Chapter 3
The Influence of Manufacturing System Characteristics on the Emergence of Logistics Synchronization: A Simulation Study

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Abstract The term "synchronization" in manufacturing refers to the provision of the right components to the subsequent production steps at the right moment in time. It is still unclear how manufacturing system characteristics impact synchronization. Thus, the purpose of this paper is to investigate the effect of manufacturing systems' characteristics on the emergence of logistics synchronization in them. We conduct a discrete-event simulation study to examine the effect of three system characteristics: (1) material flow network architecture, (2) work content variation, and (3) order arrival pattern. Our findings suggest that the material flow network architecture and the work content variation are related to logistics synchronization. Linear manufacturing systems with stable processing times such as flow shops operate at high logistics synchronization levels, while highly connected systems with high variability of processing times such as job shops exhibit lower synchronization levels.

Keywords Synchronization · Manufacturing system · Discrete-event simulation

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3.1 Introduction

Synchronization phenomena from various scientific fields have been intensively studied as part of the theory of dynamical systems (Pikovsky et al. 2003). In the context of manufacturing systems, the term "synchronization" refers to the provision of the right components to the subsequent production steps at the right moment in time. These just-in-time material flows are believed to lead to higher efficiency for manufacturing systems (Miller and Davis 1989). Previous work has focused on defining this form of logistics synchronization (Chankov et al. 2014), identifying if it occurs in job shop manufacturing environments (Becker et al. 2013) and on developing quantifying synchronization measures for it (Chankov et al. 2015). However, it remains unclear if synchronization can occur in any manufacturing system type, how manufacturing system characteristics impact synchronization and how the emergence of synchronization affects logistics performance.

The purpose of this paper is to contribute to closing this gap by investigating the effect of manufacturing systems' characteristics on the emergence of synchronization in them. We study three main system characteristics: (1) material flow network architecture, (2) work content variation, and (3) order arrival pattern. A discrete-event simulation study is applied in order to study types of manufacturing systems with diverse network architectures and varying work content distributions (line production, flow shop production, job shop production and cellular manufacturing) in order to compare the synchronization phenomena occurring in them. The paper is organized as follows. Section 3.2 presents different types of synchronization phenomena occurring in manufacturing and appropriate measures for them. Section 3.3 explains the methodology used in this study. We present and discuss our results in Sect. 3.4. Finally, Sect. 3.5 provides a brief summary of the investigation, its limitations and outlook for further research.

3.2 Synchronization in Manufacturing Systems

There are two views of synchronization: flow-focused and system-focused (Chankov et al. 2015). Within the manufacturing and logistics domain, synchronization is seen as the flow-oriented coordination of materials between systems (Wiendahl 1998) and thus closely related to the just-in-time philosophy, while within the natural science domain synchronization is defined as the adjustment of rhythms of systems due to interaction (Pikovsky et al. 2003). Chankov et al. (2015) term the two separate views logistics and physics synchronization. Based on the flow-focused view, they define logistics synchronization as "the coupling of work systems (WSs) that are linked by material flows," while physics synchronization is derived from the system-focused view as "the rhythm and repetitive behavior of production processes in a manufacturing system." In addition, they observe differences in the synchronization behavior of job shops and flow shops, and thus suggest that the type of manufacturing system influences its synchronization behavior. However, they do not examine which manufacturing system characteristics lead to those differences. Both network connectivity (Becker et al. 2012) and the variability in processing times (Bondi and Whitt 1986) have been suggested as distinctive system characteristics and found to impact manufacturing systems. Moreover, a study on the synchronization in railway timetables by Fretter et al. (2010) indicates that the type of arrival events in their avalanche model affects synchronization. Transferring this to the manufacturing context, we suggest that the order arrival pattern has similar effects on the synchronization level of manufacturing systems. Accordingly, we hypothesize that the following three manufacturing system characteristics affect the emerging in manufacturing systems synchronization: (1) material flow network architecture, (2) work content variation, and (3) order arrival pattern.

