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Understanding synchronizability of manufacturing networks: A multi-method study on structural network properties

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ABSTRACT

Manufacturing systems exhibit two types of synchronization phenomena: logistics and physics. Quantifying synchronization measures for both types have been suggested and it has been shown that both types of synchronization are correlated to the logistics performance of the manufacturing system. Previous studies have indicated that structural properties of the manufacturing network might be central influencing factors triggering synchronization emergence. Synchronizability is a network property widely studied in the complex networks field. It is a common measure to evaluate the stability of synchronization in networks based on its structural properties. The aim of this paper is to explore synchronizability in manufacturing for the first time in order to better understand the impact of structural properties of a network on the emerging synchronization phenomena. We apply a multi-method investigation by triangulating a profound literature analysis, a two-stage discrete-event simulation study and an empirical data analysis of feedback data from industrial practice. Our findings show that synchronizability relates positively to physics and negatively to logistics synchronization. Based on these findings we present first considerations towards a synchronization-oriented design and control of manufacturing systems.

1. Introduction

Synchronization phenomena from various scientific fields have been intensively studied as part of the theory of dynamical systems [1]. Two types of synchronization phenomena in manufacturing systems have been examined, logistics synchronization and physics synchronization, related to two views of synchronization: flow-focused and system-focused [2]. Within the manufacturing and logistics domain, synchronization is seen as the flow-oriented coordination of materials between systems [3] and thus closely related to the just-in-time philosophy in terms of the provision of the right components to the subsequent production steps within a manufacturing system at the right moment in time, while within the natural sciences synchronization is defined as the adjustment of rhythms of systems due to interaction [1]. Qualitatively speaking, logistics synchronization rather picks up *sequences of activity, while* physics synchronization is rather related to the systematics of *repetitive patterns* or *simultaneous activity* in time [2]. Based on real data analysis it was shown that both logistics and physics synchronization are correlated to the logistics performance of a manufacturing system in terms of its due date performance [2]. Further, a recent discrete-event simulation study has shown that both logistics and physics synchronization are related to other logistics performance measures such as throughput times, capacity utilisation and Work-In-Process levels [4].

While previous work has focused on defining these two synchronization types on developing quantifying measures for them, and on studying their relation to logistics performance, it remains unclear what triggers synchronization emergence. The first research findings suggest that the structural properties of manufacturing networks are central factors to explain the emergence of the two synchronization types [5,2,6].

Synchronizability is a network property, widely studied in the field of complex networks [7–14]. It is known for identifying the stability of synchronization in networks [7,8]. The purpose of this paper is to explore synchronizability for application in the field manufacturing networks. We aim to understand the effects of the material flow network synchronizability of different manufacturing system types on their emerging synchronization behaviour.

It has been established that each research method in the field of operations management has its advantages and disadvantages and that the choice of the research paradigm might bias the research

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results [15,16]. Consequently, combining multiple methods is suggested in order to minimize this bias and increase the external validity of the findings [17].

Based on a profound literature review on synchronization in a logistics and a physics understanding, we combine the advantages of a *Discrete-Event Simulation (DES)* and the *analysis of empirical feedback data*, derived from six production systems and covering the complete set of production orders at every work system for one year of production activities. These findings serve as starting points for first considerations for a synchronization-oriented design and control of manufacturing systems useful for production planners in order to influence the due date performance of manufacturing systems [2].

The paper proceeds as follows. Section 2 presents a brief literature review on the two synchronization types and on synchronizability. In Section 3 the research design is described. The results are subsequently presented and discussed in Sections 4 and 5 respectively. Finally, Section 6 concludes the paper and provides outlook for further research.

2. Literature review

2.1. Logistics synchronization

Logistics synchronization represents the flow-oriented coordination of materials within a manufacturing system and is thus defined as “the coupling of Work Systems (WSs) that are linked by material flows” [2]. There are two ways of measuring this phenomenon: logistics synchronization index on company and WS level respectively. The basic assumption of both measures is that WSs linked by material flows are more synchronized with each other than non-linked ones. Below we present a summary of the derivation of the two measures previously introduced by Chankov et al. [2].

The logistics synchronization measures utilise cross-correlation as a standard measure for linear synchronization [18,19]. The cross-correlation of two discrete univariate time series x_t and y_t spanning over a time period $t = 1 \ldots N$ 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 are the mean and the standard deviation of the time series, respectively, while τ is the time lag. An absolute value of one for c indicates perfect synchronization, while zero means no synchronization. In the logistics context, x_t and y_t represent the time series for the Work-In-Process (WIP) levels of two WSs.

Their cross-correlation provides information about their synchronization for a specific time lag. Obtaining a global quantification index for the whole manufacturing system requires using the maximal correlation independent of the time delay at which it occurs given by:

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

Further, logistics synchronization is present in a manufacturing system, if the maximum cross-correlations of the WS pairs linked by material flows are higher than the maximum cross-correlations of the non-linked pairs. Thus, the logistics synchronization index is given by:

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

where $x \to y$ stands for a material flow from WS x to WS 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-correlations among the linked WS pairs to the average of the cross-correlations among all WS pairs. The comparability of results across systems requires the use of a z-score:

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

where $\mu^{(R)}_{I_{LS}}$ and $\sigma^{(R)}_{I_{LS}}$denote the mean and standard deviation of the logistics synchronization index for given number of random scenarios (obtained by shuffling maximal cross-correlations values randomly among the WS pairs).

I_{LS} and z_{LS} represent logistics synchronization on company level. Using the same steps, logistics synchronization index on WS level $I^x{}_{LS}$ and a corresponding z-score $z^x{}_{LS}$ for the WS x are given by:

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

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

where L^x denotes the number of WSs that x is linked to and M^x the total number of WS pairs that x can be part of.

2.2. Physics synchronization

Physics synchronization is derived from the natural sciences domain and is defined as “the rhythm and repetitive behaviour of production processes in a manufacturing system” [2]. Previous studies have also examined physics synchronization in linear supply chain models [45,46]. There are two ways in which physics synchronization can emerge in a manufacturing system: (1) external and (2) intrinsic physics synchronization. External physics synchronization measures how ‘regular’ processes are with respect to an external clock, while intrinsic physics synchronization assesses the co-activity patterns in the network, i.e. how often a large number of WSs are simultaneously active. Below we present the quantification measures for both approaches as derived by Chankov et al. [2].

A common quantification approach for synchronization in the natural sciences is to compare the phase distributions of coupled phase oscillators representing the synchronized systems [7]. This phase synchronization can be quantified using the Kuramoto order parameter [20]. The Kuramoto order parameter requires a list of events as input for each WS such as its operation start times. These times are converted to phase values with respect to a reference time scale (or phase length ω).

The Kuramoto order parameter can be applied to manufacturing systems in two ways corresponding to the two physics synchronization types. Firstly, the external physics synchronization is calculated on a WS level and for a given phase length ω. Let $\left\{t^{(k)}_j, j = 1 \ldots T_k\right\}$ be the set of operation start times at WS k, where T_k is the total number of start events at WS k. The conversion into phases $\phi^{(k)}_j(\omega)$with a period length of ω and the derived external physics synchronization index σ_k for WS k, depending on phase length ω are given by:

$$\phi^{(k)}_j(\omega) = \frac{2\pi}{\omega}\left(t^{(k)}_j \bmod \omega\right) \tag{7}$$