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Production Decisions of Manufacturing and Remanufacturing Hybrid System Considering Downward Substitution: A Comprehensive Model Integrating Financial Operations

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ABSTRACT Traditional approaches for production decisions of the manufacturing/remanufacturing hybrid system usually focus on physical operations and ignore the corresponding financial aspects. This paper proposes a mixed integer stochastic programming model integrating physical and financial operations based on scenario analysis, which considers the downward substitution between new and remanufactured products and selects financial performance indicator, i.e. economic value added, as the optimal objective function. The prime superiorities of the integrated approach are emphasized through a numerical example, and sensitivity analyses on some critical parameters are conducted. The findings indicate that the integrated approach can not only ensure the stability of hybrid production system, but also significantly improve financial operation efficient and reduce total financial operation cost, and thus eventually brings the manufacturer higher objective value. Furthermore, the advantage of integrated approach in objective optimization is more prominent when manufacturers intend to provide higher service level to customers. Finally, the results proposed in this paper provide applicable suggestions to manufacturers and financial institutions.

INDEX TERMS Production decisions, manufacturing/remanufacturing hybrid system, downward substitution, financial operations, economic value added.

I. INTRODUCTION

Remanufacturing, as an industrial process in which the used products are restored to an "as-new" condition, has not only obvious environmental benefits, but also considerable economic benefits [1]–[3]. Therefore, many traditional manufacturers perform remanufacturing activities based on the original production activities, and then the manufacturing/remanufacturing hybrid system (MRHS) is emerged, such as Boeing, Bosch, Sun Microsystems, Hewlett-Packard, Thomson, etc. [4].

Compared to traditional manufacturing system, MRHS has much more diverse conditions and volatility factors. Then, it is critical for manufacturers to determine how to coordinate manufacturing and remanufacturing activities and make optimal production decisions. In general, the production operation processes are simultaneously accompanied by material flows, cash flows and information flows. Many researchers pointed out that it is necessary to consider the effects of financial operations on the formulation of production decision model [5], [6]. In practice, many manufacturers have begun to attach importance to the integration of production and financial activities. For instance, Deutz, the manufacturer engaged in engine production, puts forward the effects of financial flows on the production strategies and then make optimal inventory decisions through adjusting financial strategies such as the accounts payable, accounts receivable and so on, which significantly improves the operation performance [7].

However, in the fields of manufacturing/remanufacturing decisions, most researchers only emphasized on the

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integration of material flows and information flows. They regarded production and financial operations as separate issues, and constructed corresponding independent decision models, which leads to the lower operational efficiency.

This issue leads to some interesting research questions: How do capital flows and material flows interact in the operation processes of the manufacturing/remanufacturing hybrid system? How does the manufacturer make the optimal operation decisions while considering the integration of production and financial activities, and what are the advantages of the integrated approach proposed in this paper? Moreover, what are the conditions that make the business performance of the manufacturer better?

This paper addresses multi-period production decision issues of a manufacturing/remanufacturing hybrid system considering financial operations and decisions. The manufacturer, as a monopolist enterprise, produces new and remanufactured products to meet the uncertain market demand. Since the possible quality downgrading or consumer cognitive deficiency of the remanufactured products, like [8]–[10], the segmented markets and one-way substitution strategy for new and remanufactured products are considered in this paper. In addition to production operations, the manufacturer needs simultaneously perform financial operations to ensure the coordination of material flows and cash flows over the entire planning cycle, such as short-term loans, accounts receivable and accounts payable management, and short-term investments (namely, marketable securities), etc.

Without loss of generality, taking their own benefits and risks into consideration, the lenders (such as the banks, etc.) would set the loan limit according to the income and other conditions when the short-term loans are provided, which may cause that manufacturers have not sufficient capital to cover purchasing cost, production cost and other costs. In addition, there always exists the opportunity cost or minimum rate of return when manufacturers make specific investments, (namely, capital cost). Based on the concept of capital cost, a financial indicator (Economic Value Added, EVA) was proposed to measure operational performance, which reflects the real economic profit after deducting all costs (including capital cost) for the manufacturer. Chen and Dodd [11] pointed out, as an effective indicator, the explanatory ability of EVA (41%) is apparently higher than traditional accounting index (36.5%). Furthermore, a few researchers have shown the advantages of EVA from different aspects, such as market value, accounting calculation [12], [13]. As an extension of residual income, the basic calculation formula of economic value added is shown in **Fig. 1**. Thus, the mixed integer stochastic programming model proposed in this paper aims at maximizing economic value added of the manufacturer.

The remainder of this paper is organized as follows. Section 2 is devoted to a review of the related literature. In Section 3, the planning problem is described in detail. Section 4 presents the decision optimization model, and Section 5 conducts a numerical example to illustrate the

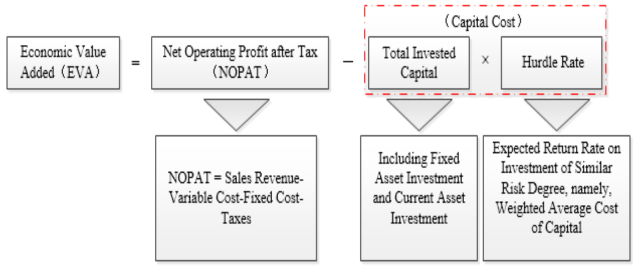

FIGURE 1. **Basic calculation formula of economic value added.**

superiorities of the integrated model proposed in this paper and sensitivity analyses on some critical parameters related to integrated model, and managerial insights are provided in Section 6. Section 7 ends the paper with conclusions and future research directions.

II. LITERATURE REVIEW

Some integration aspects of operation and financial decisions in the MRHS have received academics' attention, and a summary of relevant literature is presented in Table 1 to allow for comparison of context, logistical features, financial features and other features from these previous studies.

To the best of our knowledge, many studies have focused on issues related to production decisions in a hybrid remanufacturing/manufacturing system. Assuming the remanufactured product is equivalent to the original manufactured product and thus sold for the same price to the same market, most researchers studied production decisions of the manufacturing/remanufacturing hybrid system [14]–[16] and operation decisions of the closed-loop supply chain [17]–[19].

However, it is observed in practice that the remanufactured products are often offered at a lower price because of possible downgrading [20]–[22], and the consumer cognitive deficiency (namely, higher perceived value of original manufactured products) [23], [24]. Examples of such products include personal computers, photocopiers, automotive engines and tires [1], [25]. Compared with the original manufactured products, the remanufactured products are more likely to appear to be uncertain and out of stock [26]. Thus, a downward substitution strategy is applied to avoid losses from back orders and customer goodwill for the remanufactured products. That is to say, the demand for the remanufactured products can also be satisfied by new products but not vice versa.

For instance, under the assumption that only a certain percentage of consumers would accept the downward substitution, Bayındır *et al.* [27] studied a single-period production planning problem of new and remanufactured products. Pineyro and Viera [28] proposed a multiple-period lots sizing problem of the hybrid system considering the downward substitution strategy, but the recycling/purchasing decisions of input materials are not considered and the effects of financial factors on production decisions are ignored. Ahiska and Kurtul [10] explored the inventory issues including manufacturing/remanufacturing planning, and then analyzed the effect

TABLE 1. Context, logistical features, financial features and other features included in related studies of this paper.