Chankov et al. (2015) suggest quantitative measures for both synchronization types. Our paper aims at understanding what triggers the emergence of logistics synchronization within manufacturing systems, therefore we only consider their logistics synchronization measure. It is based on cross-correlation, which is a standard measure of linear synchronization (Becker et al. 2013). The cross-correlation of two discrete univariate time series x_t and y_t spanning over a time period $t = 1 \ldots N$ is:

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

where $\bar{x}$ and σ_x represent the mean and the standard deviation of the time series, respectively, while the parameter τ is a time lag. Thus, a value of zero represents zero synchronization and values of ± 1 indicate perfect (anti-)correlation.

The cross-correlation of the WIP development of two work systems 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

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

Chankov et al. (2015) hypothesize that “in manufacturing systems, which exhibit logistics synchronization, the maximum cross-correlations of the linked by material flows WS pairs will be higher than the maximum cross-correlations of the non-linked pairs”. Thus, a logistics synchronization index is formulated as

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

Where $x \rightarrow y$ 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. A value of 1 for the index shows that linked WSs are equally synchronized to the non-linked ones, while values above 1 show that they are more synchronized and values below 1 that they are less synchronized than the non-linked ones. The comparability of results across systems with different characteristics requires the use of a z-score:

$$z_{LS} = \frac{I_{LS} - \mu_{I_{LS}}^{(R)}}{\sigma_{I_{LS}}^{(R)}} \tag{4}$$

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

3.3 Methodology

3.3.1 Simulation Model

Discrete-event simulation is a widely used simulation method for manufacturing systems, in which components are modeled as objects that have certain attributes representing the object states. Changes in those states are triggered by events. For manufacturing systems, the objects can be machines or workers, for example, the corresponding attributes can be the time needed for a task or the object's availability, while events can be the arrival of a new order or a machine breakdown (Kelton and Law 2000). We use discrete-event simulation because of its versatility and reliability in representing manufacturing processes.

The simulation model presented in this paper was created in FlexSim 7.3. It consists of fifty work systems that can be arranged into different manufacturing system designs (see Fig. 3.1a). Each WS is composed of a pre-process buffer, a processing machine and a post-process buffer (see Fig. 3.1b). Moreover, the transport from one WS to the next is considered to be part of the subsequent WS and is modeled with the use of a processor. Thus, the model does not involve any predetermined material flows and can be used to model manufacturing systems with diverse material flows. Besides, the model allows for utilizing different priority rules, transport modes as well as the introduction of transportation times and set up times. For matters of simplicity, for this study we have used the standard first-in-first-out (FIFO) priority rule and have kept the transport and set up times at zero.

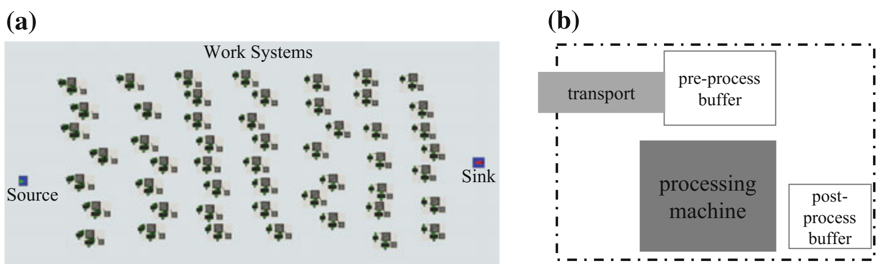

Fig. 3.1 Simulation model: **a** model overview and **b** single work system

3.3.2 Experiment Setup

To study the effect of manufacturing systems' characteristics on the emergence of synchronization, we design six cases representing different types of manufacturing systems (see Table 3.1). Although several manufacturing system classifications exist, we follow a widely used one suggested by Chryssolouris (2006), who distinguishes five manufacturing system types: flow line, cellular system, job shop, project shop, and continuous system. The first three types are different from the latter two as they represent systems in which discrete products move from WS to WS, while a project shop is used for products whose position is fixed and a continuous system produces liquids or gases. Hence, our study focuses on the first three types.

