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The Role of Industry 4.0 and Circular Economy for Sustainable Operations: The Case of Bike Industry

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Abstract: In this paper, sustainable design seeks to reduce negative impacts on the environment, and the health and comfort of building occupants, thereby improving financial performance. The basic objectives of sustainability are to reduce consumption of non-renewable resources, minimize waste, and create healthy, productive environments. A sustainable alternative to this production system is Industry 4.0 (I4.0) and circular economy (CE). The contribution of this paper is integrating sustainable production and design decisions of a supply chain in the adoption of I4.0 aimed at cost minimization, in which the decision variables include the production rate of engineered-to-order (ETO) components, design time of general components, and time period of advertising and sales promotions. The validation of the implementation of CE and its production and sale strategies are demonstrated through I4.0. The results presented in this paper may have significant practical value, notably with respect to manufacturers in the bike industry.

Keywords: circular economy; bike industry; imperfect processes; industry 4.0; applied sciences EPQ

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1. Introduction

The concept of I4.0 has gathered great importance in recent years. Manufacturing processes are usually made up of several operation stages. Typical multistage manufacturing processes (MMPs) in I4.0 are automotive assembly processes, flexible production lines, and metal-forming processes. For many enterprises, sustainable waste management is a key operational area where they can improve their environmental, social, and governance (ESG) performance, with a resulting positive impact on their carbon footprint, operational costs, and resource efficiency. ESG is an acronym developed in a 2004 report by 20 financial institutions in response to a call from Kofi Anon, Secretary-General of the United Nations. As it implies, ESG refers to how corporations and investors integrate environmental, social, and governance concerns into their business models. Gillan et al. [1] provide an excellent review of the ESG and CSR issues related to corporate finance. In recent years, new research studies have appeared that tackle the issue of circular economy. The continuing improvement in I4.0 have led to CE and fascinating applications, which can be generated in the form of data, interactivity, synergy, and mechanisms to produce sustainable supply chains that are in line with the precepts of companies committed to the circularity of resources. Early theorization of the economic ordering quantity (EOQ) model and economic production quantity (EPQ) model can be traced back to [2,3]. Four new sustainable EPQ models were investigated with different shortage situations [4]. Karim and Nakade [5] provide an excellent review of the sustainable EPQ model related to carbon emissions and product recycling. The importance of the standard EOQ model to incorporate sustainability considerations that include environmental and social criteria have been emphasized [6]. A fuzzy EPQ inventory model to achieve sustainability and profit maximization was developed [7]. A remanufacturing process-oriented model, which combined a set of remanufacturing parameters and features, was analyzed [8]. Issues of sustainability supply chain were analyzed by means of cost calculation methods, including economic and environmental costs [9]. Previous research has primarily focused on solving sustainable EOQ and EPQ problems such as economic aspects [10–15], environmental sustainability especially in carbon emissions [16–21], and social aspects [22]. Supply chain sustainability allows gathering inefficiencies in the supply chain operations. The objective of CE is to extract the advantage of materials, energy, and wastes of an industry [23,24]. In order to deepen our understanding of this framing of sustainable supply chain within a CE, Patil et al. [25] highlighted ESG performance from enterprises and growing awareness of sustainability among businesses, consumers, and investors on the current investing trends. Theeraworawit et al. [26] provide an excellent review of accelerating corporate sustainability. In terms of I4.0 technology, we often investigated the main contribution of I4.0 in the CE issue with cleaner production systems, and precision, accuracy, and efficiency in process control. Rabta [27] presented an EOQ model in a circular economy. Su et al. [22] considered an imperfect multiple-stage production system that manufactures paired products made from mixed materials containing scrap returns, in which the scrap returns are converted from defective products. Khan et al. [17] proposed a profit-maximizing production system where all the products are produced with a variable circularity. Hegedűs and Longauer [28] considered the EOQ and EPQ models with the reusability of raw materials and components in multiple product generations. While considerable attention has been paid in the past to EPQ and EOQ models related to CE, the literature on issues of I4.0 has emerged only very slowly and in a more scattered way. Doltsinis et al. [29] considered the sequential nature of ramp-up and proposes a Cyber-Physical Systems approach based on data capturing, learning mechanisms, and knowledge extraction, leading to an Industry 4.0-compliant Decision Support System (DSS) for human operators. Tsao et al. [30] incorporates the concept of I4.0 in an imperfect EPQ model with predictive maintenance and reworking. Figure 1 illustrates the continuous flow of technical and biological materials through a circular economy. A sustainable CE system consists of some phases, with designing, reused, repaired, and remanufactured products. This retains the functional value of products, rather than just recovering the energy or materials they contain and continuously making products anew. The system consists of 10 items (ex: farming/collection, regeneration/biogas/extraction of biochemical feedstock/recycle, refurbish/remanufacture, reuse/redistribute, maintain/prolong) and is divided into two parts (ex: industrial cycle/biogeochemical cycle). An increasing number of recent publications have reassessed the positive contribution that I4.0 can make to circular economy in the studies of [31–39].

The bike-sharing system (BBS) is becoming an increasingly popular item of the transport system in urban spaces in many cities around the world. The goal of BBS is to deepen our understanding of global environmental challenges and energy-saving solutions based on the sharing economy and circular economy. Macioszek and Cieśla [40] addressed the development of a public bike-sharing system, considering random factors, based on selected external environmental analysis methods. Macioszek and Granà [41] identified factors that influence the occurrence and severity of bicyclist injury in bicyclist-vehicle crashes. With the COVID-19 pandemic, we witnessed an increasing awareness of bikes as an alternative means of transport, as many people either avoid using mass transit or encounter reduced mass transit services. In times of crisis, bikes can provide resilience in transport systems, satisfying our mobility needs when mass transit systems are inaccessible. Huang et al. [42] investigated a CE policy in an imperfect production system with an ETO component and general component.

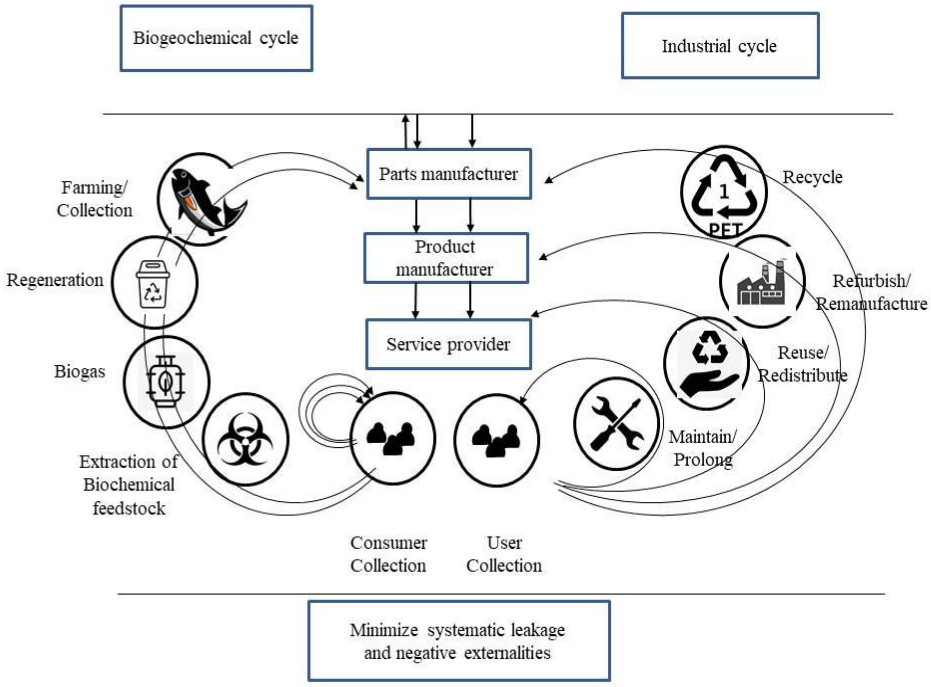

Figure 1. The circular economy system.