Reference	Context	Logistical features							Financial features						Other features					
		Demands		Cost		Constraints									Goals				Period	
		Uncertain	One-way substitution	Setup cost	Disposal cost	Service level	Inventory capacity	Recycling quantity	Budget	Financing	Investments	Receive/Payment planning	Cash position constraint	Tax	Profit/ Cost /Reward	(NPV of) Cash balance	SV/Change in equity	EVA	Single	Multiple
[32]	Operation								✓	✓	✓		✓		✓				✓	
[33]	decisions of								✓	✓	✓		✓			✓				✓
[34]	traditional			✓					✓	✓		✓			✓					✓
[35]	manufacturing	✓					✓		✓	✓	✓	✓	✓			✓				✓
[36]	system and supply chain	✓							✓	✓		✓	✓	✓			✓			✓
[37]	Closed-loop				✓		✓		✓	✓	✓	✓	✓				✓			✓
[38]	supply chain	✓			✓		✓		✓	✓	✓	✓	✓				✓			✓
[39]	design	✓			✓		✓	✓								✓				✓
[40]					✓		✓	✓	✓	✓	✓	✓		✓				✓		✓
[17], [18]	Operation	✓													✓					
[19]	decisions of closed-loop			✓	✓										✓					✓
[41]	supply chain								✓	✓					✓				✓	
[10]		✓	✓	✓	✓										✓				✓	
[14]		✓		✓		✓									✓					✓
[15]					✓			✓							✓					✓
[16]				✓	✓			✓							✓					✓
[27]	Production	✓	✓												✓				✓	
[28]	decisions of		✓	✓	✓										✓					✓
[29]	manufacturing/re-	✓	✓		✓		✓	✓							✓				✓	
[30]	manufacturing	✓	✓												✓				✓	
[31]	hybrid system	✓	✓	✓	✓		✓								✓					✓
[23]		✓	✓						✓						✓				✓	
[24]								✓	✓	✓					✓				✓	
[42]				✓			✓								✓					✓
This paper		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓		✓

of the downward substitution on incremental profit. Marshall and Archibald [29] conducted an integrated research on the recycling, manufacturing and remanufacturing decisions under different conditions, such as no substitution, two-way substitution, upward substitution and downward substitution between original manufactured and remanufactured products. Chen *et al.* [30] studied effects of carbon constraint on the production policies when one-way substitution between the green and standard products is considered. Liu *et al.* [31] formulated a multi-period mixed integer programming model for the stochastic MRHS with downward demand substitution and proposed an ant colony system algorithm with random sampling method to determine optimal production plan.

So far, there is little information available in the literature about multi-period comprehensive issues of purchasing, recycling and manufacturing/remanufacturing decisions with a one-way substitution strategy. In addition, the above literature ignored the influences of financial operations on the production decisions in a manufacturing/remanufacturing hybrid system.

Although some literature has shown that it is necessary to take financial factors into account when formulating production operation models, most researchers don't pay attentions to relative studies. Moreover, considering financial factors, existing papers mostly focus on traditional manufacturing systems and supply chain [32]–[36]. Few papers conduct the related research focusing on the closed-loop supply chain decisions and manufacturing/remanufacturing decisions. Ramezani *et al.* [37] addressed the integration of financial aspects to optimize closed-loop supply chain and showed advantages of proposed model through numerical examples. Then, Ramezani and Kimiagari [38] expanded the previous research by considering stochastic demand and returns. But both of them only study production problem of a single product and ignore the existence of the capital cost. In [39], a mixed integer linear programming model is proposed that integrates financial risk measures into the design of closed-loop supply chains and maximizes the net present value (NPV). Similarly, Polo *et al.* [40] conducted the robust design of a closed-loop supply chain by maximizing the economic value added (EVA). They don't consider the quality differences and substitution strategies between new and remanufactured products. For the operation decisions of a manufacturing/remanufacturing hybrid system, Wang and Zhang [41] studied the selection problem of recycling strategies considering the capital constraint and financing decision. Wang *et al.* [23] and Wang and Chen [24] respectively discussed the effects of the capital constraint and financing decision on the manufacturing/remanufactured decisions under the emissions trading policy. Chen *et al.* [42] explored the manufacturing/remanufacturing decision issues taking inflation and the time value of the money into account. On the one hand, the above studies mostly consider a single-period problem. Moreover, besides traditional financing decision from the bank, no more financial decisions are involved, such as short-term investments, early payment of accounts payable and the factoring of accounts receivable, etc.

Therefore, this study mainly fills up research deficiencies of the existing papers. In addition to several points mentioned above, the main differences between this study and existed papers also are showed as follows. First, this paper points out the advantages of integrated approach in the production and financial decision processes and objective function value compared to the traditional approach. In particular, this study indicates which circumstance will make the manufacturers achieve higher performance or make the integrated approach

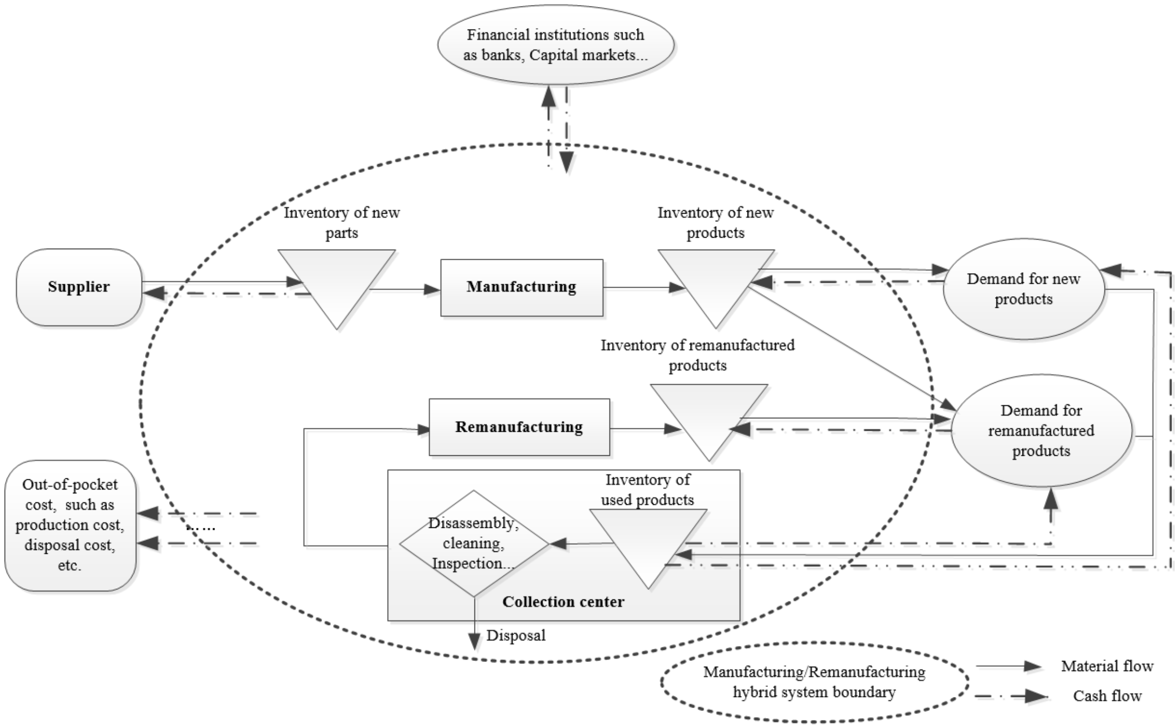

FIGURE 2. The general structure of the proposed manufacturing/remanufacturing hybrid system integrating cash flow.

show more obvious advantage. Moreover, this study conducts sensitivity analyses on some critical parameters related to integrated model, such as maximum loan amount, minimum cash balance, discount rates for factoring and early payment, and probes into effects of credit periods on the objective function value and optimal amount of working capital.

III. PROBLEM DESCRIPTION AND ASSUMPTION

A monopolistic manufacturer that produces new and remanufactured products over a multi-period planning horizon is considered in this paper. Due to the difference in product quality or consumer cognition, two kinds of products are provided to meet distinguished market demands at different prices. The general structure of the proposed manufacturing/remanufacturing hybrid system integrating cash flow is illustrated in Fig. 2.

