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Synchronization emergence and its effect on performance in queueing systems

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Abstract

Synchronization as a dynamic process has found applications in many fields. However, it remains unclear how this phenomenon relates to manufacturing systems. The aim of this study is to investigate the conditions for emergence of synchronization and its effects on the wide spectrum of production logistics performance objectives. Using queueing theory as the underlying methodology for deductive modeling of manufacturing systems, we run computer simulations on networks of queueing systems and investigate synchronization measurements in relation to system parameters and performance indicators. Our initial findings suggest that different types of manufacturing systems display different synchronization behaviors and that periodically driven systems with deterministic arrival and service rates display higher synchronization in comparison to stochastic ones. Further, we show that intrinsic physics synchronization is correlated to capacity utilization, throughput times and WIP levels, suggesting the co-activity of operations is related to highly utilized systems, while external physics synchronization is anticorrelated to throughput times and WIP levels, suggesting that higher efficiencies emerge with workstation repetitive behavior.

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Keywords: synchronization; queueing theory; production system; manufacturing system design

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1. Introduction

Synchronization phenomena in nature are common, where the interaction of some systems leads to the emergence of synchronized behavior [1]. Some examples include a large population of male fireflies coordinating their flickering to attract the female counterparts cruising overhead, or the waves of synchronous clapping at the end of a theater performance. In the context of logistics, the term synchronization has been used loosely to describe the coordination of companies' activities throughout the supply chain [2] or in job shop manufacturing environments as the simultaneous scheduling of operations to aid in production planning [3]. It is also the case that measures for synchronization from other fields are adapted to the context of supply chain coordination [4] and production logistics [5,6].

A recent study derived and formalized synchronization measures for manufacturing systems and applied them to data from production companies. The results found that the emergence of synchronization can be related to negative performance in terms of due date reliability [6]. Nonetheless, there is yet no holistic understanding of the synchronization phenomena occurring in manufacturing systems. In particular, it remains unclear on what conditions synchronization emerges and how it is related to the wider spectrum of production logistics objectives. We believe that findings of the conditions for synchronization and its effect on manufacturing systems would contribute to closing the research gap and provide valuable insights for manufacturing system design or production planning and control.

The overarching goal of this paper is to gain a more profound understanding of the conditions for the emergence of synchronization in manufacturing systems and its relation to logistics performance. We use queueing theory to model manufacturing systems and study if synchronization is influenced by certain system characteristics: (1) type of manufacturing system, (2) type of arrival and service rate, and (3) workload level. Further, we investigate the relationship between synchronization and production logistics performance indicators: (1) throughput time (TTP), (2) work-in-progress (WIP) level, and (3) capacity utilization (CU). The paper is organized as follows. Section two addresses synchronization phenomena in manufacturing and presents measures for them. Section three explains the methodology used in this study. Section four presents and discusses our results. Section five provides a brief summary of the investigation, its limitations and outlook for further research.

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2. Literature Review

2.1. Synchronization in Manufacturing and Nature

Two different views of synchronization exist: flow-focused and system-focused [6]. On the one hand, the manufacturing and logistics domains embody the flow-focused view since here synchronization is seen as flow-oriented coordination of materials between systems and thus closely related to the just-in-time philosophy. In these domains synchronization is widely seen as a contributor for higher efficiency [3,7]. On the other hand, the natural sciences domain employs the system-focused view as synchronization is perceived as a dynamic process that emerges when oscillatory systems or objects adjust their rhythms as a result of a weak interaction [1].

A recent study by [6] denotes these two views as logistics and physics synchronization respectively and presents quantitative measures for them: logistics system, logistics workstation, external physics and intrinsic physics synchronization (see section 2.2). The results indicated that the logistics synchronization measures and the intrinsic physics synchronization are related to bad due date performance. Nonetheless, their study investigated neither the conditions leading to synchronization, nor the effect of synchronization on other performance indicators.