Reviewing the applications of CE issues in a sustainable supply chain includes green logistics, waste recovered, and virgin resources use. In discussions of anxiety in CE issues, the current issues are in regard to environmental economics. The purpose of this paper is to prove that the CE is the effective utilization of resources, and I4.0 has been established to shorten the design lead-time and CNC machining time, while improving the production rate of ETO components. In light of these concerns, the following three issues are addressed:

RQ1. *When is the optimal design time of general components in stage 1?*

RQ2. *What is the optimal production rate of ETO components in stage 1?*

RQ3. *What is the optimal sales promotions time in stage 2?*

It would appear the study of I4.0 and CE might pose a fruitful and important issue in understanding the goals that Taiwan's SMEs seek to achieve through digital transformation, and the current status of and future SME needs for digital-related tools (I4.0 technology). The results are of great interest both for application and scientific research.

For convenience, Table 1 indicates a brief comparison of the results of the studies mentioned above. As shown in Table 1, Su et al.'s [22] proposed problem is formulated as a joint economic order quantity (EOQ) and economic production quantity (EPQ) model with CE and GM aimed at cost minimization. Tsao et al. [30] developed imperfect economic production quantity (EPQ) models that consider predictive maintenance (PM) and reworking of defective products by I4.0 to improve PM. This paper may be critically important in laying the groundwork for understanding how bike manufacturers use I4.0 strategies. The aim of this paper is to identify bike production (SMEs) in a sustainable way, by incorporating I4.0 and limiting the consumption and waste of resources (raw materials) as well as the production of waste in company strategy. The bike may seem like a basic form of transportation, but it is really a complex solution to urban traffic problems.

Table 1. A comparison of the major issues between some current EPQ models with the present paper.

References	Major Issues							Other Consideration(s)
	EPQ/EOQ	Product	Demand	Supply Chain	E_n	E	S	
Taleizadeh et al. [4]	EPQ	Single	Deterministic	Single	V	V		Single transportation mode, FIFO.
Ouyang et al. [10]	EPQ	Single	Price-quality	Two-echelon	V			Game theory.
Ouyang et al. [11]	EOQ/EPQ	Single	Deterministic	Single	V		V	Inspection improvement investment.
Chang et al. [14]	EPQ	Single	Deterministic	Single	V	V	V	Discounted cash flow.
Arora et al. [16]	EPQ	Single	Deterministic	Single	V		V	Cap-and-trade regulation.
Khan et al. [17]	EPQ	Single	Cicular-index	Two-echelon	V	V	V	Carbon tax, circular economic index.
Stindt [19]	SSCM	Single	Deterministic	Two-echelon	V		V	Synthesize concepts and methods.
Liao and Deng [20]	EOQ	Single	Uncertainty	Single	V		V	Carbon footprint.
Condeixa et al. [21]	EOQ	Multiple	Deterministic	Single	V	V	V	Reverse logistics.
Su et al. [22]	EPQ	Multiple	Deterministic	Single	V	V		Green manufacturing (GM), scrap returns, CE.
Rabta [27]	EOQ	Single	Linear form	Single		V		Circularity index.
Hegedűs and Longauer [28]	EOQ/EPQ	Single	Deterministic	Two-echelon	V			CE, sustainability.
Doltsinis et al. [29]								I4.0.
Tsao et al. [30]	EPQ	Multiple	Deterministic					I4.0, Corrective maintenance.
This paper	EPQ	Single	Deterministic	Two-echelon	V	V		CE, I4.0.

Notes: environmental (**E_n**), economic (**E**), social (**S**), sustainable supply chain management (**SSCM**).

The remainder of this paper is divided into six sections. The authors discussed the introduction in Section 1. Section 2 describes the problem of the model. In the next section, we will describe the general notation and assumption for this research. Sections 3 and 4 describe the context of this study and the model formulation for this research. Section 5 provides a numerical example that can be used to do sensitivity analysis. Finally, conclusions are presented, and suggestions are made for further research.

2. The Context of this Study

The main object in this study selected by the authors for research is the Taiwan bike manufacturer since it has an important meaning to Taiwan and has a strong supply chain in the global bike industry (Taiwan Excellence Award [43]). In addition, Figure 2 will describe the simple production system of LC Enterprise (LASCO) in the bike industry.

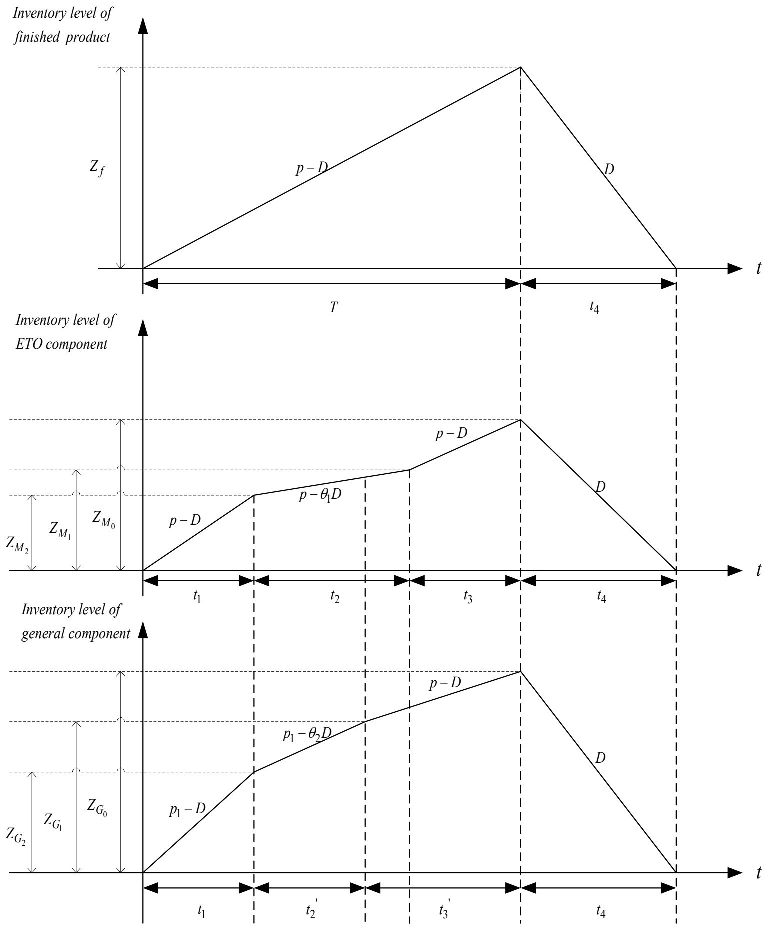

Figure 2. Graph of inventory levels for the ETO component and general component.

