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An Optimal Control Approach for Additive Manufacturing Production with Waste Recycling Process

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Abstract— **Economic damage due to the supply chain turmoil in the past few years has been more severe than the pandemic, labor shortages, and domestic conflict combined. The primary cause of such a crisis is that the current supply chain analysis tool, relying heavily on static optimization, is insensitive to non-eligible changes such as policy changes due to the pandemic. As a result, such analysis needs to be conducted regularly whenever there is a change in the economic environment, which dramatically increases the computational cost. In this paper, the main purpose is to achieve agile sustainability supply chain management through dynamic system modeling and control for production processes of supply chain networks (SCNs), which involves both theoretical and numerical analysis. In particular, we first formulated a chain-like dynamic system to represent the daily production process, which is a discrete-time dynamic system from the control engineering perspective. Then, an optimal control problem can be developed for decision-making on production. Several numerical cases are presented in this paper to demonstrate the applicability of this developed dynamic system and further discuss the potential optimal production.**

I. INTRODUCTION

Large-scale complex dynamic networks are prevalent in nature, human society, and even engineering infrastructures on different scales [1]–[3]. Among them, supply chain networks (SCNs), which businesses use to produce and distribute goods and services to customers, have drawn increasing concerns [4]–[7]. It gives rise to the idea of supply chain management (SCM) [8], [9], namely, the management of multiple relationships across the supply chain, that focuses on improving the overall efficiency and benefits of supply chains [10], [11]. The term "SCM", which started along the lines of physical distribution and transport [12] based on the theory of industrial dynamics, has been used in various perspectives on SCNs [13], [14] - to explain the logistics activities for planning and control of materials and information flows internally within a company or externally between companies [15], to describe inter-organizational issues [16], to discuss an alternative organizational form to vertical integration [17], [18], to identify and describe the relationship a company develops with its suppliers [19], [20], and to address the purchasing and supply perspective [21], [22].

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Supply chain turmoil, which is the most severe challenge of SCM under the pandemic, has gained increasing interest due to the current environment and policy restrictions [23], such as, but not limited to, geopolitical instability, labor shortages, and domestic conflict. Before the pandemic, cost reduction and productivity enhancement drove supply chain process improvements, digitization, and investment, whereas many businesses found they could no longer meet customer expectations with those SCM drivers. McKinsey Global Institute highlighted the vulnerability of manufacturers by showing supply-chain-disruption losses, which presents 42% of one-year earnings before interest, taxes, depreciation, and amortization on average over a decade [24]. Probably the most obvious to many of us, was the unprecedented pressures on global supply chains created by the COVID pandemic and the subsequent series of lock-downs and restrictions which varied in their timing and severity from country to country. This unprecedented chaos threatened the competitive position - even the survival - of many businesses, which has forced companies to shift the focus of innovation and restructuring efforts to ensure business continuity by building resiliency and flexibility. Companies must develop more sustainable supply chain practices - business as usual is simply no longer an option if a sustainable future is to be achieved. The big question is how all this complexity can be handled, particularly in terms of design, planning, and execution [25], [26], which is still in its early stages [27]. Successful supply chain management requires cross-functional integration where planning must play a critical role. In this paper, we focus on establishing the preliminary operation planning on producing strategies, assuming issues in aspects such as cash flow, quality control, pricing, and accountability, have been addressed by currently available methods [28].

An accurate understanding of the dynamic nature of SCNs, especially the producing process, is the foundation of SCM and hence the key to its smart management to achieve sustainability [29]–[31]. Therefore, extracting the dynamics of such a SCN is an essential, but challenging, step that utilizes mathematical analysis and the resulting decision-making process. Recently developed computational tools [32]–[34], have explored this class of problems from different perspectives to improve the efficiency of SCM, many of which focus either on the robustness for large-scale optimizations [33] or on the non-dominating stochasticness of SCNs [34]. Yet very few methods account for the vulnerability when there are non-negligible changes in the business environment and policies, which directly leads to choked ports, out-of-place shipping containers, and record freight rates. With the pandemic restrictions remaining an issue and supply chains continuing to evolve, an efficient tool that quantitatively models the dynamic of SCNs, particularly for the producing process, and hence provides change-sensitive supply chain management with dynamic planning is desperately in demand [35].