On the operational side, the MRHS contains the forward and backward material flows. In the forward direction, the manufacturer needs to procure new parts from the suppliers, and then put on production. The new products are shipped to the markets to satisfy the customers' demands. In the backward direction, similar to [37]–[40], one type of recycling process is considered, which will not affect the results proposed in this paper. The used products from customers are shipped to collection center and stored, and then are disassembled, cleaned and inspected. It should be noted that the disassembled, cleaned and inspected cost are included in the remanufacturing cost [27], [31]. The remanufacturable returns are shipped to the remanufacturing center, and the non-remanufacturable returns are disposed and would not be processed in the following operation activities. That is, only a certain percentage of returns are suitable for remanufacturing [15], [16], [31]. Moreover, after remanufacturing activities, the remanufactured products are used to satisfy the customers' demand of the secondary market. Finally, it should be noted that the ability of responding to customer demands represents the competitiveness of the manufacturer [10], [43]. Thus, the integrated model also considers the minimum customer service levels. The proposed problem in this paper considers the following assumptions to ensure the tractability of the model developed later.

Assumption 1: The demands of new and remanufactured products are uncertain, but both of them are predictable in each scenario that could be quantified, namely, the probability of each scenario can be roughly estimated [44].

Assumption 2: There are no backorders, and the shortage cost is not considered [19], [28], [29].

Assumption 3: Since the possible quality downgrading or consumer cognitive deficiency, the remanufactured products are sold at lower price. Moreover, the downward substitution strategy for new and remanufactured products are considered in this paper [23], [24].

Assumption 4: In order to confirm the rationality of employing a remanufacturing activity, unit remanufacturing cost is lower than manufacturing cost [17], [18], [22].

Assumption 4: It is assumed that the earlier supply of new products is the only source to obtain used products, and the recovery rate is known [22], [24], [39].

Assumption 5: Infinite capacity for manufacturing, remanufacturing and disposing is assumed [28]. In addition, this paper does not consider lead times of procurement and production [19], [28].

Assumption 6: In order to avoid trivial cases and to focus on the goals of this research, the setup costs of manufacturing and remanufacturing activities are not considered [35], [36], [40].

On the financial side, firstly, the manufacturer needs to determine whether to make short-term loans and the loan amount according to the operation decisions, initial capital amount and maximum loan limit set by the bank. Meantime, it is assumed that the manufacturer must pay back the loan principal and interest in the next period. In addition, the factoring of accounts receivable is allowed to make up the capital shortage. Accordingly, the cash discount would be obtained when early the payment of accounts payable happens on the basis of the discount period and discount value as well as the capital condition. Furthermore, the manufacturer could obtain a certain amount of revenues through the short-term investments (such as marketable securities) if there exists surplus capital in each period. Without loss of generality, the return rate of the short-term investments should be lower than the current interest rate of the short-term loans. It needs to be noted that accounts receivable is mainly related to the sales of the final products, and accounts payable mainly involves in the procurement of new parts and used products. However, other costs or expenditures (such as production cost, inventory cost, loan interests, taxes) and earnings (such as investment income) are out-of-pocket. It is assumed that the fixed costs in each period (including employee-training expense, travel expense and maintenance cost) are always consistent, and the fixed asset investments in each period are also constant. Finally, this paper does not consider the acquisition and update of the fixed asset and other long-term financial decisions [44], [45].

Finally, it should be noted that the short-term horizon is set in this paper and some variable values such as the inventory, cash flows, loans at the end of the planning horizon will be the initial quantities in the next planning horizon belonging to the same long-term horizon.

IV. MODEL FORMULATION

Next, referring to [37], [38], [40], [45], a mixed integer stochastic programming model based on scenario analysis is formulated and corresponding notions are shown in **Appendix**.

A. OBJECTIVE FUNCTION

Unlike [37], [38], the integrated model considers the capital cost and selects the expected economic value- added *EVA* as the objective function as shown in Equation (1), which is equal to the difference between the net operating profit after tax *NOPAT* and total cost of the invested capital as shown in Equation (IV-A). *NOPAT* is calculated as total marginal profit TMP minus fixed cost *FC* and corresponding taxes, in which *TR* represents tax rate. The capital cost is equal to total quantity of the invested assets (including fixed assets *FA* in current period and liquid assets *LA* at the end of last period) multiplied by the minimum rate of return i^W. It should be assumed that the fixed cost *FC* and fixed assets *FA* are constant in each period [45].

$$\max \sum_{s\in S} Pr_s \cdot EVA_s \tag{1}$$

$$EVA_s = \sum_{t=1}^{T}(TMP_{s,t} - FC_t)(1-TR) - \sum_{t=1}^{T}(FA_t + LA_{s,t-1}) \cdot i^W, \quad s \in S \tag{2}$$

Total marginal profit *TMP* is equal to the sales revenue *SR* minus the variable cost *VC* in current period as shown in Equation (3). Unlike [37], [38], the new and remanufactured products are considered in the proposed model. Meanwhile, the model considers the quality differences and one-way substitution strategy between the new and remanufactured products, which is different from [39], [40]. Thus, the revenue function *SR* is equal to the total sales revenue of both product types plus the substitute revenue as shown in Equation (4). The variable cost *VC*, as shown in Equation (5), includes procurement cost (minus the cash discounts), disposal cost, production cost, storage cost and factoring loss. The costs for procurement, production and storage are calculated form respective quantities *PQ, IQ*, I^M, I^P multiplied by the corresponding unit costs *y, c*, cs^M, cs^P. The cash discount or factoring loss is derived from prepayment amount of the accounts payable *APP* or the factoring amount of the accounts receivable *AF*, and respective discount rates ψ, ϕ. Equation (6) represents the operating liquid assets *LA*, which is equal to the sum of cash position *Cash*, accounts receivable *AR*, marketable securities *AM*, inventories of inputs and products I^M, I^P evaluated with respective prices *y, x*, minus the accounts payable *AP* in current period.

$$TMP_{s,t} = SR_{s,t} - VC_{s,t}, \quad \forall s,t \tag{3}$$

$$SR_{s,t} = \sum_j x_{j,t} \cdot SQ_{j,s,t} + x_{r,t} \cdot RQ_{s,t}, \quad \forall s,t \tag{4}$$

$$\begin{aligned} VC_{s,t} = &\sum_j y_{j,t} \cdot PQ_{j,s,t} - \sum_{t\le t''\le t+\Delta p} \psi_{t,t''} \cdot APP_{s,t,t''} \\ &+ (1-\theta)cd_t \cdot PQ_{r,s,t} + \sum_j c_{j,t} \cdot IQ_{j,s,t} \\ &+ \sum_j cs^M_{j,t} \cdot I^M_{j,s,t} + \sum_j cs^P_{j,t} \cdot I^P_{j,s,t} \\ &+ \sum_{t\le t''<t+\Delta r} \phi_{t,t''} \cdot AF_{s,t,t''}, \quad \forall s,t \end{aligned} \tag{5}$$

$$\begin{aligned} LA_{s,t} = &Cash_{s,t} + AR_{s,t} + AM_{s,t} + \sum_j y_{j,t} \cdot I^M_{j,s,t} \\ &+ \sum_j x_{j,t} \cdot I^P_{j,s,t} - AP_{s,t}, \quad \forall s,t \end{aligned} \tag{6}$$

B. LOGISTICAL CONSTRAINTS

In this subsection, the constraints related to the physical domain in the manufacturing/remanufacturing operation processes are described. Equations (7) ~ (13) are associated with the balance and capacity constraints of inputs. Equation (7) shows that the inventory of new parts I^M is equal to the inventory in the previous period plus the difference between the procurement quantity PQ and the input quantity IQ. Equation (8) states that the input quantity cannot exceed the summation of inventory quantity in the previous period and procurement quantity in the current period. Unlike the new parts, there will be a certain percentage of the used products $(1\text{-}\theta)$ cannot be remanufactured because of the quality dissatisfaction, which are disposed at a cost cd. Therefore, the inventory quantity of the used products I^M is equal to the inventory quantity in the previous period plus the remanufacturable returns (the procurement quantity PQ multiplied by a remanufacturing rate θ), minus the input quantity IQ as shown in Equation (9). Equation (10) represents the input quantity IQ cannot exceed the summation of the inventory quantity in the previous period and the remanufacturable returns in the current period. In addition, the procurement quantity of the used products PQ cannot exceed the recoverable quantity AQ at the end of previous period, which covers recoverable quantity AQ in the earlier period, sale quantity of new products SQ and substitution quantity RQ in the current period, and procurement quantity of the used products PQ is deducted as shown in Equations (11) ~ (12). Equation (13) shows the inventory capacity constraint of the inputs for scenario s in period t.