As shown in Figure 1, some of the most important components of finished product are the ETO component (crank) and general component (gears). The transmission system of circular gears connect crank-slider mechanism has been presented and mathematical model of the driving mechanism has been established. The top three are inventory level of finished product, inventory level of ETO component, and inventory level of general component.

3. Model Formulation

When this model has been adopted in the bike industry, it differs from the previous studies because there are different characteristics compared with other industries. We sought to determine the optimal production rate, design period, and time period of advertising and sales promotions through practices as the LC company, which is currently the bike company in Taiwan. To determine the effects of the optimal model in this paper, five assumptions were conducted:

- A single product, single period is considered;
- All components and finished products must pass the inspection process. The digital interconnection of machines, processes, data, departments, suppliers, partners, and customers is the essential element in I4.0 technologies;
- Shortages cannot be allowed;
- Product design therefore determines the circularity potential of a product and includes the longevity, reparability, recyclability, proportion of recycled and renewable material in the product, and its suitability for refurbishment or remanufacture;
- In most finished products, the ratio of ETO components is a critical element to increase manufacturer's profit, $\beta \geq \gamma$.

It is critical that if the manufacturer must dispose of its defective products that it does so through a certified product disposal process. The continuous tracking of data during a bike's production and lifetime can provide information for reuse and refurbishment and enable recycling by way of providing information on the bike's components and disassembly. Therefore, t_1, t_2, and t_3 can be presented in turn as follows:

$$t_1 = \frac{Z_{\mathrm{M}_2}}{(p-D)}, \tag{1}$$

where $t_2 + t_3 = t_2' + t_3'$, $\beta Z_{M_0} = Z_{M_1}$, $\gamma Z_{M_0} = Z_{M_2}$, $\beta Z_{G_0} = Z_{G_1}$, $\gamma Z_{G_0} = Z_{G_2}$.

We obtained:

$$t_2 = \frac{Z_{M_1} - Z_{M_2}}{p - \theta_1 D} = \frac{(\beta-\gamma)Z_{M_0}}{p-\theta_1 D} t_1, \tag{2}$$

$$t_3 = \frac{Z_{M_0} - Z_{M_1}}{p-D} = \frac{Z_{M_0}(1-\beta)}{p-D} = \frac{D(1-\beta)}{p-D} t_4, \tag{3}$$

$$t_4 = \frac{Z_{G_0}}{D} = \frac{Z_{M_0}}{D} = \frac{Z_f}{D}, \tag{4}$$

and:

$$T = t_1 + t_2 + t_3 = \frac{Z_f}{p-D}, \tag{5}$$

respectively.

Based on five equations from (1) to (5), with the influence of four costs, the total cost per unit time will be established as follows:

- Setup cost (SC);

The company can identify and evaluate new designs to improve performance by evaluating how product and process designs affect activities and costs, ex design drawing

$$\text{The setup cost per cycle} = S + \alpha\left[(1-\gamma)c_{me} + \gamma c_{mg}\right], \tag{6}$$

- Holding cost (HC);

The holding cost per cycle for ETO components and general components is given by:

$$\begin{aligned} HC &= \tfrac{1}{2}h_f\left[Z_f \times (T+t_4)\right] + \tfrac{1}{2}h_e\left[Z_{M_2} \times t_1 + \left(Z_{M_1} + Z_{M_2}\right) \times t_2 + \left(Z_{M_0} + Z_{M_1}\right) \times t_3 + Z_{M_0} \times t_4\right] \\ &\quad + \tfrac{1}{2}h_g\left[Z_{G_2} \times t_1 + \left(Z_{G_1} + Z_{G_2}\right) \times t_2' + \left(Z_{G_0} + Z_{G_1}\right) t_3' + Z_{G_0} \times t_4\right] \\ &= \tfrac{1}{2}h_f[T(p-D)(T+t_4)] + \tfrac{1}{2}h_e D t_4\left[\gamma \times t_1 + (\beta+\gamma) \times \tfrac{(\beta-\gamma)Dt_4}{p-\theta_1 D} t_1 + (1+\beta) \times \tfrac{D(1-\beta)}{p-D} t_4 + t_4\right] \\ &\quad + \tfrac{1}{2}h_g[\gamma \times t_1 + (\beta+\gamma) \times t_2' + (1+\beta)t_3' + t_4]Dt_4. \end{aligned} \tag{7}$$

- Rework costs (RC);

The rework costs for ETO components and general components per cycle (denoted by RC) is given by:

$$RC = \left[\left(r_f\theta_f + r_g\theta_1\right)p + r_e\theta_2 p_1\right]T, \tag{8}$$

- Production costs (PC);

  The production costs for finished products per cycle (denoted by PC) is given by:

$$PC = \left[p\left(c_{pf} + c_{pg}\right) + c_{pe}p_1\right]T, \tag{9}$$

The objective function of the proposed model consists of four parts to minimize the total cost per unit time and is given by optimizing t_1, t_4, and p. Therefore, the total cost per unit time (denoted by $AC(t_1, t_4, p)$) is given by:

$$\begin{aligned} AC(t_1,t_4,p) &= \tfrac{1}{T+t_4}(SC + HC + RC + PC) \\ &= \tfrac{1}{T+t_4}\Big\{S + \alpha\left[(1-\gamma)c_{me} + \gamma c_{mg}\right] + \tfrac{1}{2}h_f[(p-D)T(t_2+t_3+t_4)] \\ &+ \tfrac{1}{2}h_e[(p-D)t_1t_2 + (p-\theta_1 D)t_2(t_2+t_3) + Dt_4(t_3+t_4)] \\ &+ \tfrac{1}{2}h_g[t_2'((p_1-\theta_2 D)(t_2+t_3) + t_1(p_1-D)) + Dt_4(t\prime_3 + t_4)] \\ &+ \tfrac{1}{2}\left[h_e(p-D) + h_g(p_1-D)\right]Tt_1 \\ &+ \left[\left(r_f\theta_f + r_g\theta_1 + c_{pf} + c_{pg}\right)p + \left(r_e\theta_2 + c_{pe}\right)p_1\right]T\Big\}. \end{aligned} \tag{10}$$