A flow line, also known as a flow shop, is a manufacturing system in which "the machines and other equipment are ordered according to the process sequences of the parts to be manufactured" (Chryssolouris 2006). Thus, a sequence of work systems is dedicated to one particular product or product family. The simplest form of a flow shop is the transfer or assembly line, which only contains a single

Table 3.1 Overview of selected manufacturing systems

No	Networks	Work systems	Orders	Operations (k)	Average operations per order
I	Line production	50	400	20	50
II	Flow shop production 1	50	2000	20	10
III	Flow shop production 2	50	2000	20	10
IV	Cellular manufacturing	15	5320	20	4
V	Job shop production 1	50	3532	20	6
VI	Job shop production 2	50	1851	20	11

sequence of WSs that take in material flow one at a time. Network I in our study represents such a flow line. It is a traditional flow shop with a single line containing 50 WSs.

More sophisticated flow shops involve not just a single sequence of machines but several ones that run in parallel, which allows for manufacturing a high volume of a limited variety of goods (Chryssolouris 2006). Flow shops can generally be organized in two fashions. The first is a pure parallel fashion, in which each line is dedicated to a different product family (Becker and Scholl 2006). The second is parallel fashion with crossovers, in which materials can be transferred from one line to another (Freiheit et al. 2004). Networks II and III represent those two flow shop types. Both have 50 WSs grouped in 5 parallel lines, but while Network II is a pure parallel flow shop, network III allows crossovers at all stages.

Further, a cellular system is similar to a parallel flow-shop since it can manufacture several product families. In cellular manufacturing, work systems are grouped into cells and each cell is dedicated to a particular product family (Chryssolouris 2006). Network IV represents such a cellular manufacturing system with 15 WSs split in two cells and is based on the system presented by Witte (1980).

Finally, job shops group machines with similar functions together and can produce products with largely differing process sequences (Chryssolouris 2006). As a result their material flow networks are rather complex and involve numerous production path options, which makes them difficult to model. We suggest modelling job shops with random graph networks (Erdős and Rényi 1959). Random graphs are networks in which an edge between two nodes exists with a given probability p. Since the material flow networks of job shops contain a large variety of links between the WSs, we argue that it is appropriate to model them with random graphs. Accordingly, we generate two job shop production networks. The first one (network V) is a directed random graph of 50 WS nodes in which the edges occur with a probability $p = 0.10$ and the second one (network VI) also has 50 WS nodes but this time the first 5 WSs are connected in a production line, which is subsequently followed by a directed random graph of the remaining 45 WSs, in which the edges occur again with a probability $p = 0.10$. The logic behind network VI is that even though job shops involve largely differing process sequences, some job shops have process sequences that always have the same start of the process sequence (for example, quality control of parts). This can also be observed in the material flow networks of five real-world job shop manufacturers presented in Chankov et al. (2015). The material flow networks for all six cases of our study are depicted on Fig. 3.2.

For each of the six networks, we generate production orders for a total of 20000 operations and run simulations. The equal number of operations ensures the comparability of the results. Figure 3.3 presents examples of orders from the six networks illustrating two key components: (1) WS sequence and (2) WS work content (WC).

First, it has to be noted that for some networks the WS sequence is fixed, while for others it varies. For example, orders on network I always have to go through the

