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# Towards Definition of Synchronization in Logistics Systems

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**Abstract**

Manufacturing systems, transportation networks, and supply chains are all logistics systems, which are required to operate efficiently without waste of resources or time. Synchronization is a widely used term in connection with logistics systems, and it promises to increase efficiency by coordinating supply and demand over time and space. However, there is neither a common understanding of synchronization in logistics, nor an accepted way of measuring and quantifying it. This article investigates definitions of synchronization from various disciplines with the aim to come up with a commonly applicable interpretation of synchronization in logistics systems. This new comprehensive definition of synchronization in logistics systems is intended to avoid a misleading application of the term "synchronization" and to foster future developments of a concrete quantification and operationalization of synchronization in logistics systems. Our investigations show that the measurable and quantifiable phenomenon of synchronization in logistics is mainly composed of a temporal and performance-related coupling of the state of individual logistics elements or complete systems.


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*Keywords*: synchronization; manufacturing system; supply chain;

## 1. Introduction

Customer requirements are ever-increasing, which leads to the demand to deliver high-quality customized products in short time, while simultaneously global competition is becoming more and more intense [1]. Companies are confronted with increasing demand for a wide variety of products, which in turn gives rise to a high-level complexity of their logistics systems [2]. Logistics managers have to ensure that this variety can be offered, while at the same time shareholders request a high performance level. The optimal synchronization of the material flow across logistics systems appears to be an appropriate technique to cope with variety and cost efficiency at the same time. The potential of synchronized activity for increasing the performance of logistics systems has led to a wide range of research activities in production logistics and supply chain management (SCM) as part of the just-in-time philosophy [3,4] and inventory optimization strategies, e.g., as a possible mitigation of the Bullwhip Effect [5]. However, a common understanding of the concept “synchronization in logistics systems” is still missing. It remains unclear how general definitions describing synchronization phenomena present in various natural sciences, engineering fields, and social life relate to logistics.

A long-term goal of this research on synchronization in logistics systems is the comprehensive description of synchronization as well as the future development of methods to utilize knowledge about synchronization in the design and operation of logistics systems with the effect of increased efficiency. We aim to investigate synchronization from an engineering perspective in order to gain a quantitative understanding of its emergence, its mechanisms, and its influence on


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logistics performance. Accordingly, we see synchronization as a quantifiable, observable phenomenon in logistics systems, in contrast to qualitative approaches. These qualitative approaches under the term "synchronization" are mainly prevalent in supply chain management and primarily include advice for managerial activities in the fields of communication, collaboration, information sharing, and supply chain strategy. If they do not contribute to a mathematical understanding of synchronization in logistics systems, we are not able to include them in our work.

A starting point towards our long-term goal is a clear definition of synchronization in logistics systems, along with finding metrics to quantify synchronization in logistics, which has been initiated in our previous work [6]. However, as the role of synchronization in logistics has never been clearly defined before, the following two steps are a prerequisite for the further investigation of synchronization in logistics: firstly, synchronization definitions from non-logistics fields have to be analyzed regarding to what extent they can be used to describe synchronization phenomena in logistics, and secondly, existing logistics concepts have to be checked if they already include synchronization-related mechanisms without using the term 'synchronization' explicitly. Having completed these two steps, we will be able to establish a clear definition for synchronization in logistics systems, which is the primary purpose of this paper. Such a definition would help to clearly delineate the concept from other phenomena, which is a prerequisite for analyzing and quantifying the relation between synchronization and performance in logistics systems.

The paper is structured as follows. The second section presents a brief literature review, introducing both logistic and non-logistic perspectives on synchronization. The third section collects and categorizes the current synchronization definitions from other disciplines. In the fourth section, we investigate to what extent existing logistics concepts incorporate the idea of synchronization. Section five contains our new, comprehensive definition of synchronization in logistics systems derived from the preceding analyses. The paper finishes with a conclusion.