In order to solve this nonlinear programming problem, we first ignore the restriction, and take the first-order derivation of $AC(t_1, t_4, p)$ with respect to t_1, t_4, p, respectively. We obtain:

$$\frac{\partial AC(t_1,t_4,p)}{\partial t_1} = \frac{Dt_4}{2(T+t_4)}\left[\left(h_e + h_g\right)\gamma - h_e\frac{(\beta+\gamma)(\beta-\gamma)}{p-\theta_1 D}Dt_4\right] = 0, \tag{11}$$

$$\begin{aligned} \tfrac{\partial AC(t_1,t_4,p)}{\partial t_4} &= \tfrac{1}{2}h_f(p-D)t_1 + \tfrac{1}{2}h_e Dt_1\gamma \\ &-\left[\tfrac{(\beta+\gamma)(\beta-\gamma)D}{p-\theta_1 D} + \tfrac{D(1+\beta)(1-\beta)}{p-D} + 1\right]h_e Dt_4 \\ &+\tfrac{1}{2}h_g Dt_1(2\gamma+\beta) - h_g Dt_4\left[\tfrac{1}{2}(1+\beta) + 1\right] = 0 \end{aligned} \tag{12}$$

and:

$$\begin{aligned} \tfrac{\partial AC(t_1,t_4,p)}{\partial p} &= \tfrac{1}{T+t_4}\Big\{\tfrac{1}{2}h_f T(T+t_4) \\ &-\tfrac{1}{2}h_e D^2 t^2{}_4\left[\tfrac{(\beta+\gamma)(\beta-\gamma)t_1}{(p-\theta_1 D)^2} + \tfrac{(1+\beta)(1-\beta)}{(p-D)^2}\right] \\ &+\left[\left(r_f\theta_f + r_g\theta_1\right)T\right] \\ &+\left[\left(c_{pf} + c_{pg}\right)T\right]\Big\}. \end{aligned} \tag{13}$$

where $k_1 = (\beta+\gamma)(\beta-\gamma) > 0, k_2 = (1+\beta)(1-\beta) > 0$ and $k_3 = \left(r_f\theta_f + r_g\theta_1 + c_{pf} + c_{pg}\right)$ > 0 . To find the optimal solution of (t_1, t_4, p), let $\partial AC(t_1,t_4,p)/\partial t_1 = 0, \partial AC(t_1,t_4,p)/\partial t_4 = 0$, and $\partial AC(t_1,t_4,p)/\partial p = 0$, simultaneously. By solving these equations, the feasible solution for t_4 should be chosen from 0 to $\hat{t}_4$, where:

$$\hat{t}_4 = \frac{(p-\theta_1 D)\left(h_e + h_g\right)\gamma}{Dh_e k_1}. \tag{14}$$

Thus, we can obtain the following result: once we get the value $t_4 \in (0, \hat{t}_4)$, a corresponding position ${t_1}^*$ can be uniquely determined by the following equation:

$${t_1}^* = {t_4}^*\frac{2\left\{\left(\frac{k_1 D}{p-\theta_1 D} + \frac{Dk_2}{p-D} + 1\right)h_e + h_g\left[\frac{1}{2}(1+\beta) + 1\right]\right\}}{\frac{h_f(p-D)}{D} + h_e\gamma + h_g(2\gamma+\beta)}. \tag{15}$$

The below two cases show all possible situations of t_1: (i) $\beta > \gamma$ and (ii) $\beta < \gamma$.

Case 1: (**With I4.0 technology**) $\beta > \gamma$

In this case, customers place more order products, they typically select or identify parameters to meet their requirements. ETO components are critical to have a robust and flexible production system in place to help manage that complexity. The key result is the demonstration of the concept of I4.0-enabled monitoring through low-cost devices. While the main supported functionality of the presented case supports the key constituents of a condition monitoring data process chain, from data acquisition and signal pre-processing, to detection, diagnosis, and prediction, the prime focus of this study has not been to develop a new approach for such data processing, but showcase that such processing can be delivered through low-cost IoT-enabled simple architecture.

Case 2: (**Without I4.0 technology**) $\beta < \gamma$

In this case, one way to support the design process of ETO building components is to use a coherent platform model that focuses on the reuse of engineering assets, which is more of the skills and knowledge to accomplish higher efficiency during development. Obviously, from Equations (14) and (15), t_1 and t_4 can be uniquely determined as functions of p. Then, if we are trying to find the optimal solution of (t_1, t_4, p), a reasonable thing is to substitute t_1 and t_4 given by Equations (14) and (15) into Equation (13), and then obtain:

$$\begin{aligned} L(p^*) &= \frac{(p^* - \theta_1 D)(h_e + h_g)\gamma h_f}{D h_e k_1} + 2k_3 \\ &- \frac{1}{h_e}\left[\frac{(p^* - \theta_1 D)(h_e + h_g)\gamma}{k_1}\right]^2 \left[\frac{k_1 t_1}{(p^* - \theta_1 D)^2} + \frac{k_2}{(p^* - D)^2}\right]. \end{aligned} \tag{16}$$

Taking the first-order derivative of $L(p)$ with respect to p:

$$\frac{dL(p)}{dp} = \left\{\frac{\theta_1(h_e + h_g)\gamma h_f}{h_e k_1} - \frac{2}{h_e}\left[\frac{(h_e + h_g)\gamma}{k_1}\right]^2 (k_1 {t_1}^* + k_2\theta_1)\right\}.$$

It is not difficult to understand that $L(p)$ is a strictly decreasing function during $p \in [p^L, \infty)$. To that end, the following results were posed:

Theorem 1. *For any given* $t_1 \geq 0$,

(a) *If* $L(p) < 0$, *then the solution* (t_1^*, t_4^*, p^*) *which minimizes* $AC(t_1, t_4, p)$ *not only exists but also is unique, and* $p^* \in (0, \infty)$.

(b) *If* $L(p) \geq 0$, *then optimal value of* p is $p^* \to 0$. *The production system should not be opened.*

The proof of this theorem is given in Appendix A.

Summarizing the above results, we obtain the following Algorithm 1.

Algorithm 1: Optimal solution of inventory problem.

1: STEP 1: Start with $i = 1$ and t_{4j};
2: STEP 2: Put t_{4j} into Equation (15) to obtain the corresponding value of t_1 and then from Equation (16) to calculate $L(p)$
3: STEP 3: If $L(p) < 0$, put $\widetilde{t}_1$ into Equation (16) to obtain the corresponding value of p, i.e., $\widetilde{p}_{j,\tau+1}$ otherwise, let $\widetilde{p}_j = 0$;
4: STEP 4: If the difference between $p_{j,\tau}$ and $p_{j,\tau+1}$ is sufficiently small, set $\widetilde{p}_j = p_{j,\tau+1}$. Otherwise, set $p_{j,\tau+1} = p_{j,\tau} + \varepsilon$, where ε is any small positive number, and set $\tau = \tau + 1$; then, go back to STEP 2;
5: STEP 5: Substitute $t_1 = \widetilde{t}_{1j}$ and $p_j = \widetilde{p}_j$ into Equation (10) to calculate the value of $AC(t_1, t_4, p)$.
The objective is to determine the optimal the number of shipments, lot size per shipment and capital expenditure that minimizes the joint total expected cost per unit time of the integrated supply chain.

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4. Application Example

In this section, we use one case study to show how CE can be used to help in the explaining of the proposed model. By means of two numerical examples and sensitivity analysis, the study has collected rich data which enable descriptions of managerial insights of the EPQ model with CE.