$$I^M_{n,s,t} = I^M_{n,s,t-1} + PQ_{n,s,t} - IQ_{n,s,t}, \quad \forall s,t \tag{7}$$
$$IQ_{n,s,t} \le I^M_{n,s,t-1} + PQ_{n,s,t}, \quad \forall s,t \tag{8}$$
$$I^M_{r,s,t} = I^M_{r,s,t-1} + \theta \cdot PQ_{r,s,t} - IQ_{r,s,t}, \quad \forall s,t \tag{9}$$
$$IQ_{r,s,t} \le I^M_{r,s,t-1} + \theta \cdot PQ_{r,s,t}, \quad \forall s,t \tag{10}$$
$$PQ_{r,s,t} \le AQ_{s,t-1}, \quad \forall s,t \tag{11}$$
$$AQ_{s,t} = AQ_{s,t-1} + SQ_{n,s,t} + RQ_{s,t} - PQ_{r,s,t}, \quad \forall s,t \tag{12}$$
$$\sum_j I^M_{j,s,t} \le I^M_{\max}, \quad \forall s,t \tag{13}$$

Equations (14) ~ (17) are associated with the balance and capacity constraints of the final products. Two kinds of products are provided to meet distinguished market demands and have a downward substitution. Therefore, the inventory of the new products I^P is equal to the sum of inventory quantity in the previous period and production quantity IQ, minus the sum of sale quantity SQ and substitution quantity RQ in the current period as shown in Equation (14). The inventory quantity of the remanufactured products I^P is equal to the inventory quantity in the previous period plus the production quantity IQ, minus the sale quantity SQ in the current period as shown in Equation (15). Without loss of generality, the inventory of each kind of product is restricted to the non-negative domain in Equation (16). Meantime, Equation (17) shows the inventory capacity constraint of the products for scenario s in period t.

$$I^P_{n,s,t} = I^P_{n,s,t-1} + IQ_{n,s,t} - SQ_{n,s,t} - RQ_{s,t}, \quad \forall s,t \tag{14}$$
$$I^P_{r,s,t} = I^P_{r,s,t-1} + IQ_{r,s,t} - SQ_{r,s,t}, \quad \forall s,t \tag{15}$$
$$I^P_{j,s,t} \ge 0, \quad \forall j,s,t \tag{16}$$
$$\sum_j I^P_{j,s,t} \le I^P_{\max}, \quad \forall s,t \tag{17}$$

The ability of responding to customer demands represents the competitiveness of the manufacturer [10], [43]. Thus, the integrated model should also consider the minimum customer service levels σ, which is also a difference from the existing literature related to this paper. Equations (18) and (19) impose the lower and upper bounds of the supply quantities, in which the lower bounds are equal to the minimum customer service levels multiplied by actual demands. It should be pointed that the sale quantity represents the supply quantity of the new products, while the supply quantity of the remanufactured products includes both the sale quantity SQ and substitution quantity RQ. Equation (20) shows the initial inventories of the inputs and products in the entire planning horizon, and Equation (21) expresses the non-negative and integer character of some variables.

$$\sigma_n \cdot D_{n,s,t} \le SQ_{n,s,t} \le D_{n,s,t}, \quad \forall s,t \tag{18}$$
$$\sigma_r \cdot D_{r,s,t} \le SQ_{r,s,t} + RQ_{s,t} \le D_{r,s,t}, \quad \forall s,t \tag{19}$$
$$I^M_{j,s,0} = MI^0_j,\ I^P_{j,s,0} = PI^0_j, \quad \forall j,s \tag{20}$$
$$PQ_{j,s,t}, IQ_{j,s,t}, SQ_{j,s,t}, RQ_{s,t}, I^P_{j,s,t}, \quad I^M_{j,s,t} \in N \tag{21}$$

C. FINANCIAL CONSTRAINTS

The key point of the production decisions integrated the financial operations lies in the balance and coordination of the material flows and cash flows in the hybrid manufacturing/remanufacturing system, and the main reason for the link between them is that production operations will result in cash outflows and inflows for the manufacturer, such as procurement of the new parts and used products (cash outflows), sales of the new and remanufactured products (cash inflows), etc. Therefore, it is necessary to formulate an optimization model of the manufacturing/remanufacturing production decisions integrated the financial operations.

Then the constraints related to financial domain in the manufacturing/remanufacturing operation processes are described as follows. In Equation (22), the cash balance is computed based on the inflows and outflows of the cash, which covers the cash in the previous period and cash flows from the accounts receivable $Crec$, short-term investments $CInv$, short-term loans $Cloan$, operations $Cope$, accounts payable $Cpay$, taxes $Ctax$ and fixed cost FC. Equation (23) ensures the cash position in each period to be higher than a minimum value $Cash_{min}$, which is held to deal with daily expenditures or emergency events.

$$Cash_{s,t} = Cash_{s,t-1} + Crec_{s,t} + CInv_{s,t} + Cloan_{s,t} - Cope_{s,t} - Cpay_{s,t} - Ctax_{s,t} - FC_t, \quad \forall s,t \tag{22}$$

$$Cash_{s,t} \geq Cash_{\min}, \quad \forall s,t \tag{23}$$

The remanufacturer can sell accounts receivable to obtain a certain amount of the face value $(1-\phi)$, and the discount rate ϕ depends on the maturity date of the accounts receivable Δr. Without loss of generality, the closer the maturity date, the higher the discount rate, which can reduce the risk of the factors. Equation (24) shows that the cash flows from the accounts receivable *Crec* derives from the accounts receivable incurred Δr periods ago, which are due in current period (namely, sales revenue *SR*), the factoring amount between period $t-\Delta r$ and period $t-1$, and the cash inflows on account of the factoring between the period $t-\Delta r+1$ and period t. The balance of the accounts receivable *AR* is calculated from the balance of accounts receivable in the previous period plus accounts receivable due to sales revenue *SR* in the current period, minus the factoring amount *AF* between the period $t-\Delta r+1$ and period t and the amount of accounts receivable not for factoring *Arec* incurred in period $t-\Delta r$ as shown in Equation (25). The accounts receivable of each period not for factoring *Arec* is equal to the amount of accounts receivable due to sales revenue *SR* minus the factoring amount *AF* in periods t to $t+\Delta r-1$. It needs to be noted that the credit periods of the accounts receivable Δr in each period are constant, and the factoring of the accounts receivable happens only when the short-term loans are constrained because of the higher cost for the factoring.

$$\begin{aligned} Crec_{s,t} &= SR_{s,t-\Delta r} - \sum_{t-\Delta r \leq t' < t} AF_{s,t-\Delta r,t'} \\ &\quad + \sum_{t-\Delta r < t' \leq t} (1-\phi_{t',t}) AF_{s,t',t}, \quad \forall s,t \end{aligned} \tag{24}$$

$$\begin{aligned} AR_{s,t} &= AR_{s,t-1} + SR_{s,t} - (\sum_{t-\Delta r < t' \leq t} AF_{s,t',t} \\ &\quad + Arec_{s,t-\Delta r}), \quad \forall s,t \end{aligned} \tag{25}$$

$$Arec_{s,t} = SR_{s,t} - \sum_{t \leq t'' < t+\Delta r} AF_{s,t,t''}, \quad \forall s,t \tag{26}$$