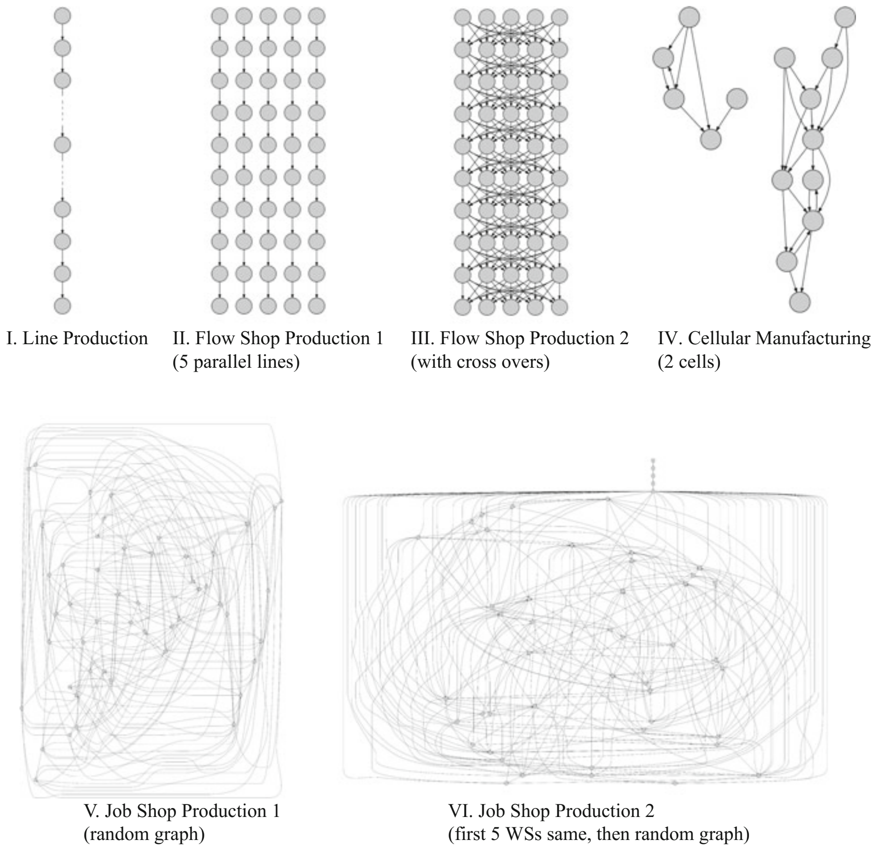

Fig. 3.2 Material flow networks of selected manufacturing systems

entire line of the 50 WSs it contains (thus each order has 50 operations) and orders on network II always go on one of the five lines with 10 WSs (thus each order has 10 operations). Further, network III involves orders with 10 operations but the sequence of the 10 WSs depends on the crossovers between its 5 lines (each crossover is chosen at random). Network IV has orders that are dedicated to one of its cells and the exact material flows are based on the example of Witte (1980). Network V starts at a random WS and goes through the system by selecting at random each of the possible subsequent WSs. The orders of network VI always go through the same five WSs and then proceed in the same way as network V.

Second, some networks have stable WC distributions while others don't. Flow line production normally utilizes cycle time (Becker and Scholl 2006) and thus we have assumed that all WSs belonging to network I have constant WC of 0.1 days. The parallel flow shops without crossovers normally have a fixed cycle time per line, accordingly we have assigned constant WC per line for network II (0.2 days for the chosen example of Fig. 3.3). The flow shop with crossovers requires the