To initiate the research on developing such a dynamic system, we first focus on the SCM of a local SCN – additive manufacturing (AM) SCN with waste recycling process. AM, which refers to 3D printing (i.e., the process of depositing materials layer-by-layer from 3D model data), can offer a higher level of design flexibility, enhanced manufacturing complexity and capability, faster production, and lower production cost. With these advantages, AM technologies have been adopted in a wide range of industries such as architecture, medical, aerospace, and automotive, making its global market estimated to increase by 13% from 2009 to 2024. With the global AM market, especially the polymer-based AM market, rapidly growing, potential sustainability issues caused by AM polymer waste need to be evaluated, which lays the foundation of SCM to achieve sustainable supply chains [36]. In current literature, the system-level studies on AM waste recycling are mainly focused on the evaluation of life cycle environmental impact, yet the optimal strategy of the supply chain for AM waste recycling remains unexplored [37], [38]. To close this gap in understanding the economic and social impacts caused by AM waste recycling and improving the overall performance of AM waste recycling supply chain, strategies such as optimal daily production and optimal delivery route play dominant roles. The development of the dynamic model will be presented in this paper to enable the discussion of the optimal daily production decisions from the business providers' perspective, which will lay the foundation for future discussion on the delivery route design.

An AM waste recycling supply chain embedded with waste pickup and recycled feed-stock delivery routes will be examined to validate the reliability and applicability of the proposed work. Built upon the integrated production-inventory-transportation (PIT) structure [36] quantifying the overall costs and greenhouse gas emissions, an optimization control problem will be formulated to obtain the fastest, most cost-effective scenario that meets customers' requirements. Contradict to the typical first-order-first-delivery (FOFD) scheme, a numerical algorithm that can interpret the AM waste pickup information and categorize the AM waste for reuse will be processed by solving a nonlinear constrained optimization problem with all requests' information being considered, e.g., service area, customer density, and material characterization complexity, etc. This further enables later discussions on the multi-layer framework combining both AM waste recycled feedstock delivery and AM waste pickup. The possible future outcome of this project is its implementation to other supply chain networks in providing straightforward technical assistance to local small businesses involving SCNs, and thus further help create a sustainable environment for local green manufacturing businesses.

In this paper, we first interpolate the dynamic nature of the producing process of AM supply chain and formulate a chain-like dynamic system to represent the daily production process, which is a discrete-time dynamic system from the control engineering perspective. Then, an optimal control problem can be developed for decision-making on production. Several numerical cases are presented in this paper to demonstrate the applicability of this developed dynamic system and further discuss the potential optimal production.

II. A Mathematical Dynamic Model to Achieve Agile Reaction for Production Management

A fundamental step for dynamic network modeling of the producing process is establishing an easy-to-track but representative mathematical model that can capture features for real-time decision-making, such as order information, materials/capacity limits, etc. First, for a business provider, a discrete-time chain-like dynamic system is introduced to incorporate all customers' order information on product demands and waste pickup requests, which provides a day-to-day tracking of the warehouse inventories, as illustrated in Fig. 1, for both production and waste materials. Then, a constrained control problem can be formulated based on this discrete-time model to solve for optimal production strategy with agile reaction.

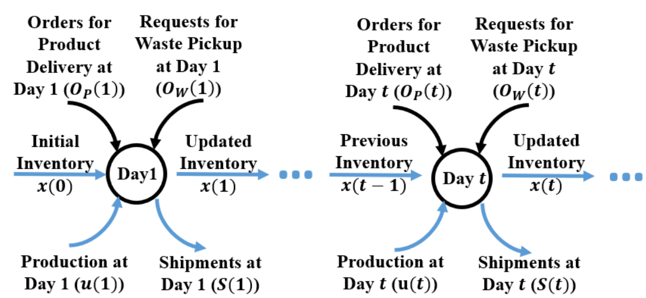


Fig. 1. Illustration of the discrete-time chain model with the inventory flow illustrated in blue.

From the system engineering point of view, a dynamic discrete-time chain model can be employed here to describe the inventory flow from day to day, month to month, with all customers' order information on product demands $O_P(t)$ and waste pickup $O_W(t)$ requests interpreted as time-varying data. Fig. 1 describes the formulation of this discrete-time dynamic system, where the daily inventory for each category of material waste and product will be denoted as the state variable of interest, i.e., $x(t)$ at day t, $t = 0, 1, \cdots, T$. Hence, the evolution of the inventory can be expressed as the following discrete-time time-varying dynamic system,

$$x(t+1) = f(x(t)) + g(u(t)) - h(S(t)), \qquad (1)$$

where f, g, and h functions measure the impact of inventory $x(t)$, production $u(t)$, and shipment $S(t)$ to the next-day inventory, respectively. Our ultimate goal is to obtain equation (1), that is, revealing the functional forms [39] of f, g, and h from data collected through survey and collaboration. For now, it suffices to first start with the simplest model, where all f, g, and h functions are linear, that is,

$$x(t+1) = Ax(t) + Bu(t) - CS(t), \quad (2)$$

where A, B, C are constant matrices, $S(t)$ records the order information characterized for day t based on the specified delivery time, and $u(t)$ denotes our daily usage for each type of materials due to daily production that will be determined in an optimal manner.