Equation (27) shows the cash from the securities transactions *CInv* is computed as the principal and interest due to the investments of k-period marketable securities in period $t-k$, minus the cash outflows from the purchase of marketable securities *Invest* in period t. The balance of the marketable securities *AM* is equal to balance of the marketable securities at the end of the previous period plus the amount of marketable securities invested in the current period, and minus the amount of marketable securities matured in the current period purchased in period *t-k* as shown in Equation (28).

$$\begin{aligned} CInv_{s,t} &= \sum_k Invest_{s,t-k,k}(1+i_k^{MS}) \\ &\quad - \sum_k Invest_{s,t,k}, \quad \forall s,t \end{aligned} \tag{27}$$

$$\begin{aligned} AM_{s,t} &= AM_{s,t-1} + \sum_k Invest_{s,t,k} \\ &\quad - \sum_k Invest_{s,t-k,k}, \quad \forall s,t \end{aligned} \tag{28}$$

Equation (29) states that the cash relevant to the short-term loans *Cloan* is calculated as the cash obtained from short-term loans *SL* in the current period minus the principal with interest of the precious period considering interest rate i^r. In Equation (30), the maximum loan amount SL_{max} is expressed.

$$Cloan_{s,t} = SL_{s,t} - SL_{s,t-1}(1+i^r), \quad \forall s,t \tag{29}$$

$$SL_{s,t} \leq SL_{\max}, \quad \forall s,t \tag{30}$$

Equation (31) shows that the cash flows from production operations *Cope* mainly include expenditures for disposal, processing, and inventory in the current period.

$$\begin{aligned} Cope_{s,t} &= (1-\theta)cd_t \cdot PQ_{r,s,t} + \sum_j c_{j,t} \cdot IQ_{j,s,t} \\ &\quad + \sum_j cs_{j,t}^M \cdot I_{j,s,t}^M + \sum_j cs_{j,t}^P \cdot I_{j,s,t}^P, \quad \forall s,t \end{aligned} \tag{31}$$

The accounts payable can be paid in advance to obtain a certain cash discount of the face value ψ for the manufacturer, and the earlier the repayment period, the higher the discount rate ψ. Equation (32) shows that the cash flows from the accounts payable *Cpay* are equal to the accounts payable incurred Δp periods ago and matured in the current period (namely, procurement costs of the inputs computed from respective procurement quantities *PQ* multiplied by the corresponding unit costs *y*), minus the prepayment amounts *APP* in periods $t-\Delta p$ to $t-1$, plus the cash paid for the early payment of the accounts payable incurred between the period $t-\Delta p+1$ and period t. The balance of accounts payable *AP* is equal to the sum of the balance of accounts payable in the previous period and accounts payable due to procurement of the inputs in the current period, minus total payment of the accounts receivable incurred between the period $t-\Delta p$ and period t in the current period as shown in Equation (33). Moreover, it needs to be noted that the credit periods of the accounts payable Δp in each period are also constant.

$$\begin{aligned} Cpay_{s,t} &= (\sum_j y_{j,t-\Delta p} \cdot PQ_{j,s,t-\Delta p} - \sum_{t-\Delta p \leq t' < t} APP_{s,t-\Delta p,t'}) \\ &\quad + \sum_{t-\Delta p < t' \leq t} (1-\psi_{t',t}) APP_{s,t',t}, \quad \forall s,t \end{aligned} \tag{32}$$

$$\begin{aligned} AP_{s,t} &= AP_{s,t-1} + \sum_j y_{j,t} \cdot PQ_{j,s,t} \\ &\quad - \sum_{t-\Delta p \leq t' \leq t} APP_{s,t',t}, \quad \forall s,t \end{aligned} \tag{33}$$

Equation (34) states that the cash relevant to taxes *Ctax* is calculated from the difference between the total marginal profit *TMP* and fixed cost *FC* considering tax rate *TR*. Initial positions of financial variables are expressed in Equation (IV-C) in the entire planning horizon, and Equation (IV-C) denotes the non-negative character of some variables.

$$Ctax_{s,t} = (TMP_{s,t} - FC_t) \cdot TR, \quad \forall s,t \tag{34}$$

TABLE 2. Demand combination of new and remanufactured products.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Possibility	0.15	0.20	0.35	0.30
Demand combination	(55000,65000)	(55000,55000)	(65000,55000)	(65000,65000)

$$Cash_{s,0} = Cash_0, AR_{s,0} = AR_0, AP_{s,0} = AP_0, AM_{s,0} = AM_0, SL_{s,0} = SL_0, \quad \forall s \quad (35)$$

$$Cash_{s,t}, AR_{s,t}, AP_{s,t}, AM_{s,t}, AF_{s,t,t''}, AEP_{s,t,t''}, Invest_{s,t,k}, \quad SL_{s,t} \geq 0 \quad (36)$$

V. NUMERICAL ANALYSIS

Next, a numerical example is provided to analyze the results and advantages of the integrated model. Since real data was not available, the base parameters are designed, combined with data obtained from investigating remanufacturers in China and the actual situation in practice, to acquire realistic scenarios. The example covers a planning horizon of 18 periods with a length of three weeks each are considered. The manufacturer produces two kinds of products, which are provided to meet distinguished market demands and have a downward substitution. As mentioned above, examples of such products include personal computers, photocopiers, automotive engines and tires [1], [25]. The demands of new and remanufactured products are uncertain and are predictable in each scenario that could be quantified as shown in **Table 2** [44]. The minimum customer service levels of two kinds of products are 0.9 with the aim of better meeting the demands. In addition, new and remanufacturing products or new and used parts are stored in the same warehouse in the entire planning horizon, and the corresponding upper bound of inventory capacity is 20000 or 30000. The initial inventories of all products and inputs are 5000. Moreover, the remanufacturing rate of used products is 0.8 and the disposal cost of non-remanufacturable returns is supposed to be equal to 0.15, while the new parts can be completely used to produce. Finally, based on assumptions 3 and 4, and referring to [28] and [31], the sale price, production cost of the new products and procurement cost of the new prats are higher than those related to the remanufactured products, and the storage cost of the final products are higher than that of the raw materials as shown in **Table 3**.

TABLE 3. Parameters relevant to production operations.

	Sale price	Production cost	Procurement cost	Storage cost
New product	18.0	3.0	--	0.35
Remanufactured product	13.6	2.0	--	0.35
New part	--	--	13.0	0.25
Used product	--	--	10.0	0.25

Associated with financial aspects, the paper supposes there doesn't exist marketable securities investments in the beginning of planning horizons, and the manufacturer can invest in marketable securities of one period at return rate 0.2% or two periods at return rate 0.3%. In addition, there doesn't exist short-term loans in the beginning of planning horizons, and according to the agreement with banks, the manufacturer can obtain a certain amount of capital not more than one million (maximum allowance loan) at a 0.7% interest rate in each period. In order to avoid the manufacturer's vicious investments through the bank loans, this case sets the interest rate on loans to be higher than the return rate on the short-term investments. Similar setting can be found in [37] and [45], which is consistent with the actual situation. Then, the weighted average cost of capital (namely, minimum rate of return) can be estimated to be 0.65% according to capital assets pricing model. Furthermore, the initial cash balance is supposed to be 150000, namely the minimum cash stock. The initial balances of accounts receivable and payable are 400000 and 300000, which are maturing in the first period of entire planning horizon. Sales revenue incurred in each period will be paid with a delay of four periods (namely, credit period) and the discount rate for factoring is 4% or 4.5% when accounts receivables are sold within two periods or over three periods. Correspondingly, accounts payables on procurement of inputs have to be repaid within four periods (namely, credit period), and the discount period is two periods and discount rate is 2%. That is to say the manufacturer can obtain 2% cash discounts when early payment of accounts payable happens within two periods, or accounts payable must be repaid in full. For simplicity, this paper assumes that average balance of fixed assets is 350000 and fixed cost is about 29000 in each period.