4.1. CE in the Context of a Bike Company

In the following, we introduce a well-established OEM bike company in Taiwan. Maleque et al. [44] proposed that the successful design of a folding bike should take into account the function, material properties, and fabrication. It is essential to include all key stakeholders in the process design. Design engineers should understand the organization's objectives and process work preface diagram. We also indicate in Figure 3 the existence of some main parts: drivetrain system design (3D computer graphics, CNC machining, finished product assembly), the general components (crank, chain wheel) are design and CNC machining to form drivetrain system via grinding, and surface treatment and assembly processes. Figure 3 helps to define: A reveals the start point of CNC machining specified for machining the crankshaft; B is the waiting time of finishing process with the crankshaft—I4.0 will revolutionize this process through real-time quality assurance (QA) such as automated virtual metering (AVM) systems; and C reveals the start point of grinding and surface treatment—I4.0 provides the communication standards of human–machine interfaces. Most laborers will perform daily operations with robots and machines (often called collaborative robots). The integration of CNC machinery and CAM (Computer-Aided Manufacturing) helps to shorten manufacturing time and ensure the production of defect-free components. In this diagram, we constructed the components of the bike drivetrain system as shown in Figure 4 that consists of inner claw piece, chain cover, crank, chain wheel, and the appearance (Figure 5). As Figure 4 indicates, CNC machining is a manufacturing process suitable for a wide variety of industries. The most common mechanical CNC machining operations including: Drilling (A), Milling (B), Turning(C).

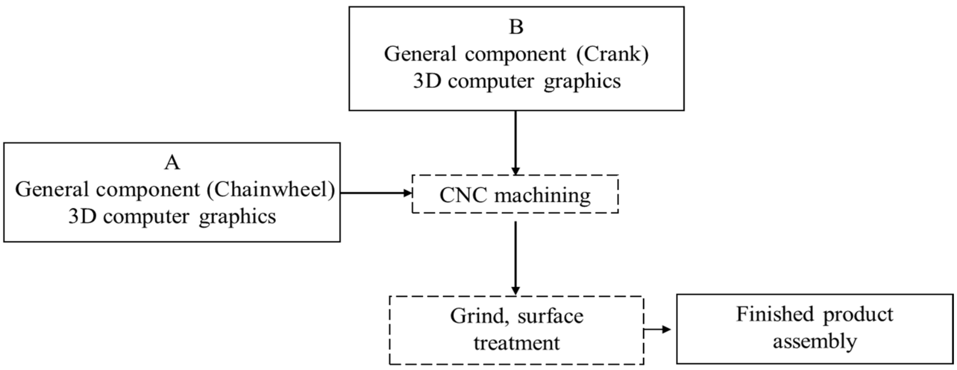

Figure 3. Component assembly for finished product.

4.2. Numerical Example

In order to clarify the relative utilization of the proposed model, this subject was selected from the bike industry. We consider two numerical examples of CE problems to illustrate the model and verify the obtained analytical results. In the first example, it would be the situation of Case 1 due to $\beta > \gamma$. By applying the proposed algorithm, we have the optimal solutions, t_1^* = 1.21012, t_4^* = 3.07002, p^* = 398.703, and $AC(t_1^*,\ t_4^*,\ p^*)$ = 2963.04. In the second example, which meets the situation of Case 2 due to $\beta < \gamma$, we have the optimal solutions, t_1^* = 1.0307, t_4^* = 3.9635, p^* = 504.723, and $AC(t_1^*,\ t_4^*,\ p^*)$ = 6529.57. Next, the effect of CE practices was carried out on the enterprise's inventory policy. To analyze the proposed algorithm, the effect of changes in various parameters was carried out in the model. Here is Table 2, which shows CE problems for examples 1 and 2.

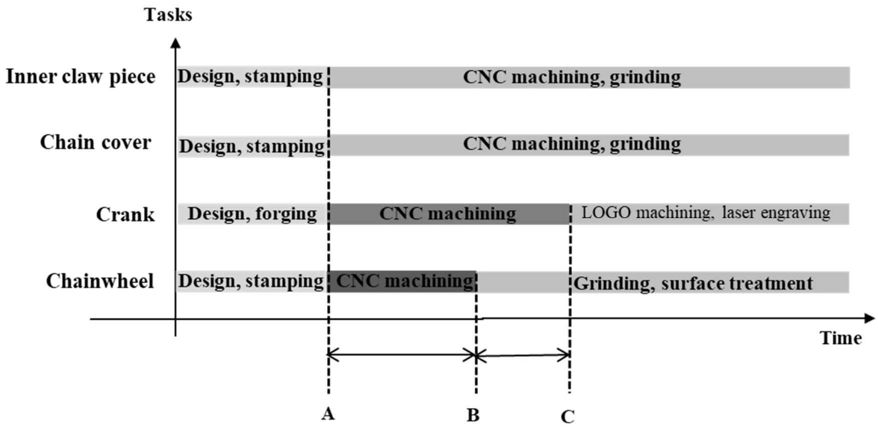

Figure 4. Major procedure of production for the bike drivetrain system.

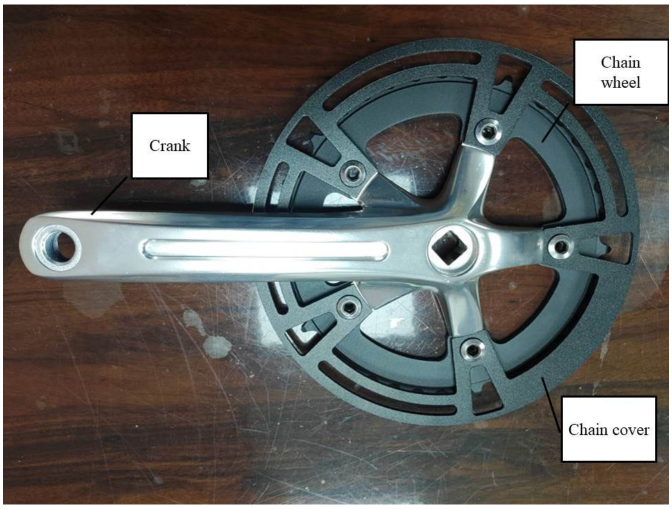

Figure 5. The appearance of the bike drivetrain system.

Table 2. The value of parameters for two examples with CE problems for examples 1 and 2.

Example 1 (Case 1)			
P_1 = 12,000	c_{pe} = \$0.5	c_{pf} = \$0.375	c_{pg} = \$0.4
r_f = \$0.04	r_g = \$0.03	r_e = \$0.005	h_f = \$10
h_g = \$5	h_e = \$7	θ_1 = 0.04	θ_2 = 0.03
θ_f = 0.01	$\alpha = 0.3$	β = 0.2	γ = 1
$k_1 = 0.03 > 0$	$k_2 = 0.96 > 0$	$k_3 = 0.7766 > 0$	
Example 2 (Case 2)			
P_1 = 10,000	c_{pe} = \$0.5	c_{pf} = \$0.375	c_{pg} = \$0.4
r_f = \$0.04	r_g = \$0.03	r_e = \$0.005	h_f = 0.3
h_g = 0.2	h_e = 0.1	θ_1 = 0.04	θ_2 = 0.03
θ_f = 0.01	$\alpha = 0.3$	β = 0.2	γ = 1
$k_1 = -0.96 < 0$	$k_2 = 0.96 > 0$	$k_3 = 0.7766 > 0$	

Next, the effect of CE practices was carried out on the enterprise's inventory policy. To analyse the proposed algorithm, the effect of changes in various parameters was carried out in the model.