Here, we consider the AM production for four types of materials, i.e., brand-new, second-hand, third-time, and four-time, with the respective produce rate per unit material denoted as μ_i, $i = 1,2,3,4$. And we consider three types of delivery requests - regular delivery requests that are to be fulfilled within a week, speed delivery requests that are to be fulfilled within three days, and next-day delivery requests that, namely, are to be fulfilled by the next day. Here, $S(t) = \sum_j S_j(t)$ records the daily shipment, to all jth customers, required for day t to meet all delivery time requests including next-day $\sum_i O_{(\text{next-day},i)}(t-1)$, speed $\sum_i O_{(\text{speed},i)}(t-2)$, and regular $\sum_i O_{(\text{regular},i)}(t-6)$. And $u(t) = \sum_i u_i(t)$ denotes our daily production, with $u_i(t)$ characterizing the production for company i on day t. With these assumptions, equation (2) can be modeled by $S(t) \in \mathbb{R}^8$, $u(t) \in \mathbb{R}^4$, $A = I_8 \in \mathbb{R}^{8\times 8}$,

$$B = \begin{bmatrix} \mu_1 & 0 & 0 & 0 \\ 0 & \mu_2 & 0 & 0 \\ 0 & 0 & \mu_3 & 0 \\ 0 & 0 & 0 & \mu_4 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \in \mathbb{R}^{8\times 4},$$

and $C = \text{diag}[1,1,1,1,-1,-1,-1,-1] \in \mathbb{R}^{8\times 8}$.

III. An Optimal Control Problem for AM Production with Recycling

In this section, a constrained optimal control problem based on the dynamic model (1) (or (2)), is developed to obtain the best daily production strategy for agile reaction to changes in demand and policies, with the major objectives to (i) keep track of the daily inventory; (ii) meet all customers' requests with different levels of emergency; and (iii) maximize the utility of the production in terms of energy cost, producing time, etc.

The inequality constraints are constructed by the fact that the inventory is restricted to practical needs such as the capacity and actual demand of the customers' orders. This becomes inequalities posted to the state variable $x(t)$ and targeted input $u(t)$, i.e., $x_{\text{lower}} \le Dx(t) \le x_{\text{upper}}$ and $u_{\text{lower}} \le Eu(t) \le u_{\text{upper}}$, respectively. In particular, $x(t) \ge 0$ and $u(t) \ge 0$ are set to guarantee that all customers' orders can be fulfilled and taken care of; the total warehouse capacity for the product and waste materials can be expressed in the form of inequality $Dx(t) \le x_{\text{upper}}$, with $D = [1,1,1,1,1,1,1,1]$ and $x_{\text{upper}} = \text{CapIn}$ (CapIn denotes the warehouse storage capacity) being constant matrices; the maximum productivity due to labor and machine can be expressed as an inequality $Eu(t) \le u_{\text{upper}}$, with $E = [\delta_1\mu_1, \delta_2\mu_2, \delta_3\mu_3, \delta_4\mu_4, 0,0,0,0]$ and $u_{\text{upper}} = \max_t$ (δ_i denotes for the respective manufacturing time) being constant matrices, etc.

As for the total manufacturing cost $TC(t)$ of each day, from our previous study [40], [41], includes electricity cost $EC(t)$, overhead cost $OC(t)$, labor cost $LC(t)$, and material cost $MC(t)$, that is,

$$TC(t) = EC(t) + OC(t) + LC(t) + MC(t).$$

Hence, the net profit $P(x,u,t)$ is determined by the incentive $I(x,u,t)$, which is mainly due to the quantity of the fulfilled orders on that day, and the total manufacturing cost $TC(t)$, i.e.,

$$P(x,u,t) = I(x,u,t) - TC(t),$$

which can be further simplified as $P(x,u,t) = lu$ where $l \in \mathbb{R}^{1\times 4}$ denotes the overall net profit for each material type.