## 2. Literature Review

Synchronization in a broader sense means aligning a certain behavior or state over time [7]. Synchronization phenomena have been observed and thoroughly studied in various disciplines such as physics, biology, and chemistry [8]. As Strogatz & Stewart [9] put it, synchronization is "a subtle mathematical thread [that] connects clocks, ambling elephants, brain rhythms, and the onset of chaos." Accordingly, various views on synchronization exist in the literature. To begin with, some researchers have a rather descriptive view on synchronization. According to Osipov et al. [7] "synchronization is usually understood as the capacity of objects of different nature to form a common operation regime due to interaction or forcing". Pikovsky et al. [10] define the term as "the adjustment of rhythms due to interaction" and according to Manrubia et al. [11] "systems are synchronized when rigid correlations between their internal dynamical states appear". These descriptive definitions all focus on diverse objects which exhibit harmony in their behavior as a result of a certain form of interaction between them. Another way to look at synchronization is from a rather quantitative view, which puts the emphasis on measuring the exhibited harmonious behavior. A common mathematical approach for quantifying synchronization is to consider the synchronized systems as phase oscillators and to compare their phase lengths. This so-called phase synchronization can be measured with the Kuramoto Model [6,12,13].

Few attempts have been made to define the term "synchronization" in the context of logistics. According to Fastabend [14], logistic synchronization occurs when a flow-oriented coordination is present in the production-logistic process chain. Wiendahl [15] defines logistic synchronization as the output-input coupling, i.e. a firm determination of the input by the output. Our recent study on industrial feedback data shows that synchronization is intrinsically present in job shop manufacturing environments [6]. However, a holistic understanding of the concept "synchronization in logistics systems" is still missing. It remains unclear what objects can be synchronized, if synchronization emerges in the system by itself, or it is present only when it is enforced into the system by means of a controlling mechanism. Therefore, this paper proceeds with categorizing the various terms used in the different synchronization definitions and transferring them to the logistics field.

## 3. Different Views on Synchronization

The definitions presented in Section 2 all refer to synchronization, but put different aspects in focus. Consequently, various views on synchronization can be considered (see Table 1). Since synchronization primarily relates to activities occurring at the same time, according to its etymologic origin from Ancient Greek, the first view on synchronization is the *temporal view*. This time focus is mostly present in the synchronization definition by Pikovsky et al. [10]. Secondly, the *causal view* is emphasized in the majority of definitions. It sees synchronization as the concept of events triggering other events, which implies some sort of interaction, correlation, forcing, or coupling. Moreover, these triggers or causes can be initiated from within the system or from the outside, and thus one can distinguish between an *endogenous* and an *exogenous view*. Synchronization can be a self-emerging phenomenon in the system caused by internal correlations or interactions (endogenous view) or a controlled phenomenon induced in the system by means of external forcing or coordination (exogenous view). Further, synchronization can occur between states of the system or between processes running in the system. The *process view* is strongly emphasized in the logistics definitions of synchronization (Fastabend [14] and Wiendahl [15]), while the *state view* is present in the definitions from other scientific disciplines (Osipov et al. [7] and Manrubia et al. [11]). Finally, the *object view* considers the nature of the items that can be synchronized and their unique characteristics, which enable them to act in synchrony.

Table 1: Synchronization Views

| Synchronization Definitions | temporal | causal | endogenous | exogenous | state | process | object |
|---|---|---|---|---|---|---|---|
| capacity of objects of different nature to form a common operation regime due to interaction or forcing (Osipov et al. [7]) | | x | x | x | x | | x |
| adjustment of rhythms due to interaction (Pikovsky et al. [10]) | x | x | | | | | |
| rigid correlations between internal dynamical states (Manrubia et al. [11]) | | x | x | | x | | |
| flow-oriented coordination (Fastabend [14]) | | | | x | | x | |
| output-input coupling (Wiendahl [15]) | | x | x | | | x | |

Having categorized the synchronization definitions from non-logistics fields, we continue by assessing existing logistics concepts which can be associated with synchronization or have been in the past.