4.3. Sensitivity Analysis

I4.0 is identified as one of the main determinants to drive the application towards a more sustainable production through an economy that reuses, reduces, and recycles resources. The numerical examples in the above subsection are considered to study the effects of changes in the system parameters (p_1, h_f, h_e, $h_g\theta_1$, θ_2, θ_f, c_{pf}, c_{pe}, r_e, r_g, α, β and γ) on the optimal values of p^*, t_1^*, t_4^* and $AC(p^*,\ t_1^*,\ t_4{}^*)$. Therefore, the effects of changes in the parameters of a model are determined by solving the model and comparing the results with respect to changes made with parameters by +50%, +25%, −25%, and −50%, taking one parameter at a time and keeping the remaining parameters unchanged. The analytical results are shown in Tables 3 and 4. Other detailed results are tabulated in Table 5 to illustrate some managerial insights for bike company.

Table 3. Effect of changes in various parameters of the model for example 1.

Parameter	Change (%)	Optimal Solutions			
		p^*	t_1^*	t_4^*	$AC(p^*, t_1^*, t_4^*)$
p_1	50%	436.98	1.0686	3.7668	4020.82
	25%	419.47	1.1776	3.1692	3916.01
	−25%	362.76	1.8736	3.0194	2706.39
	−50%	278.78	2.6666	2.7895	2601.58
h_f	50%	337.439	1.9686	3.3733	3903.41
	25%	344.952	1.8761	3.1449	3857.31
	−25%	446.238	0.8659	3.0315	2765.10
	−50%	451.165	0.8567	3.0256	2719.00
h_e	50%	394.441	1.1452	2.7618	3284.07
	25%	394.957	1.1561	2.7758	3256.24
	−25%	399.771	1.6601	3.8019	2972.56
	−50%	399.592	1.6898	3.8199	2900.73
h_g	50%	383.598	1.1781	3.9862	2917.13
	25%	386.711	1.1949	3.3030	2972.77
	−25%	425.238	1.6743	2.4454	3384.04
	−50%	430.651	1.7204	2.3511	3539.67
c_{pf}	50%	402.703	1.1912	3.3701	3817.24
	25%	399.703	1.2012	3.1701	3814.22
	−25%	391.703	1.2212	2.9701	3808.18
	−50%	382.703	1.2312	2.8701	3805.16
c_{pg}	50%	502.322	1.2312	5.1512	2969.65
	25%	457.434	1.2212	4.1232	2966.42
	−25%	348.447	1.1912	2.9871	2960.98
	−50%	300.512	1.1812	2.5678	2957.75
c_{pe}	50%	406.568	2.1664	3.2438	3135.37
	25%	401.717	1.3311	3.2384	2973.28
	−25%	379.631	0.9036	1.1935	2649.12
	−50%	344.729	0.6090	1.1775	2487.04
θ_1	50%	401.325	1.2071	3.9700	2963.24
	25%	399.172	1.2092	3.7712	2963.24
	−25%	396.091	1.2112	2.9189	2962.02
	−50%	392.858	1.2134	2.8650	2961.84
θ_2	50%	398.501	1.2108	3.0691	2963.24
	25%	398.603	1.2111	3.0698	2963.14
	−25%	398.901	1.2115	3.0710	2963.03
	−50%	398.921	1.2118	3.0720	2963.02

Table 3. *Cont.*

Parameter	Change (%)	Optimal Solutions			
		p^*	t_1^*	t_4^*	$AC(p^*, t_1^*, t_4^*)$
θ_f	50%	398.751	1.2106	3.0722	2963.04
	25%	398.721	1.2107	3.0712	2963.04
	−25%	398.681	1.2116	3.0691	2963.03
	−50%	398.661	1.2118	3.0682	2963.01
r_e	50%	399.891	1.2108	3.0901	2963.05
	25%	399.822	1.2109	3.0802	2963.05
	−25%	397.401	1.2114	3.0603	2963.01
	−50%	396.301	1.2115	3.0401	2962.99
r_g	50%	398.901	1.2107	3.0712	2963.12
	25%	398.821	1.2109	3.0708	2963.09
	−25%	398.711	1.2115	3.0698	2963.04
	−50%	398.612	2.2118	3.0691	2963.01
α	50%	398.691	1.2116	3.0691	2973.04
	25%	398.692	1.2114	3.0697	2963.04
	−25%	398.705	1.2109	3.0705	2953.04
	−50%	398.708	1.2106	3.0709	2943.04
β	50%	402.145	1.1812	6.1934	3213.26
	25%	401.178	1.1934	4.1980	3014.16
	−25%	396.013	1.2319	2.1982	2960.15
	−50%	392.124	1.2681	1.7841	2958.11
γ	50%	412.013	1.2601	3.2146	5019.21
	25%	401.456	1.2213	3.1561	4311.09
	−25%	381.781	1.1927	2.9811	1865.19
	−50%	361.890	1.1789	2.8157	1618.01

Table 4. Effect of changes in various parameters of the model for example 2.

Parameter	Change (%)	Optimal Solutions			
		p^*	t_1^*	t_4^*	$AC(p^*, t_1^*, t_4^*)$
p_1	50%	125.399	3.0843	4.1282	6621.91
	25%	393.338	2.9481	3.3552	6575.74
	−25%	516.398	0.7995	3.0995	6483.41
	−50%	553.813	0.6426	2.7981	6437.24
h_f	50%	199.344	0.9985	5.7014	6623.82
	25%	298.280	1.0294	4.1272	6576.71
	−25%	530.233	1.1246	3.1402	6524.14
	−50%	539.372	1.9993	3.0511	6515.32
h_e	50%	157.571	1.0023	1.4074	6786.60
	25%	160.434	1.0748	3.3701	6657.23
	−25%	526.985	1.0975	4.3503	6400.21
	−50%	541.887	1.1898	6.1973	6398.50
h_g	50%	71.7052	0.9946	1.9803	6476.52
	25%	191.372	1.0172	2.3185	6503.91
	−25%	446.400	1.0929	8.9382	6553.54
	−50%	612.191	1.9649	9.6048	6579.21
c_{pf}	50%	119.715	1.0010	3.1432	6532.77
	25%	166.646	1.0272	3.6996	6529.47
	−25%	519.728	2.9220	4.1268	6526.28
	−50%	529.365	3.0534	5.0842	6524.67