Now, our goal is to come up with an optimal $u(t)$ such that the total net profit $P(x,u,T)$ is optimized, which is directly determined by the day-to-day inventory and production limitations that involve costs such as electricity, overhead, labor, and material:

$$\begin{aligned} &\max_u P(x,u,T) \quad (3)\\ &\text{s.t. } x(t+1) = Ax(t) + Bu(t) - CS(t),\\ &\qquad x(t) \ge 0, u(t) \ge 0, Dx(t) \le x_{\text{upper}}, Eu(t) \le u_{\text{upper}}. \end{aligned}$$

With the well-quantified model (2), this constrained optimal control problem (3) can be tackled by implementing our recent work on learning controls [42], [43], where the necessary condition for the optimal solution, supported by Pontryagon's Maximum Principle [44], will be used to provide hints to search for possible scenarios for daily production. From Pontryagon's Maximum Principle, we define the Hamiltonian associated to this problem as:

$$H(x,u,t) = lu + \lambda'(Ax + Bu - CS), \quad (4)$$

(Note: λ' is Transpose of λ) where $\lambda(t) \in \mathbb{R}^8$ denotes the co-state that satisfies the following recursive law by the transversality condition:

$$\lambda(t) = A'\lambda(t+1), \qquad \lambda(T) = 0.$$

which results in $\lambda(t) \equiv 0, \forall t = 0,1,\cdots,T$. (Note: A' is Transpose of A) This unique outcome allows us to further simplify $H = lu$. Therefore, denoting the switching function $\Phi = l$, we are able to determine the daily production u as the largest possible value for each day, i.e.,

$$Dx(t) = x_{\text{upper}} \text{ and } Eu(t) = u_{\text{upper}}.$$

Note that the details of production management, including order requests, the warehouse's total capacity, overall productivity due to limited available labor and machine, emergency levels of orders, etc., should be considered thoroughly in the mathematical modeling.

IV. Numerical Case Studies

In this section, we will show the applicability of this developed model through a couple of numerical examples, where the order information was randomly generated with sparsity assumed. The following table provides a list of notations, extracted from our previous work [40], [41], used in the numerical implementation of this constructed dynamic model.

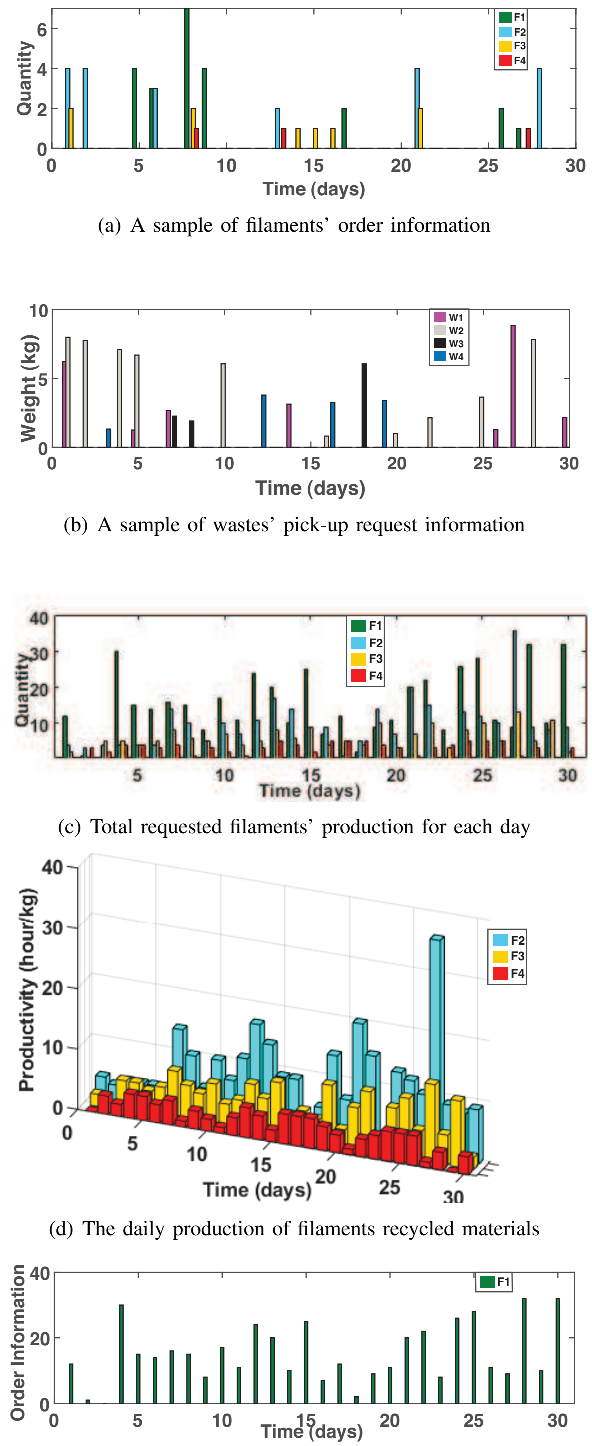
Notation	Meaning (unit)	Values
T	total time duration (day)	30
$\max_t$	maximum manufacturing time (hour)	7.5
n	number of customers (-)	20
CapIn	maximum capacity for inventory (kg)	2000
Sp	sparsity rate of orders (-)	1%
δ_i	produce time per material (hour/kg)	$\begin{bmatrix}0.0333\\0.0322\\0.0311\\0.0306\end{bmatrix}$
μ_i	produce rate per unit material (-)	$\begin{bmatrix}0.98\\0.96\\0.95\\0.93\end{bmatrix}$
l	net profit per unit production	$\begin{bmatrix}17.800\\16.527\\15.496\\14.331\end{bmatrix}$