## 4. Logistics Concepts and Their Relation to Synchronization

### *4.1. Logistics Concepts*

Aspects that are attributed to synchronization are also prevalent in definitions of logistics. An established definition of logistics is given by Plowman [16] "Logistics means ensuring the availability of the right goods, in the right amount, in the right condition, at the right place, at the right time for the right customer at the right costs". This so-called "seven Rs" definition characterizes logistics passively, because it describes the outcome of successful logistics activities as a defined state. From an active perspective, the definition requires from logistics to align activities in space and time, which implies that a certain amount of synchronization is a prerequisite for successful logistics operations.

In addition, the following logistics concepts established both in the literature and practice are directly related to synchronization. The *takt time* in a paced assembly line is derived from the customer demand per time unit and is then subsequently used to determine the time each of the workstations on the line has to execute its assigned tasks. This so-called cycle time is the same for all stations and thus ensures that the products move "in sync" [17]. As a result, the paced assembly line can be considered to serve as a role model of a highly synchronized logistics system.

Another well-established logistics concept related to synchronization is the *just-in-time (JIT) philosophy*. Being one of the main pillars of the Toyota Production System, just-in-time fundamentally means that the right parts needed for a certain logistics process are delivered only at the time they are needed and only in the amount needed [18]. Moreover, some authors consider a concept known as *synchronous manufacturing*, which is similar to just-in-time but also emphasizes the "issue of supplying the exact needs of the customer" [19].

The notion of *synchronized supply* is also defined in the literature and is comparable to the Vendor Managed Inventory perception, where "the supplier takes charge of the customer's inventory replenishment" [5]. This concept eliminates one ordering decision point from the supply chain and thus connects two tiers directly.

Further, there are related concepts available in the field of supply chain management: *supply chain collaboration* [20], *supply chain coordination* [21] and *supply chain integration* [22]. According to Simatupang & Sridharan [23], "a collaborative supply chain simply means that two or more independent companies work jointly to plan and execute supply chain operations with greater success than when acting in isolation", while Simatupang et al. [24] define supply chain coordination as "the extent to which participating actors become involved in information sharing and decision synchronization". The focus in these definitions is on sharing private information (e.g., customer demand) and on having joint-decision making (e.g., resolving conflicting objectives) between the supply chain actors. Supply Chain Integration is "used to describe the intensity and nature of supply chain relationships", where a true integration is rare because it involves full alignment of objectives [25]. Some researchers use the word synchronization synonymously to all of the above-mentioned supply chain terms (collaboration, coordination and integration) or consider it as an inherent subconcept of these terms. For example, Rudberg & Olhager [26] define "synchronize" as one out of four types of supply chain coordination depending on the number of organizations and sites per organization in the supply chain network.

Finally, the warehousing strategy *cross docking* can also be associated with synchronization due to the timely transshipment of goods. Cross docking is defined as "the process of moving product through distribution centers without storing it" [27].

### *4.2. Link from Logistics Concepts to Synchronization*

All concepts introduced in the previous section are associated with synchronization to a certain extent. However, in order to systematically evaluate and examine this connection, we now proceed by checking how each of the concepts relates to the previously established synchronization definitions. Table 2 provides an overview of the established relationships.

Table 2: Logistics Concepts and Their Relation to Synchronization

| Synchronization Definitions | takt | JIT | synchronous manufacturing | synchronized supply | SC coordination | cross docking |
|---|---|---|---|---|---|---|
| capacity of objects of different nature to form a common operation regime due to interaction or forcing (Osipov et al. [7]) | | | | | | |
| adjustment of rhythms due to interaction (Pikovsky et al. [10]) | x | | | | | |
| rigid correlations between internal dynamical states (Manrubia et al. [11]) | | | | | | |
| flow-oriented coordination (Fastabend [14]) | | x | x | | | |
| output-input coupling (Wiendahl [15]) | | x | x | | | x |

First of all, the *takt time* can be said to lead to adjustment of rhythms in the manufacturing systems. Following the customer demand, the takt time determines how much time each of the assembly line workstations has available to execute its task. A change in the takt time would lead to changes in the times for all workstations; hence we will observe an adjustment of rhythms due to interaction.