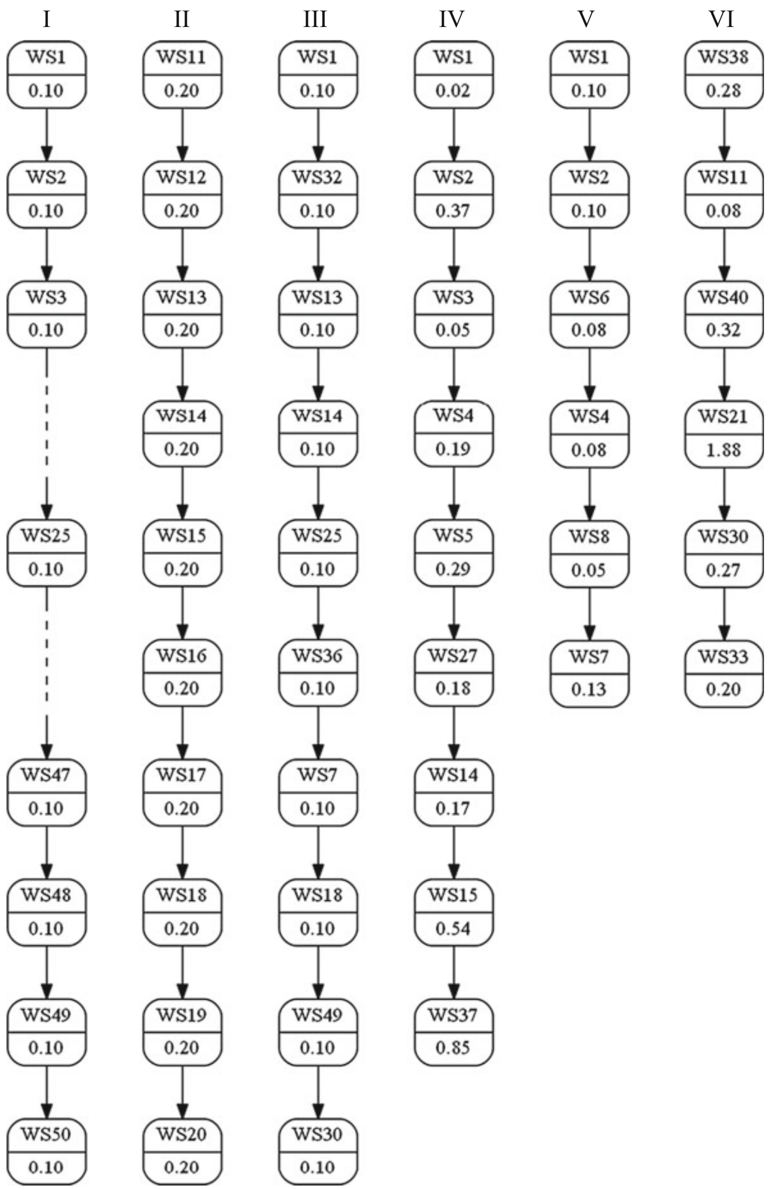

Fig. 3.3 Examples of orders for selected manufacturing systems

different lines to operate at the same cycle time, hence all WSs part of network III have constant WC of 0.1 days. Further, cellular systems do not utilize cycle times and the WC can vary among the WSs. In our study, the WC of network IV is based on Witte (1980). Finally, job shops have largely differing work contents. Consequently, the WC of networks V and VI is not fixed. Instead, each WS is assigned an average WC between 0.05 and 0.5 days and the WC for each operation is drawn from a normal distribution with that average and a corresponding standard deviation ensuring a coefficient of variation (CV) of 100 % (log-normal distribution is used in order to avoid negative numbers for WC as suggested by Mood et al. (1974)).

In order to control for effects of the order arrival, we run simulations using three order arrival patterns: (1) fixed-interval, (2) Poisson-process, and (3) batch. In the fixed-interval case, an order arrives every 0.10 days, in the Poisson-process case, the inter-arrival times between orders follow an exponential distribution with $\beta = 0.05$, and in the batch case 20 orders arrive in the beginning of every day (with the exception of network IV, where the daily batch size is based on Witte (1980)).

3.4 Results and Discussion

After running experiments on the described above model, we are able to calculate the emerging in every scenario logistics synchronization (Eqs. 1–4). The obtained logistics synchronization z-scores are shown on Fig. 3.4. It can be seen that the *line* and *flow shop production 1* scenarios exhibit the highest synchronization levels (z-scores reaching values of 15), while the two *job shop production* cases exhibit no synchronization with z-score values close to zero. Moreover, the *flow shop production 2* and the *cellular manufacturing* scenarios have average positive z-scores, with the exception of the fixed-interval order arrival case of *flow shop production 2*, which shows a negative z-score of −5.

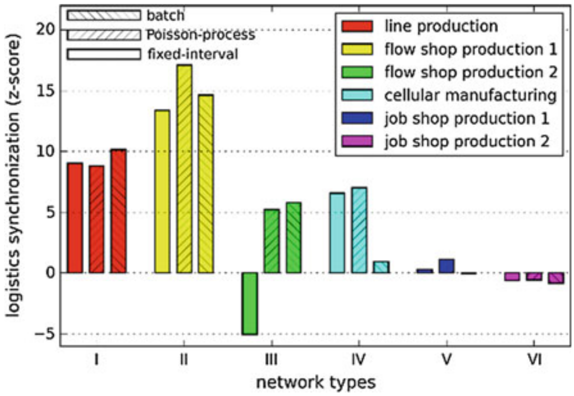

Fig. 3.4 Logistics synchronization results

To examine the relation between manufacturing system characteristics and emerging synchronization, we study the influence of three parameters (1) material flow network architecture, (2) work content variation, and (3) order arrival pattern.

