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Dynamics of assembly production flow

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HIGHLIGHTS

- We propose a model of assembly production systems.
- Parts are represented by particles transported on a tree network.
- We investigate the response of production flow against demand and supply fluctuations.
- The stock level in each segment of the systems highly depends on the fluctuations and buffer size.
- We summarize key factors to improve assembly production rate.

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ABSTRACT

Despite recent developments in management theory, maintaining a manufacturing schedule remains difficult because of production delays and fluctuations in demand and supply of materials. The response of manufacturing systems to such disruptions to dynamic behavior has been rarely studied. To capture these responses, we investigate a process that models the assembly of parts into end products. The complete assembly process is represented by a directed tree, where the smallest parts are injected at leaves and the end products are removed at the root. A discrete assembly process, represented by a node on the network, integrates parts, which are then sent to the next downstream node as a single part. The model exhibits some intriguing phenomena, including overstock cascade, phase transition in terms of demand and supply fluctuations, nonmonotonic distribution of stockout in the network, and the formation of a stockout path and stockout chains. Surprisingly, these rich phenomena result from only the nature of distributed assembly processes. From a physical perspective, these phenomena provide insight into delay dynamics and inventory distributions in large-scale manufacturing systems.

1. Introduction

The twentieth century saw industrialized societies develop with the support of organized modern manufacturing, accompanied by a rapid increase in demand and consumption of goods. Scientific management of production systems dates back to the early twentieth century [1]. After Taylor's pioneering work, innumerable studies have been undertaken to control, optimize, and predict production flow in factories [2,3]. These studies have contributed to the design and

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management of manufacturing systems. However, the description of production flows by these theories, including the queuing theory, remains unsatisfactory, especially for complex, dynamic production systems [4,5]. A pivotal factor impeding our understanding of production flows is the dynamic properties of a complex production system as a "many-body system". In general, constraints pertaining to the volume of components and the finite capacity (buffer) for each job make the system dynamics complex.

This paper proposes a physical approach – suitable for dealing with dynamic phenomena – to the complex system dynamics. We use a simple model that captures the essence of the dynamics and makes it *visible*. In the context of nonequilibrium statistical physics, the asymmetric simple exclusion process (ASEP) [6–8] has been vigorously studied as the most archetypal model of particle flow with the exclusion (blocking) effect, and nontrivial behaviors specific to nonequilibrium systems have been discussed. In addition, the connection between the queuing theory and ASEP has been reported in recent studies [9,10]. Thus, we find the intersection of studies on manufacturing systems and physics. Note that in the supply-chain management field, it is known that even a simple system can lead to highly complex behavior, including chaos [11,12] and the so-called *bullwhip effect* [13–17], which has also been investigated from a physical perspective [18–21].

Hopp and Spearman [22] attempted the idea of using a physical approach called *factory physics* to study production flow. They successfully systemized the fundamental knowledge about production systems with simple mathematics and static analyses. However, recent physical approaches using stability analyses [18–21] and the formulation presented in this paper use a dynamic treatment, and are thus beyond the scope of the factory physics concept. The main goal of the present study is to uncover and understand dynamic phenomena observed in complex manufacturing systems that are beyond intuitive prediction. For this purpose, simple models are used to identify the correlation between phenomena and causes. Different from recent similar attempts [18–21], we use a full discrete model – space, time, and inventories are discretized – to realize this approach. This enables us to understand the system at the microscopic level, disregarding relatively less important factors (e.g., input and output buffers at each job, and prediction and adaptation mechanisms), and to focus on the nature of "assembly".

In this paper, we focus on a set of jobs in a single manufacturing unit that constitutes a supply chain. Each job corresponding to materials' processing does not predict its supply and demand, but follows the state of neighboring jobs. In the absence of prediction, the bullwhip effect does not occur. The primary goal of this study is to reveal how "assembly" processes on a large production line affect the overall system. The system is perturbed by three types of fluctuations: demand fluctuations, supply fluctuations, and removal of defective products. The assembly process involves merging two or more production flows, where material provisions from these streams synchronize (couple) [23]. This significantly increases complexity when the system is under perturbations, thus making rigorous analysis of such system very challenging.

In previous studies, a set of assembly processes has been represented abstractly by a network of jobs, buffers (nodes), and topology of parts flow (links) [24,25,4,23,26]. Here, we reformulate an assembly system as an interacting particle system [6] and observe its dynamic aspects. The collective behavior of exclusive particles moving in a discrete network has received considerable attention from physicists [27–31]. However, the effect of particle coalescence (assembly) on these systems has not yet been fully understood.

The reminder of the paper is organized as follows. The focal model definition is given in the next section. To understand the model in detail, we first focus on the dynamics of a restricted parameter set (Section 3) and then consider variations in the fixed parameters (Section 4). Finally, we summarize the results and discuss the outlook of the study in Section 5.

2. Model

Consider a directed regular tree network whose indegree and outdegree are k and 1, respectively (Fig. 1). Parts (particles) are transported along links, and at each node, k different parts are assembled, generating a part for the next node. A node has a buffer of size b for each incoming part; that is, a node can contain b parts of one type at the same time. Hence, the stock status at a node is described by a set of parts for the k buffers. The network has $s \in \mathbb{N}$ assembly stages, resulting in the need for k^s raw materials. To investigate the statistical properties of large-scale production systems, we assume that k^s is large.

Basic rules of particle transportation in the system are as follows: at each time step, an assembly node sends a part to the next node if and only if all the required parts corresponding to the incoming links are stored in its buffers, and the buffer in the next node for the product the current node is creating is not full. Here, this node state is referred to as the "production state". If even one part required in the production is absent, the node does not send a part. This node state is referred to as the "stockout state". Even if the necessary materials are available, the node cannot send the product to the next node if the buffer of the next node is full. This state is referred to as the "demand-deficiency state". In this paper, these three states comprise the "operational state". Noted that, regardless of the state, each node can accept a part only if the corresponding buffer is not full. These procedures are performed in parallel at each node. Thus, the transition of a particular type of parts in a node in stage-σ ($\sigma = 2, 3, \ldots, s-1$) is summarized as follows. In the production state, the transition is -1 if the part is not provided by its upstream process; otherwise, it is ± 0. In the stockout or demand-deficiency state, the transition is ± 0 if the part is not provided by its upstream process; otherwise, it is $+1$. At stage-s (the network "leaves"), k parts are provided, each with probability $1-\epsilon_{\text{in}}$. The end product is removed at stage- 1 (the "root") with probability $1-\epsilon_{\text{out}}$. The probabilities $\epsilon_{\text{in}} \in [0, 1)$ and $\epsilon_{\text{out}} \in [0, 1)$ are the error rate of supply and demand, respectively. These rates are related to the intensity of their fluctuations.