[6] suggests that different manufacturing system types exhibit varying synchronized behavior (flow shops behave differently from job shops). Besides, a study on the synchronization in railway timetables by [8] indicates that the type of arrival events in their avalanche model affects synchronization (deterministic arrival leads to higher synchronization than stochastic one). Transferring this to the manufacturing context, we hypothesize that the type of arrival and service rates has similar effects on the synchronization level of manufacturing systems. Furthermore, the workload level of manufacturing systems influences their overall behavior [9] and could thus affect synchronization emergence as well. Accordingly, we study if synchronization is influenced by (1) manufacturing system type, (2) type of arrival and service rate, and (3) workload level. Finally, even though [6] only study the effects of synchronization on due date performance, they point out that it needs to be researched if synchronization influences other performance indicators such as TTP, WIP and CU as widely assumed in literature and practice. Hence, we study synchronization in relation to these three performance indicators.

2.2. Logistics Synchronization Measures

The first measure presented in [6] quantifies logistics synchronization on a system level. Manufacturing systems are composed of highly networked material flows, therefore this measure considers network linkages. It is derived from the cross-correlation function of two time-series, which is as measure for linear synchronization [5]. It assumes that in manufacturing systems that exhibit logistics synchronization the maximum cross-correlations of the linked workstation (WS) pairs would be higher than the maximum cross-correlations of the non-linked pairs, i.e. the linked WSs within a manufacturing system are more synchronized than the non-linked ones. Below we present a summary of the derivation of [6]:

The cross-correlation of two discrete univariate time series x_i and y_i spanning over a time period $t = 1 \dots N$ is:

$$c_{x,y}(\tau) = \frac{1}{N-\tau} \sum_{t=1}^{N-\tau} \left(\frac{x_t - \bar{x}}{\sigma_x} \right) \left(\frac{y_{t+\tau} - \bar{y}}{\sigma_y} \right) \tag{1}$$

where $\bar{x}$ and σ_x denote the mean and the standard deviation of the time series, while the parameter τ is a time lag. For our purposes x_i and y_i represent the time series for the WIP levels of two WSs. The absolute value of $c_{x,y}$ is zero for no synchronization and one for perfect synchronization. Further, the maximum of the absolute value of the cross-correlation function $c^*_{x,y}$ and the derived from it logistics synchronization index on system level I_{LS} are given by:

$$c^*_{x,y} = \max_{\tau>0} |c_{x,y}(\tau)| \tag{2}$$

$$I_{LS} = \frac{\frac{1}{L} \sum_{x \to y} c^*_{x,y}}{\frac{1}{M} \sum_{i,j} c^*_{i,j}} \tag{3}$$

where $x \to y$ indicates a material flow from x to y, L is the number of linked WS pairs, and M is the total number of WS pairs. Thus, the logistics synchronization index represents the ratio of the average cross-correlation among the linked WS pairs to the average cross-correlation among all WS pairs. A z-score is used to ensure that randomness in the system configuration does not influence the resulting index so it remains comparable across systems:

$$z_{LS} = \frac{I_{LS} - \mu^{(r)}_{I_{LS}}}{\sigma^{(r)}_{I_{LS}}} \tag{4}$$

where $\mu^{(r)}_{I_{LS}}$ and $\sigma^{(r)}_{I_{LS}}$ denote the mean and standard deviation of the logistics synchronization index for a given number of random scenarios. A random scenario can be derived by shuffling the cross-correlation values $c^*_{x,y}$ randomly among WS pairs. The resulting index can then be calculated for each random scenario and allows for obtaining $\mu^{(r)}_{I_{LS}}$ and $\sigma^{(r)}_{I_{LS}}$.

The above presented index measures synchronization on a manufacturing system level. The index I^x_{LS} for a specific WS x and the corresponding z-score z^x_{LS} are given by:

$$I^x_{LS} = \frac{\frac{1}{L^x} \sum_{x \to y} c^*_{x,y}}{\frac{1}{M^x} \sum_{i,j} c^*_{x,j}} \tag{5}$$

$$z^x_{LS} = \frac{I^x_{LS} - \mu^{(r)}_{I^x_{LS}}}{\sigma^{(r)}_{I^x_{LS}}} \tag{6}$$

where M^x is the total number of WS pairs that x can be part of and L^x is the links of x.