Table I: List of model parameters

A. *With Unlimited Supply of Brand-new Materials*

We start our investigation from the simplest case, which assumes unlimited supply of brand-new materials (for filament F_1), or in other words, we could always grab brand-new materials from local suppliers. Based on the parameters set in Table I and the Pontryagon's Maximum Principle, the best producing strategy to maximize net profit $p(x,u)$ is to produce extra F_1 after completing the requested orders everyday. The reason is because that F_1 has the highest manufacturing net profit per time.

The following numerical example, shown in Fig. 2, supports this idea perfectly. Everyday, the priority is to produce the requested quantity of F_2, F_3, F_4 to fulfilled the orders, and then focus on producing as many F_1's as possible – not only meets the order requests, but also produce extra filaments and store for future to maximize the potential productivity. Fig. 2(a) and 2(b) illustrates the order information we may receive from our customers, respectively. Hence, the total requested production requested by our customers can be obtained by simply combining every customer's order information, as shown in 2(c). With this total production requests for filaments implemented as the data in our model, that is, the shipment information $S(t)$ in the dynamic model (2), we can then solve the associated constrained optimal control problem 3 and obtain the best daily production from the geometric optimal control theory. Among those, we discovered that the decision on F_2, F_3, F_4's daily production was just to fulfilled the orders, where as the production of F_1 was way more than requests. This phenomenon matches with the assumption to maximize the overall potential productivity



(a) A sample of filaments' order information

(b) A sample of wastes' pick-up request information

(c) Total requested filaments' production for each day

(d) The daily production of filaments recycled materials

(e) The daily production of filaments with brand-new materials

Fig. 2. (a) A sample of the order request for filaments production from customers, for which we assume the sparsity rate of placing orders for each kind is 1%. (b) A sample of wastes pick-up request from our customers, with the unit being kilograms. (c) The decision on daily production of filaments with recycled materials, obtained from the geometric optimal control theory, that meets the total filaments production requests. (e) The daily production of filament F_1 that not only fulfills the order.

in dollar values, since the filament of brand-new materials, e.g., F_1, is with the greatest net profit per time.

B. With Limited Local Supply of Brand-new Materials

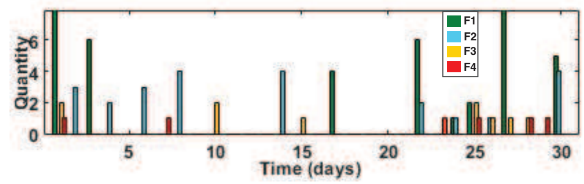
However, the assumption that the brand-new materials W_1 is unlimited may be too ideal, especially for small business providers. At least, urgent demand of W_1 may result in material price increase, even net profit being zero. So we further modified our model with limited local supply of materials of all kinds, including the brand-new type. To incorporate this, another inequality interpreting the material restriction needs to be in place, and the decisions on daily production need to be adjusted accordingly since the admissible domain for such a control changed due to this extra inequality.