A. COMPARATIVE ANALYSIS

The main contribution of this paper is to study production decision issues of a hybrid manufacturing/remanufacturing system integrated financial factors. Thus, it is necessary to evaluate the value of this contribution by comparing results of the integrated approach proposed in this paper and the traditional approach ignoring financial factors. Under the traditional approach, the manufacturer determines the manufacturing/remanufacturing production strategies by achieving the profit maximization, and sequentially makes financial decisions by optimizing the EVA. The models are solved by means of CPLEX 12.5 in less than three seconds using a standard PC.

Fig.3 shows the objective function values EVA of the integrated approach and traditional approach. It is found that the integrated approach improves the economic value added as much as 41.4% (450589.86 for the integrated approach and 318650.63 for the traditional approach), which indicates the superiority of the integrated approach. The main reasons are that the traditional approach incurs more loss for the factoring of the accounts receivable and obtains less cash discounts for early payment of the accounts payable, which will be explained in detail below. Therefore, although the integrated approach needs more investments of operating liquid assets,

TABLE 4. **Financial operations of traditional approach and integrated approach.**

	Amount of factoring				Amount of early payment				Investments		Loans
	t	t+1	t+2	t+3	t	t+1	t+2	t+3	t+1	t+2	
Traditional approach	4486181	0	1527187	1956487	1246366	1084299	0	0	39875	0	3577956
Integrated approach	1515615	0	0	0	0	2924640	0	0	0	0	12818685

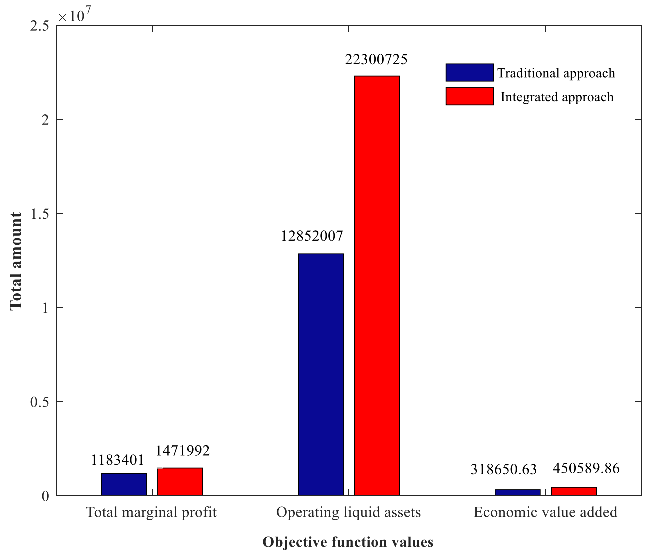

FIGURE 3. **Objective function values of traditional approach and integrated approach.**

the higher total marginal profit results in the higher economic value added.

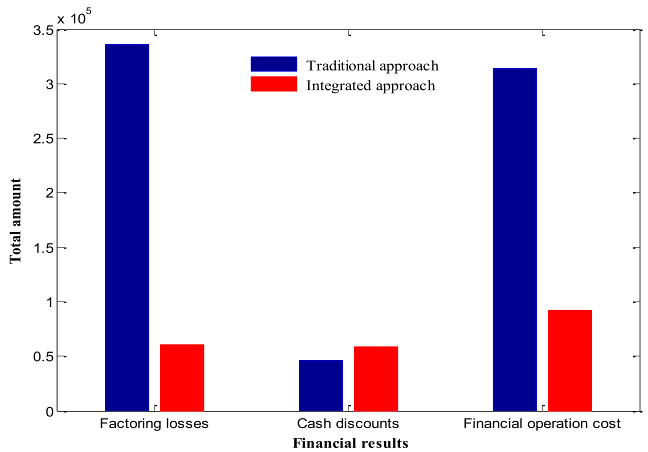

FIGURE 4. **Financial results of the traditional approach and integrated approach.**

It can be observed from **Table 4** that, one the one hand, more accounts receivables are sold to the factors for traditional approach in the entire planning horizon. On the other hand, the factoring only happens in the first period of credit periods with the lower discount rate for the integrated approach, while many accounts receivables are sold in the last two periods of credit periods with higher discount rate for the traditional approach. Thus, the factoring loss of the traditional approach (336213) are about 5.55 times that of the integrated approach (60625) in the entire planning horizon as shown in **Fig.4**. Moreover, as seen from **Table 4**, more accounts payable being repaid in advance and early payments just happen in the second period of credit periods for the integrated approach. It not only makes the manufacturer obtain more cash discounts (see **Fig.4**), but also ensures more reasonable allocation of the capital. That is to say, for the traditional approach, the earlier payments of the accounts payables are not advantageous to the capital availability and may lead to more short-term loans or sales of the accounts receivables since there exists the same discount rate within the discount period. Furthermore, the integrated approach resorts to more short-term loans to make up for the capital shortage as shown in **Table 4**, which results in the less financing cost. Therefore, the integrated approach significantly improves the efficiency of the financial operations, and the total financial operation cost (including factoring loss, cash discounts for early payment and loan interest, etc.) is apparently lower as shown in **Fig.4**.

Numerical results also show that the integrated approach has not obvious influence on total amount of each production decision variable but greatly improves the stability of production decision processes. Then, **Fig.5** and **Fig.6** describe the manufacturing and remanufacturing decisions under different demand scenarios for above two approaches to state the superiorities of the integrated approach in production decisions. As seen from **Fig.5** and **Fig.6**: (1) Manufacturing/remanufacturing quantities of the integrated approach among different periods in each demand scenario are more stable than those of the traditional approach. (IV-A) Meantime, for the integrated approach, there exists the lower differences of the manufacturing and remanufacturing quantities among different demand scenarios in each period. From the above, compared to the traditional approach, the integrated approach can better not only reduce the fluctuations of the production decisions among different periods, but also ensure the stability of the hybrid production system when the market demands are significantly fluctuant. In summary, the manufacturer is more convenient to cope with changes in the operating environment, such as the market demand and price fluctuation etc.

The downward substitution strategy is applied to avoid losses from customer goodwill for the remanufactured products when they are out of stock [10]. However, this strategy

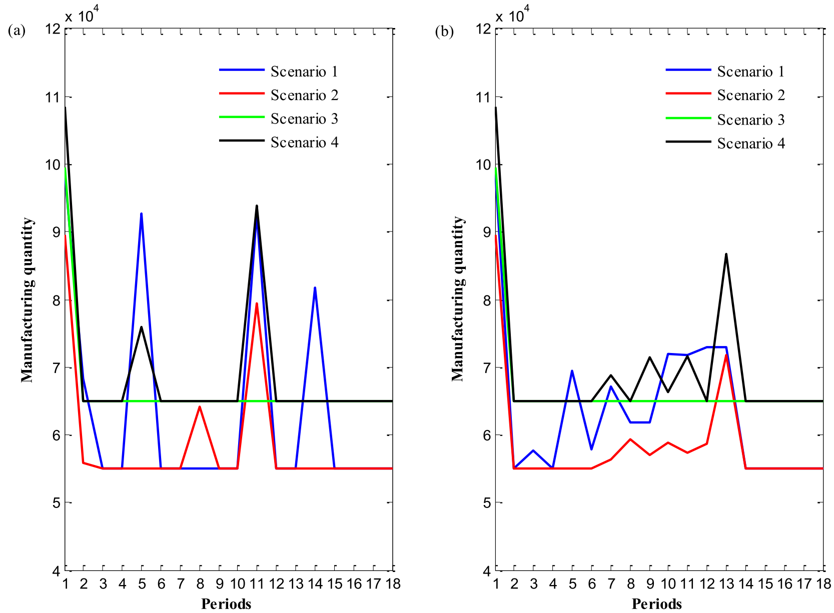

FIGURE 5. Manufacturing quantities of (a) traditional approach and (b) integrated approach.