Table 4. *Cont.*

Parameter	Change (%)	Optimal Solutions			
		p^*	t_1^*	t_4^*	$AC(p^*, t_1^*, t_4^*)$
c_{pg}	50%	119.714	2.9419	1.1438	6532.98
	25%	119.718	2.9368	1.1395	6531.28
	−25%	585.505	0.9148	0.3861	6527.87
	−50%	591.946	0.8944	0.3665	6526.16
c_{pe}	50%	411.648	1.0000	8.8623	6672.35
	25%	507.545	1.0269	4.4774	6600.96
	−25%	619.926	2.2554	2.4523	6458.18
	−50%	620.329	2.5789	1.7692	6386.79
θ_1	50%	119.721	2.9318	3.1282	6529.61
	25%	279.927	2.0342	3.4481	6529.59
	−25%	523.091	1.0318	4.1386	6529.55
	−50%	591.721	0.9317	4.3503	6529.53
θ_2	50%	959.383	0.9613	4.8483	6529.66
	25%	617.581	1.0267	4.6210	6529.61
	−25%	217.586	1.0433	3.4905	6529.53
	−50%	225.004	1.0488	3.6877	6529.49
θ_f	50%	268.496	1.0244	3.3183	6529.67
	25%	351.181	1.0264	3.3222	6529.57
	−25%	905.177	1.0425	4.8095	6529.47
	−50%	952.832	1.0826	4.8479	6529.47
r_e	50%	419.583	1.3165	1.8924	6529.61
	25%	495.711	1.2702	2.8304	6529.59
	−25%	529.404	0.8844	4.5494	6529.55
	−50%	628.991	0.8845	8.4646	6529.51
r_g	50%	398.901	1.2107	3.0712	2963.12
	25%	398.821	1.2109	3.0708	2963.09
	−25%	398.711	1.2115	3.0698	2963.04
	−50%	398.612	2.2118	3.0691	2963.01
α	50%	210.182	1.0231	3.2298	6559.57
	25%	363.959	1.0268	3.7892	6549.57
	−25%	519.721	2.9318	3.9761	6539.57
	−50%	569.489	3.0068	3.9911	6529.57
β	50%	436.780	1.1715	1.2687	6466.63
	25%	502.420	1.0487	1.1120	6493.74
	−25%	573.259	0.9411	0.8959	6582.69
	−50%	646.242	0.7510	0.7197	6678.85
γ	50%	363.959	1.0268	1.7892	6429.59
	25%	500.011	1.0302	2.0055	6429.47
	−25%	530.111	1.9592	5.6479	6429.37
	−50%	619.721	2.9318	6.1352	6429.29

There are two situations to consider to improve the average time of design stage (t_1) and average time of sales promotions stage (t_4): (i) when the I4.0 technology is implemented in the production system as (1.6966, 3.1862; p_1), (1.4419, 3.0214; h_g), (1.2062, 3.7073; c_{pg}), (1.4482, 3.304; r_g) (see Figure 6); and (ii) when the I4.0 technology is not implemented in the system as (1.8686, 3.3452; p_1), (1.2674, 5.7104; h_g), (0.7589, 4.7589; c_{pg}), (1.6861, 4.6048; r_g) (see Figure 7), respectively. Obviously, as observed in Figures 6 and 7, the design time of components with I4.0 are shorter than those without I4.0. The adoption of I4.0 could lead to a 20% reduction design time of the general component. I4.0 technological solutions make possible to exchange data in real-time between interconnected companies, reducing costs (ex: purchase cost, holding cost, rework cost, production rate for general component) and response times (ex: design time, time period of advertising and sales promotions for general component). I4.0 enables increased flexibility of production processes to fabricate products with a high level of customization. Thus, the analyzed result is to identify the role of I4.0 to promote sustainable business performance in SMEs.

Table 5. Some detailed results of the sensitivity analysis.

Parameter(s)	Example 1 (Case1) $\beta>\gamma$	Example 2 (Case2) $\beta<\gamma$
h_f, h_e	Customization-based interaction for ETO-based component can be complicated and small batch and multi-species order batch.	Enterprise offers flexibility in modeling ETO-based component, and build at a relatively fast pace, but must also be flexible and account for any design changes a customer may have.
c_{pf}, c_{pg}, c_{pe}	Enterprise works with design for assembly (DFA) methods for different reasons. Some enterprises want to take cost out of their products, some want to make more products in their factories, and some want to simplify the product to increase quality and reliability.	Adding to this environment is the push for mass customization by consumers and purchasers of ETO products, requiring an already difficult process to move faster with a higher degree of customized design.
$\theta_1, \theta_2, \theta_f$	When new activities occur (e.g., due to changes or defects), planned activities need to be replanned, including considering the consequences of such changes or delays for other activities from the customer's specification.	A large number of defects usually occur in the initial stages of a project and early defect detection will lower the overall cost of the project.
r_e, r_g, r_f	Defects, delays, disconnects (DDD) cause rework, repairs, returns (RRR) that consume valuable resources to contain problems, correct deviations, and restore customer relationships.	Liability for personal injuries caused by a product's defective design can be imposed under several underlying legal theories, among them negligence, breach of warranty, and strict product liability.
α, β, γ	Products require limited custom design per customer order because they have standard designs that can be altered to fit the customer requirements. Products may even be manufactured using an MTO strategy.	The components also differ in degree of standardization, where some components are standardized and unaltered across many products and others may be changed and redesigned for each customer order.

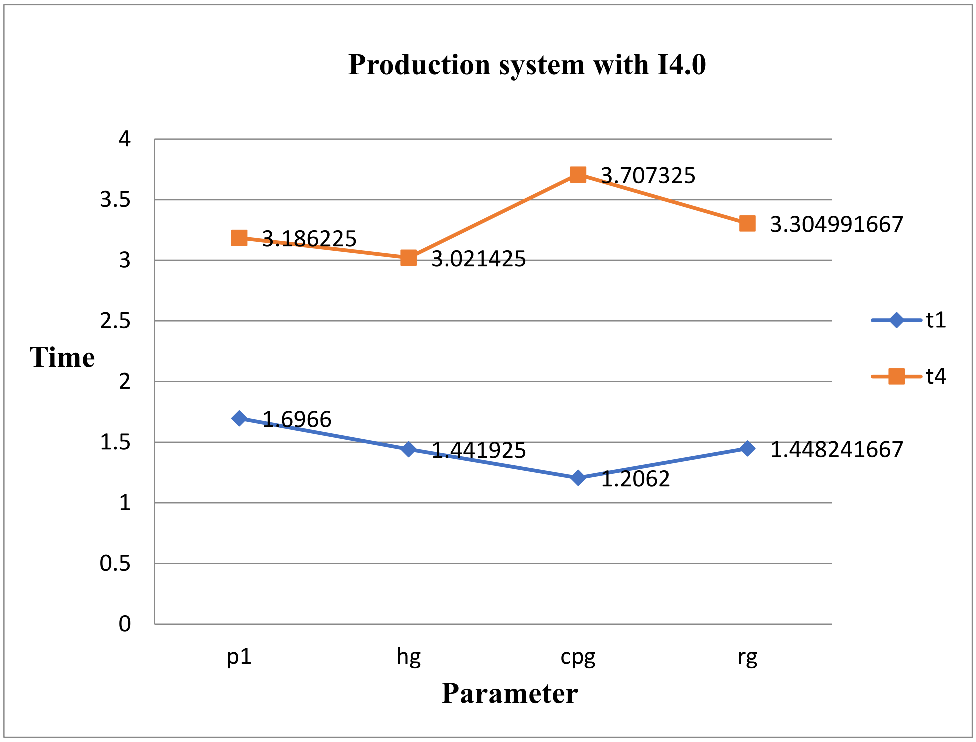

Figure 6. Design (t_1 and sales promotions time (t_4) with I 4.0.