Here is another numerical example, under the assumption that we may only have limited resources for materials, from a small business provider's perspective, shown in Fig. 3. The priority is to produce the requested quantity of F_1, F_2, F_3, F_4 to fulfilled all the orders. Then, based on the current warehouse storage of all materials W_1, W_2, W_3, W_4, decisions are made to maximize the total net profit, with limited time and limited capacity. Fig. 3(a) and 3(b) illustrates the order information we may receive from our customers, respectively, which are similar compared to those in Fig.2. As a result, the total requested production requested by our customers is shown in 2(c). Similar as in the unlimited case, Fig. 2, we can then solve the associated constrained optimal control problem 3. The only difference is that we have one more inequality condition posted on the material availability. The best daily production can be obtained from the geometric optimal control theory. We discovered that the decision on F_1, F_2, F_3, F_4's daily production all greater than just fulfilling the orders. Moreover, there is a hierarchy in production – first manufacture F_1 until we use up all available materials and then go for the second best option, producing F_2, and so on so forth – this phenomenon matches with the assumption to maximize the overall potential productivity in dollar values as well.

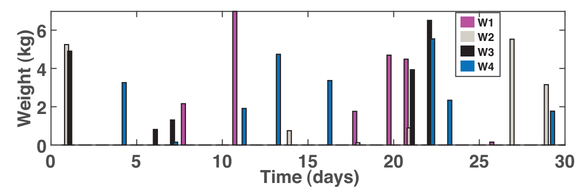
V. Conclusions

In this paper, we initiated the research on supply chain management and, for the first time ever, modeled it as a discrete-time dynamic system. This modeling enabled us to further explore the best production scenario from the optimal control approach. A preliminary study on the simplified linear dynamic system for AM supply chain with recycling process was included here, with several numerical cases demonstrating the applicability of this developed model. Future discussions may involve more delivery request scenarios, more detailed classification of product/waste type and quality, penalties for possible late delivery or defective product, etc. Details such as the preference for material types, net profit of products made of recycled materials, etc., will need to be carefully examined since they are influential for the decision of production strategy.

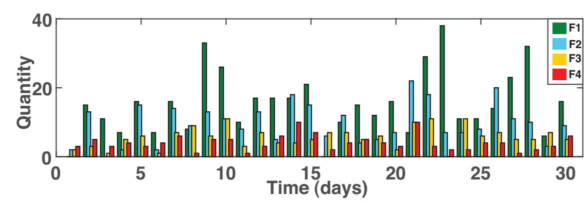
We plan to extend this work for a more generalized framework involving a nonlinear dynamic system. A key challenge here is the sensitivity of the f, g, and h functions to environment features including the pricing, competition with other suppliers in the industry, policies, etc., which may



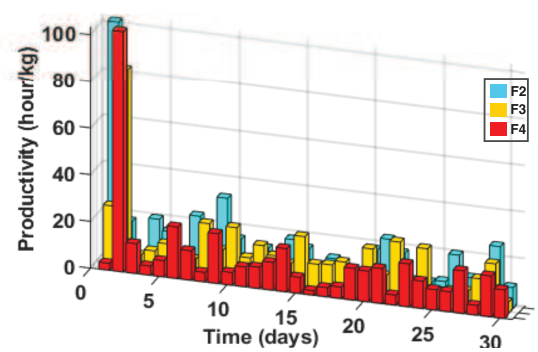
(a) A sample of filaments' order information



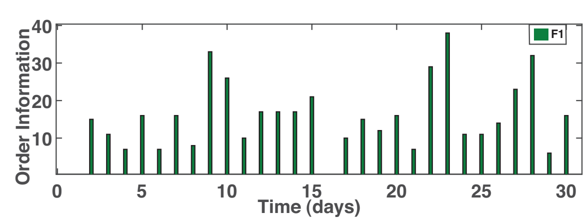
(b) A sample of wastes' pick-up request information



(c) Total requested filaments' production for each day



(d) The daily production of filaments recycled materials



(e) The daily production of filaments with brand-new materials

Fig. 3. (a) A sample of the order request for filaments production from customers, for which we still assume the sparsity rate of placing orders for each kind is 1%. (b) A sample of wastes pick-up request from our customers, with the unit being kilograms. (c) The decision on daily production of filaments with recycled materials, obtained from the geometric optimal control theory. (e) The daily production of filament F_1.

affect the resulting production strategy greatly and hence change the inventory status. The inherent region-sensitive and application-specific properties of the targeted SCN may also require discussions and interpretations from perspectives such as virtuality, process integration, market sensitivity, and network modeling.

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