746	-50.94%	0.00506	-17.49%

Table C-2
Various crucial fabricating-expense-related parameters impacted by π_0

π_0	$E[TCU(T_\pi^*, n^*)]$ (E)	n^*	(E) % surge	Standard part subcontracting expense (F)	(F) / (E) %	Standard part's quality relevant-cost	Standard part's other fabrication-related-cost	Standard part's total fabrication-expense	End products quality related-cost	End products shipping cost	Customer stock holding cost
0.00	$2,189,250	4	-	$0	0.00%	$6,176	$723,593	$729,769	$75,754	$81,507	$98,304
0.05	$2,207,148	4	0.82%	$53,525	2.43%	$5,867	$688,165	$747,557	$75,754	$80,404	$99,748
0.10	$2,220,246	4	1.42%	$102,255	4.61%	$5,558	$652,828	$760,641	$75,754	$80,299	$99,887
0.15	$2,233,371	4	2.02%	$150,985	6.76%	$5,249	$617,517	$773,752	$75,754	$80,199	$100,020
0.20	$2,246,523	4	2.62%	$199,716	8.89%	$4,941	$582,233	$786,890	$75,755	$80,105	$100,146
0.25	$2,259,703	4	3.22%	$248,447	10.99%	$4,632	$546,977	$800,056	$75,755	$80,017	$100,265
0.30	$2,272,910	4	3.82%	$297,179	13.07%	$4,323	$511,748	$813,250	$75,755	$79,934	$100,376
0.35	$2,286,144	4	4.43%	$345,911	15.13%	$4,014	$476,547	$826,472	$75,755	$79,856	$100,480
0.40	**$2,299,407**	**4**	**5.03%**	**$394,643**	**17.16%**	**$3,705**	**$441,374**	**$839,722**	**$75,755**	**$79,784**	**$100,577**
0.45	$2,312,696	4	5.64%	$443,375	19.17%	$3,396	$406,228	$853,000	$75,755	$79,718	$100,667
0.50	$2,326,014	4	6.25%	$492,108	21.16%	$3,088	$371,111	$866,307	$75,755	$79,658	$100,749
0.55	$2,339,359	4	6.86%	$540,842	23.12%	$2,779	$336,022	$879,642	$75,755	$79,603	$100,823
0.60	$2,352,733	4	7.47%	$589,575	25.06%	$2,470	$300,961	$893,006	$75,755	$79,554	$100,890
0.65	$2,366,134	4	8.08%	$638,309	26.98%	$2,161	$265,929	$906,399	$75,755	$79,510	$100,949
0.70	$2,379,563	4	8.69%	$687,044	28.87%	$1,853	$230,925	$919,821	$75,755	$79,472	$101,001
0.75	$2,393,020	4	9.31%	$735,778	30.75%	$1,544	$195,950	$933,272	$75,755	$79,440	$101,045
0.80	$2,406,506	4	9.92%	$784,514	32.60%	$1,235	$161,004	$946,753	$75,755	$79,413	$101,081
0.85	$2,420,019	4	10.54%	$833,249	34.43%	$926	$126,087	$960,262	$75,755	$79,392	$101,110
0.90	$2,433,560	4	11.16%	$881,985	36.24%	$617	$91,198	$973,800	$75,755	$79,377	$101,130
0.95	$2,447,130	4	11.78%	$930,721	38.03%	$309	$56,338	$987,368	$75,755	$79,368	$101,143
1.00	$2,444,634	4	11.67%	$979,675	40.07%	$0	-	$985,190	$75,754	-	-