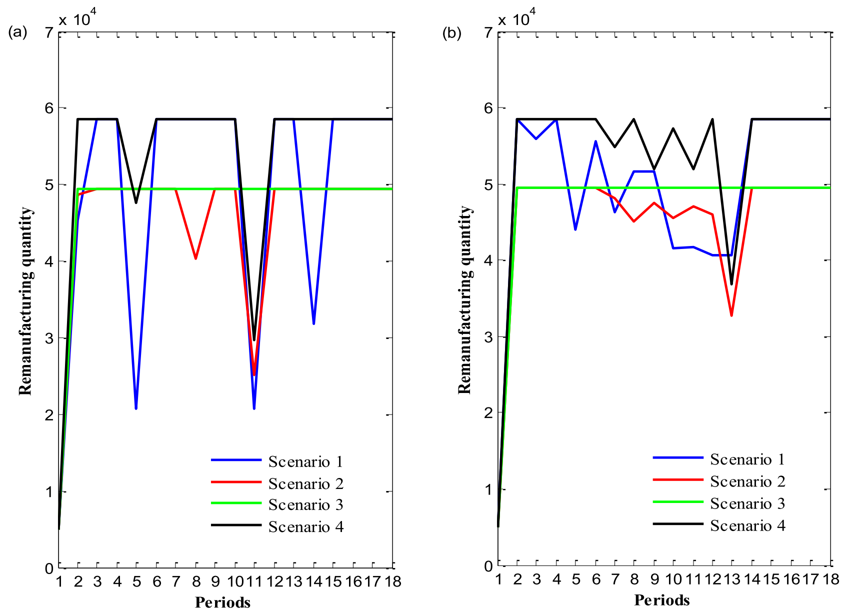

FIGURE 6. Remanufacturing quantities of (a) traditional approach and (b) integrated approach.

also reduces the total marginal profit and affects corresponding economic value added on account of the higher production cost of the new products. Meanwhile, the substitution quantity is, to a certain extent, depends on the minimum customer service level. Therefore, the varying of the minimum customer service level would have obvious influence on the function objective as shown in **Table 5**. As seen from **Table 5**, the objective function values of above two approaches are reducing with the increase of the minimum customer service level. The main reason, as interpreted above, is that the higher minimum customer service level will increase the substitution quantity when the remanufactured products are out of stock. Then, the increments of the recoverable quantity of the used products encourage the manufacturer to procure more used products and produce more remanufactured products. Moreover, the higher input cost enforces the manufacturer to sell

TABLE 5. Effects of minimum customer service level on objective function values of traditional approach and integrated approach.

Minimum customer service level	Economic value added		Gap	
	Traditional approach	Integrated approach	Absolute value	Percentage (%)
0.80	431402.40	572039.58	140637.18	32.60%
0.85	384693.25	520419.96	135726.71	35.28%
0.90	318650.63	450589.86	131939.23	41.40%
0.95	262307.45	380739.28	118431.82	45.15%
1.00	209124.92	310759.62	101634.71	48.60%

more accounts receivable and reduces the early payments of the accounts payable, which will greatly improve the total variable cost. Therefore, the increase of the substitution loss and total variable cost severely decrease the total marginal profit, and eventually result in the lower objective function values. It can also be observed from **Table 5** that although the difference of the objective function values under above two approaches is decreasing, the incremental percentage is increasing with the rising of the minimum customer service level. It indicates that the advantage of the integrated approach is more prominent when the manufacturer intends to provide the higher service levels to customers. In summary, the integrated approach can bring the higher operating performance if customers attach more importance to the service level. This is mainly because the manufacturer can ensure more adequate supply of the products to reduce loss from customer goodwill, which is consistent with the downward substitution strategy.

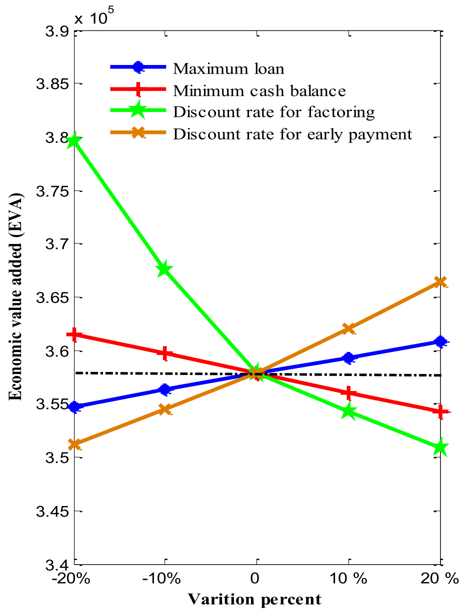

FIGURE 7. Results of sensitivity analysis.

B. SENSITIVITY ANALYSIS

In this subsection, sensitivity analyses on some critical parameters of integrated model are conducted. Firstly, the study begins by varying four parameters, such as the effects of maximum loan amount SL_{max}, minimum cash balance $Cash_{min}$, discount rate for factoring ϕ and discount rate for early payment ψ, in the ranges of $\pm 10\%$ to $\pm 20\%$ to explore the way in which the optimal objective functions change as shown in **Fig.7**. The discount rate for factoring ϕ shows the greatest effect and is negatively correlated with the expected EVA. The reasonable explanation for this is that the increasing of discount rate ϕ results in the higher total variable cost and thus directly reduces total marginal profit, and ultimately induces the decreasing of the expected EVA. As previously mentioned, there exists differential discount rates for the factoring when accounts receivables are sold within different periods. Then, shortening receivables days can not only cut down factoring loss, but also improve the capital utilization efficiency. Similarly, the expected EVA also has a negative correlation with the minimum cash balance $Cash_{min}$. A possible explanation for this is that, on the one hand, the higher minimum cash balance $Cash_{min}$ enforces the manufacturer to have to hold more cash and then leads to the increase of the operating liquid assets. On the other hand, more cash holdings may increase the factoring amount of accounts receivable and induce the higher total variable cost. Therefore, the operating liquid assets increase while total marginal profit decreases and eventually the expected EVA reduces.

Conversely, the discount rate for early payment ψ and maximum loan amount *SLmax* are positively correlated with the expected EVA. The former has more significant effect, which is because a large number of accounts payable happen in the entire planning horizon, and thus the changing in discount rate ψ will directly increase the total marginal profit and expected EVA. Finally, the increment of the maximum loan amount SLmax will result in the lower financing cost. Therefore, a relaxation of the upper bound of the short-term loan SLmax increases the expected EVA.

In the following, this paper analyzes the effects of the credit periods of accounts receivable Δr and accounts payable Δp by varying them with ranges from 1 to 7 on the optimal amount of working capital (operating liquid asset LA minus short-term loans SL) and expected EVA as shown in Fig.8. With the decrease of Δr or the increase of Δp, the change trend of the optimal amount of working capital is rising. Meantime, from a general viewpoint, the varying of Δp has more significant impact on the optimal amount of working capital. The main reason is that the changing in Δp induces the similar tendencies of the operating liquid asset and short-term loans change, while the changing in Δp makes the operating liquid asset and short-term loans have inverse change trends. In addition, as shown in Fig.8, the credit periods of accounts receivable Δr and accounts payable Δp are negatively and positively correlated with the expected EVA, respectively. It is also found that the increasing in the expected EVA caused by the longer Δp is higher than the decreasing caused by the longer Δr on the whole. Therefore, although the longer Δr can improve sales revenue and reduce working capital pressure, it severely restricts value enhancement for the manufacturer, and there exists reverse effects for Δp.