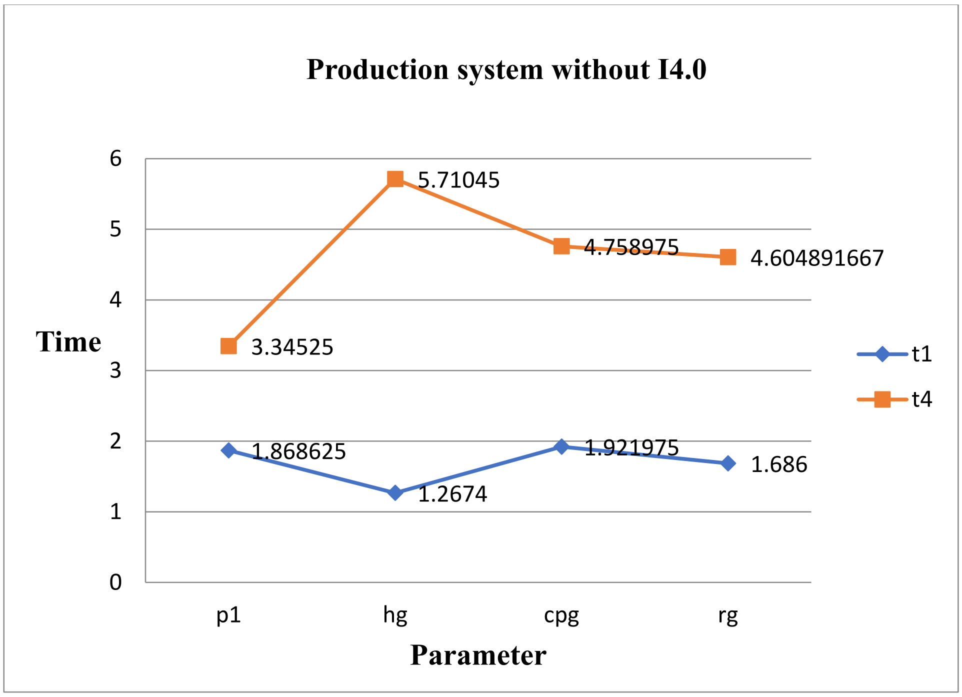

Figure 7. Design (t_1) and sales promotions time (t_4) without I4.0.

5. Conclusions

Gurjanov et al. [45] studied the principles of cyber-physical system constitution at I4.0 company of the item designing components of assembly production. Dutta et al. [46] investigated the functional areas which can implement digital transformation according to I4.0 technology in Indian SMEs. This paper focuses on exploring the link between I4.0 and CE. A key challenge facing the high cost of designing and manufacturing generic components is the main drawback in working towards increased resource efficiency and material circularity through I4.0. First, we exhibit necessary and sufficient conditions for the optimal solution. Next, a simple algorithm was used to identify the optimal solution of (t_1, t_4, p), which would minimize the total cost per unit time. The findings identified several challenges that need to be addressed in searching for circular materials, for example, a multidisciplinary approach combining fundamental science and engineering to create the necessary materials and technologies to underpin circular systems but also policy and economics to enable society to make the transition to a circular economy. Torn and Vaneker [47] provided extensive discussions of I4.0 to increase the capacities of SMEs to capitalize on mass personalization via a collaborative network. In light of these concerns, this case study has led to the following observations: (1) with a simulation model, companies must be automated and measure the impact of technological tools on productivity and variability without upsetting daily production activities; (2) the company uses real-time to power decision making, resulting in the total cost per unit time shrinking by 2.9%. An important area for future research in the years to come will be to investigate to which degree and for which types of products, materials, and personalization is expectedly profitable.

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Appendix A

In order to gain a better understanding of CE issues through I4.0, the same notation in the production system.

Table A1. System Parameters.

p_1	production rate for general component.
D	demand rate per unit time.
S	buyer's ordering cost per order.
c_{mg}	design cost for general component per unit time.
c_{me}	design cost for ETO component per unit time.
c_{pf}	purchase cost for finished product per unit time.
c_{pg}	purchase cost for general component per unit time.
c_{pe}	purchase cost for ETO component per unit time.
θ_f	defective rate for finished product.
θ_1	defective rate for ETO component.
θ_2	defective rate for general component.
α	design fee (installment/payment).
β	finished product with a ratio of ETO-based components.
γ	percentage for designing ETO-based components.
h_f	holding cost for finished products per unit time.
h_g	holding cost for general component per unit time.
h_e	holding cost for ETO component per unit time.
r_f	rework cost for finished products per unit time.
r_g	rework cost for general component per unit time.
r_e	rework cost for ETO component per unit time.
Z_f	maximum inventory level of finished products.
Z_{M_0}	maximum inventory level of ETO component can be assembled.
Z_{G_0}	maximum inventory level of general component can be CNC machined.
Z_{G_2}	maximum inventory level of general component can be stamped.
t'_2	time period prior to begin to CNC machining for ETO components in stage 2.
t_3	time period prior to begin to surface finishing for ETO components in stage 2.

Table A2. Decision Variables.

p	production rate of ETO components in stage 1.
t_1	design time of general components in stage 1.
t_4	time period of advertising and sales promotions in stage 2 (the maturity stage).

Appendix B

Proof of Theorem A1

(a) From, Equation (16), there exists a unique solution $t_1{}^* \in [0, \infty)$ if $L(p^*) \geq 0$. Furthermore, we derive the following differential equations and the determinant of the Hessian matrix, det (H) at the stationary point in order to examine the second-order sufficient conditions (SOSC) for a minimum value. Taking the second partial derivatives of $AC(t_1, p|t_4)$ with respect to t_1 and p, respectively, yields.

$$\mathrm{H}_{11} = \left.\frac{\partial^2 AC(t_1, p|t_4)}{\partial t_1{}^2}\right|_{(t_1,p)=(t_1^*,p^*)} = \frac{Dt_4}{2(T+t_4)^2}\left[(h_e+h_g)\gamma + h_e\frac{k_1}{p-\theta_1 D}Dt_4\right] > 0,$$

$$\mathrm{H}_{22} = \left.\frac{\partial^2 AC(t_1, p|t_4)}{\partial p^2}\right|_{(t_1,p)=(t_1^*,p^*)} = h_e D^2 t^2{}_4\left[\frac{k_1 t_1}{(p-\theta_1 D)^3} + \frac{k_2}{(p-D)^3}\right] > 0,$$

and

$$\mathrm{H}_{12} = \mathrm{H}_{21} = \left.\frac{\partial AC(t_1, p|t_4)}{\partial t_1 \partial p}\right|_{(t_1,p)=(t_1{}^*,p^*)} = 0.$$

Therefore, we can determine the nature of stationary point $(p^*, t_1{}^*)$ by considering value of Hessian matrix and whether Hessian is negative definite.

$$\begin{aligned}\det(H) &= \mathrm{H}_{11}\times\mathrm{H}_{22} - \mathrm{H}_{12}\times\mathrm{H}_{21}\\ &= \left[(h_e+h_g)\gamma + \tfrac{h_e k_1 D t_4}{p-\theta_1 D}\right]\times\left[\tfrac{h_e D^2 t^2{}_4 k_1 t_1}{(p-\theta_1 D)^3} + \tfrac{h_e D^2 t^2{}_4 k_2}{(p-D)^3}\right] > 0.\end{aligned}$$

(b) From Equation (11), for $t_1 \in [\hat{t}_1, \infty)$, we obtain that $\frac{\partial AC(t_1,t_4,p)}{\partial t_1} > 0$. This implies that a large value of t_1 causes a higher value of $AC(t_1, t_4, p)$. Hence, the minimum value of $AC(t_1, t_4, p)$ occurs at the point $t_1^* = t_1^L$. It seems reasonable to conclude that the production system will not be opened. This completes the proof. □

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