First, the material flow networks of the different manufacturing system types are differently connected. The average node degree (ratio between number of nodes and links in a network) has been suggested as an indicative measure for the connectivity of material flow networks (Becker et al. 2012). Accordingly, to study the relation between material flow network architecture and logistics synchronization, we perform a Pearson's correlation analysis with the hypothesis that the average node degree of the material flow network of a manufacturing system is related to logistics synchronization. The results shown on Fig. 3.5a are significant on the 1 % level and indicate that more connected networks show lower synchronization levels.

Second, the level of variability of processing times differs across manufacturing system types. The CV (ratio of the standard deviation and the mean) of the work content of all operations performed by a WS has been suggested as practical measure of this variability (Bondi and Whitt 1986). Hence, to examine the relation between WC variation and logistics synchronization, we perform a Pearson's correlation analysis with the hypothesis that the average CV of WC among all WSs part of a manufacturing system is related to logistics synchronization. Figure 3.5b shows the results, which are significant on the 1 % level and indicate that manufacturing systems with higher variability of processing times have lower synchronization.

Third, to investigate if there are differences in synchronization across the different order arrival patterns, we perform a repeated measures analysis of variance (ANOVA) (Field 2013) with the null hypothesis that the synchronization measurements across the three arrival patterns in our study have the same means. The results show that logistics synchronization is not significantly affected by the order arrival pattern, $F(2, 10) = 1.09, p > 0.05$. Hence, we accept the null hypothesis and can conclude that the arrival pattern does not affect the emergence of synchronization.

Our results suggest that two of the three studied manufacturing system characteristics are related to synchronization emergence: material flow network

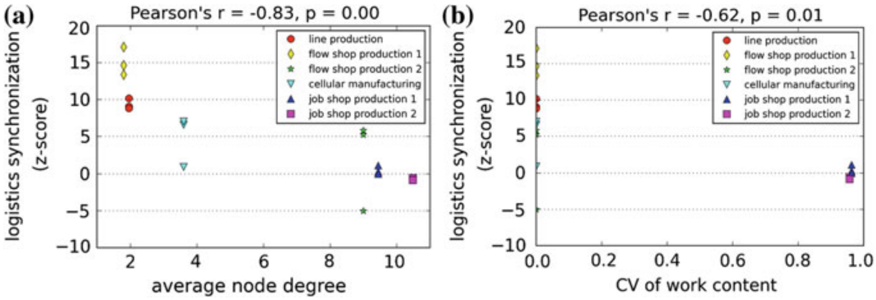

Fig. 3.5 Relation between manufacturing system characteristics and synchronization: **a** average node degree and **b** coefficient of variation of work content

architecture and WC variation. To begin with, systems with lower connectivity and WC variations exhibit high logistics synchronization. The examined *line production* and *flow shops production 1* are linear systems that operate at defined cycle times. Thus, a high coupling level between connected WSs emerges. Further, despite the presence of some variation in terms of available production sequences, the *cellular manufacturing* system and *flow shop production 2*, also show relatively high synchronization that can be explained by the stable processing times in those systems. Finally, it is not surprising that highly connected systems with high variability of processing times exhibit low logistics synchronization. *Job shops* are such systems which manufacture a high variety of products that undergo diverse production se-quences and involve varying processing times at each WS. As a result the coupling between connected WSs is weak, leading to low logistics synchronization. The last studied parameter, order arrival pattern, did not have a significant relation to synchronization, which could be due to the fact that inherent system characteristics play a more important role for the synchronization emergence than varying conditions.

3.5 Conclusion

In this paper, we conducted a discrete-event simulation study to investigate the effect of manufacturing system characteristics on the emergence of logistics synchronization. Our findings suggest that the material flow network architecture and the work content variation are two features of manufacturing systems that are related to logistics synchronization. Linear manufacturing systems with stable processing times such as flow shops operate at high logistics synchronization levels, while highly connected systems with high variability of processing times such as job shops exhibit lower synchronization levels. However, our simulation study does not consider several manufacturing system parameters, such as setup and transport times, priority rules, applied production planning and control methods, and machine breakdowns. Further research is required to investigate if these parameters also affect the emergence of logistics synchronization. Besides, studying factors that trigger the emergence of physics synchronization in manufacturing is also suggested.

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