VI. MANAGERIAL INSIGHTS

This study provides important managerial insights for manufacturers. On the one hand, although the main purpose of this study is not to develop a comprehensive operations indicator set, according to the provided literature, this paper indicates the significance of financial indicators and suggests that manufacturers should consider financial constraints, operations or objectives in addition to non-financial indicators to make production operation decisions. To support this viewpoint, the methodology developed in the paper puts forward integrated

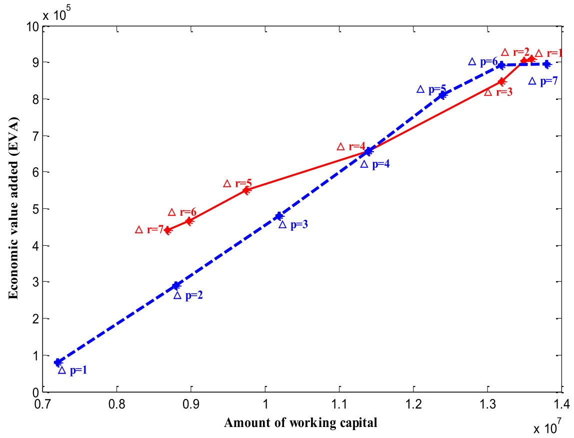

FIGURE 8. Effects of credit periods Δr, Δp on the optimal amount of working capital and expected EVA.

approach by comprehensive consideration of physical and financial operations. The above mathematical modeling and numerical analysis mainly illustrate the advantages of the integrated approach proposed in this paper.

The analyses and results indicate that the integrated approach can bring the manufacturer higher EVA. In the meanwhile, it not only reduces the fluctuations of production decisions among different periods and ensures the stability of hybrid system when the market demands are volatile, but also significantly improves the efficiency of financial operations and reduces the total financial operation cost. Therefore, manufacturers could reduce operational risks in the complex environment and better ensure product supply through using the integrated approach. It should be noted that the advantage of the integrated approach is more prominent when the manufacturer intends to provide higher service levels to customers. Furthermore, although the longer credit period of accounts receivable can improve sales revenue and reduce working capital pressures, it severely restricts value enhancement for manufacturers, and there exists opposite effects for the credit period of accounts payable. Then, manufacturers should strengthen the management of working capital, especially accounts receivable and accounts payable and cash on hand in perspective of integrated operations. For the financial institutions such as banks, it is important to provide an ideal financing environment, such as higher credit limit or more innovative financing instruments and policies support, which can promote the development of manufacturers.

VII. CONCLUSIONS AND FUTURE RESEARCH

This paper puts forward a mixed integer stochastic programming model integrating physical and financial operations based on scenario analysis, which takes the downward substitution between new and remanufactured products into account and selects financial performance indicator, i.e. economic value added, as the optimal objective function. Meanwhile, a numerical example is provided to points out the advantages of the integrated approach in the decision processes and results compared to traditional approach. In addition, sensitivity analyses on some critical parameters of the integrated model are conducted.

Our results suggest that the integrated approach can simultaneously improve the production and financial operations, and ultimately enhance the performance of the manufacturers compared to the traditional approach. In addition, this study also reveals the circumstances under which the manufacturers can achieve higher performance or the advantages of the integrated approach will be more obvious. Finally, this study also generates valuable managerial insights to the related manufacturers and financial institutions such as banks.

The essential future work needed to expand this study is centered on two areas described as follows. Because of the complexity of the model, lead times of production and procurement decisions are not considered, future research should try to integrate these factors and time value of capital to study manufacturing/remanufacturing production decision problems. In addition, regarding financial operations, the consideration of other related factors and constraints (such as the penalty cost of delayed payment, the minimum loan amount), and long-term decision variables (such as acquisition and sale of fixed assets, stock issues and long-term loans) in the integrated model can be another future research direction.

APPENDIX

INDICES

j types of inputs and products, $j \in \{n,r\}$
s scenarios, $s \in S$
t periods, $t = 1, \ldots, T$

PARAMETERS

θ remanufacturing rate of used products
σ_j minimum customer service level of j type of product
Δp maximum delay in accounts payable
Δr maximum delay in accounts receivable
$\psi_{t,t''}$ discount rate when early payment of accounts payable occurring in period t is proceeded in period t''
$\phi_{t,t''}$ discount rate when factoring of accounts receivable occurring in period t is proceeded in period t''
AM_0 initial position in marketable securities
AP_0 initial position in accounts payable
AQ_0 initial recoverable quantity of used product
AR_0 initial position in accounts receivable
$Cash_0$ initial position in cash
$Cash_{min}$ minimum cash balance in each period
cd_t disposal cost of used product in period t
$c_{j,t}$ production cost of j type of product in period t
$cs^M_{j,t}$ storage cost of j type of input in period t
$cs^P_{j,t}$ storage cost of j type of product in period t
$D_{j,s,t}$ demand for j type of product for scenario s in period t

FA_t	investment quantity of fixed asset in period t
FC_t	fixed cost in period t
$I_{j,0}^M$	initial inventory quantity of j type of input
I_{max}^M	maximum storage capacity of two types of inputs in each period
$I_{j,0}^P$	initial inventory quantity of j type of product
I_{max}^P	maximum storage capacity of two types of products in each period
i_k^{MS}	return rate of marketable securities of k periods
i^r	interest rate of short-term loans
i^W	minimum rate of return, namely, weighted average cost of capital
MI_j^0	initial inventory quantity of j type of input
PI_j^0	initial inventory quantity of j type of product
Pr_s	probability of scenario s
SL_0	initial position in short-term loans
SL_{max}	maximum loan amount
TR	tax rate
$x_{j,t}$	sale price of j type of product in period t
$y_{j,t}$	procurement price j type of product in period t

DECISION VARIABLES

$APP_{s,t,t''}$	amount of early payment in period t'' on accounts payable incurred in period t for scenario s
$AF_{s,t,t''}$	amount of factoring in period t'' on accounts receivable incurred in period t for scenario s
$AM_{s,t}$	position in marketable securities for scenario s in period t
$AP_{s,t}$	position in accounts payable for scenario s in period t
$AR_{s,t}$	position in accounts receivable for scenario s in period t
$Cash_{s,t}$	position in cash for scenario s in period t
$Invest_{s,t,k}$	amount of investments in marketable securities of k periods for scenario s in period t
$I_{j,s,t}^M$	inventory quantity of j type of input for scenario s in period t
$I_{j,s,t}^P$	inventory quantity of j type of product for scenario s in period t
$IQ_{j,s,t}$	production quantity of j type of input for scenario s in period t
$PQ_{j,s,t}$	procurement quantity of j type of input for scenario s in period t
$RQ_{s,t}$	substitution quantity for scenario s in period t
$SL_{s,t}$	amount of short-term loans for scenario s in period t
$SQ_{j,s,t}$	sale quantity of j type of product for scenario s in period t

AUXILIARY VARIABLES

$AQ_{s,t}$	recoverable quantity of used product for scenario s in period t
$Arec_{s,t}$	amount of accounts receivable not for factoring incurred in period t for scenario s
$LA_{s,t}$	amount of operating liquid assets for scenario s in period t
$CInv_{s,t}$	cash flow related to marketable securities for scenario s in period t
$Cloan_{s,t}$	cash flow related to short-term loans for scenario s in period t
$Cope_{s,t}$	cash flow related to operation cost for scenario s in period t
$Cpay_{s,t}$	cash flow related to accounts payable for scenario s in period t
$Crec_{s,t}$	cash flow related to accounts receivable for scenario s in period t
$Ctax_{s,t}$	cash flow related to tax for scenario s in period t
EVA_s	economic value added for scenario s
$SR_{s,t}$	sale revenue for scenario s in period t
$TMP_{s,t}$	total marginal profit for scenario s in period t
$VC_{s,t}$	variable cost for scenario s in period t

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this article, and it is the original research that has not been published previously, and not under consideration for publication elsewhere.

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