The *just-in-time* philosophy and the *synchronous manufacturing* concepts correspond directly to the synchronization definitions available in the logistics literature. Delivering the right parts exactly when they are needed requires flow-oriented coordination as well as corresponds to an output-input coupling between two consecutive logistics processes.

*Synchronized supply*, however, is a notion which does not have an explicit link to the synchronization definitions. The elimination of one decision point does not correspond to a form of interaction, correlation, coupling or adjustment of rhythms. The same holds for the SCM terms (*collaboration, coordination* and *integration*), which represent strategic considerations, but do not cover synchronization phenomena per se. Here we can speak about neither correlation between states, nor common operation regime, nor adjustment of rhythms. Instead, these qualitative terms provide strategic advice about certain managerial activities such as increased communication and information sharing.

Finally, the *cross docking* strategy brings a different perspective. Synchronization between the incoming vehicles and the outgoing vehicles is required for its implementation. This form of output-input coupling ensures very small or even no storage time of the product in the warehouse.

## 5. Definition of Synchronization in Logistics Systems

The investigation of the relation between synchronization and logistics concepts shows that there are different perspectives on this connection between synchronization and logistics. The one viewpoint on synchronization and logistics originates in the SCM literature and covers notions such as collaboration and coordination by means of information sharing, joint decision making or other improvement initiatives. As shown on Fig. 1, such coordinated actions can serve as an input to a so-called synchronization black box and trigger as an output a certain form of actively synchronized behavior. In a way these coordinated actions act as a controlling mechanism, which enforces synchronization. Besides, even if there are no deliberate coordinated actions, synchronization can emerge in the system. The other viewpoint covers the engineering perspective and concentrates on the synchronization black box itself. Here the emphasis is on questions such as how and why do certain actions enforce or lead to the emergence of synchronization in logistics systems and what is the effect of this synchronization on the logistics performance. Therefore, for this engineering perspective a clear definition and quantitative measures of the synchronization phenomena occurring in logistics systems are required as well as an investigation of its relation to logistics performance. This paper focuses on the first requirement by introducing a new definition for *synchronization in logistics systems*, which aims to establish a holistic understanding of this term.

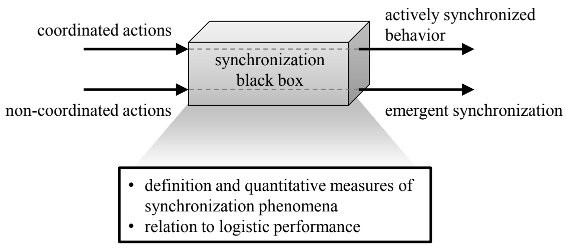


Fig. 1: Synchronization as a black box. One view on synchronization in logistics is the coordination of actions, followed by the observation of synchronized behavior, without a deeper understanding of the mechanisms in this "black box". Another view is the observation of non-coordinated actions, leading to an emergent synchronization. The explanation of this phenomenon requires quantitative measures and their linkage to logistics performance.

Accordingly, we suggest the following definition:

*"Synchronization in logistics systems is the observable and quantifiable phenomenon which represents the temporal coupling and performance-related coupling of different system elements or processes due to direct or indirect interaction. This phenomenon can occur within a single logistics system or between multiple logistics systems."*

This definition is derived from the definitions presented in Section 2 and covers all relevant aspects from the different views on synchronization (see Table 1). To begin with, the *temporal view* is important for any synchronization phenomenon, because the etymological origin of the word suggests a "temporal coupling". Secondly, as shown in Figure 1, synchronization in logistics systems can be triggered by either coordinated or uncoordinated actions. This cause-and-effect aspect is included in the definition by naming "direct or indirect interaction" as a trigger for synchronization. Hence, the *causal view* on synchronization is also contained in the definition. Moreover, synchronization phenomena can occur within a single system or between systems. For example, the development of the work-in-process (WIP) levels of one manufacturing system can exhibit repetitive behavior or the WIP developments of several manufacturing systems can be coupled amongst them. Thus, both the *endogenous* and *exogenous views* are incorporated in our definition. In addition, the *state view* is integrated as well since a vector of performance key figures is able to represent performance coupling between states of the logistics system. Finally, the *process* and *object view* are explicitly covered in our definition by defining synchronization as the "different system elements or processes". Depending on the type of logistics system, examples for such elements are workstations/machines, products/orders or vehicles/containers. A process in logistics is a sequence of actions, and an example for the coupling of two processes is the coordination of manufacturing and packaging.

Fig. 2 illustrates the two dimensions, time and performance, of a synchronization phenomenon in a logistics system. It shows the timely development of a specific performance figure for two logistics elements. The two elements exhibit a coupling of their logistics performance figures. As indicated in the chart, there are two dimensions of the coupling: temporal coupling and performance coupling. The performance of the two elements follows exactly the same pattern, but there is a time as well as a performance shift between them, as indicated by the intersections of the dotted lines. If these shifts are disregarded, the two lines representing the performance of the two elements will overlap completely.

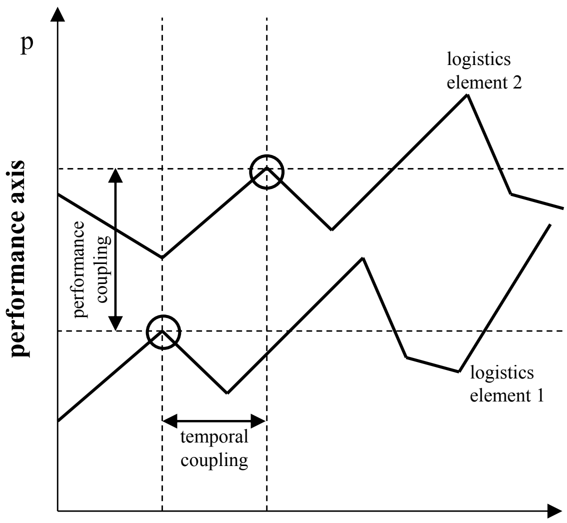


Fig. 2: Illustration of the two dimensions of a synchronization phenomenon in a logistics system. The two logistics elements (e.g., work stations on a shop floor) exhibit a correlated development of their state, represented by a performance figure (e.g., the current work in process). The coupling is two-dimensional: there is a constant temporal gap, the time lag, between the performance development of the two elements, and there is also a constant difference in performance.

## 6. Conclusion

The intention of this article was to shed light on the meaning of synchronization in logistics systems. Without any deeper analysis, it is clear that the coordination of activities in time and space is a key concept of nearly any logistic effort. Our investigations were triggered by the diverse and sometimes misleading use of the term "synchronization" in the field of logistics. We were able to gather a variety of definitions of synchronization, originating mainly from the natural sciences, but also from logistics and supply chain management. The comparison of the different definitions revealed that there were different focal views in each definition.

Furthermore, it became apparent that some classical logistics concepts, such as just-in-time or takt time, can be related to individual understandings of synchronization. Our collection of the different views on synchronization in logistics enabled us to come up with a comprehensive definition, which makes it possible to delineate synchronization from similar, but distinct phenomena in logistics. The definition points out that synchronization in logistics consists mainly of the coupling of two logistics elements or systems in two dimensions: the temporal coupling, i.e. the time delay between the related events, and the performance coupling, i.e. the quantification of the performance correlation.

Our new definition of synchronization in logistics systems serves as a clear basis for the development of specific synchronization measures. Such measures are a prerequisite for a further evaluation if synchronization is correlated with logistics performance and thus if it is beneficial to have synchronization in logistics systems or not. Without a proper investigation, the so far described interrelations between synchronization and performance in logistics would remain an assumption. Future research work will focus on the development of methods, which utilize the obtained knowledge about synchronization and its effects on performance and contribute to a further improvement of design and operation of logistics systems.

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