Physica A 393 (2014) 404–417

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Modelling and analysis of synchronised material flow with fluid dynamics

Florian Klug *

Department of Business Administration, University of Applied Sciences Munich, Am Stadtpark 20, D - 81243 München, Germany

HIGHLIGHTS

- Empirical relevance of material flow synchronisation is discussed.
- A multi-stage, continuous material flow is modelled and analysed.
- These models allow to take into account the transient behaviour of supply chains.
- A quantification method of supply chains has been found.

ARTICLE INFO

Article history:
Received 14 March 2013
Received in revised form 14 May 2013
Available online 5 September 2013

Keywords:
Econophysics
Supply chain management
Synchronised material flow
Fluid dynamics
Conservation law

ABSTRACT

We will develop and study synchronised material flow with the help of fluid dynamics. After discussing the empirical relevance of synchronised material flow we develop a deterministic supply chain model. Unlike similar approaches, this model is not based on some quasi steady-state assumptions about the stochastic behaviour of the involved supply chain, but rather on a simple deterministic rule for material flow density. Therefore a multi-stage, continuous material flow is modelled and analysed through a conservation law for material density and augmented by a state equation relating the velocity of parts to the density of the material flow. These models allow us to take into account the nonlinear and transient behaviour of different supply chain echelons and to test synchronised flow with respect to its potential impacts. Numerical simulations verify that the model is able to simulate transient supply chain phenomena. Moreover, a quantification method relating to the fundamental link between synchronisation, productivity and stability of supply chains has been found.

1. Introduction

Supply chains evolve dynamically and in a stochastic environment. These features make logistic systems highly complex, hard to describe, and challenging to optimise [1]. The present paper allows us to investigate and provide insights into nonlinear dynamic behaviour of supply chains. A very interesting and sophisticated part of nonlinear dynamics is material flow synchronisation [2]. In recent years companies in different sectors have acknowledged the importance of synchronising the flow of material in the supply chain. Improper synchronisation can lead to transitions and instabilities, which cause very complex dynamics. The research has found that synchronisation improves the overall supply chain performance [3]. Potential benefits associated with synchronised material flow include stability in both demand and supply patterns, inventory reduction, dampening of demand amplification and better long-term planning [4].

The major goal of this paper is to investigate synchronised material flow (SMF) with the help of dynamic modelling to provide a framework, or understanding, from which a firm can assess its inherent options for improving supply chains. Designing mechanisms to analyse, evaluate and control dynamic phenomena in material flows allows us to manage

* Tel.: +49 8912652778; fax: +49 89 1265 2714.
E-mail address: florian.klug@hm.edu.

0378-4371/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physa.2013.08.065

them effectively. In this paper concepts from fluid dynamics have been applied in discovering and explaining dynamical phenomena in supply chains. The aggregated fluid-dynamic description of material flows turns out to be quite successful in capturing the dynamics, nonlinear interactions, and adaption processes in supply chains. First applications of fluid-dynamic models in supply chain management are promising to lead to a better understanding, design and optimisation of logistic systems. The potential of the used physics-based approach is considerable. For example, applying the slower-is-faster effect, which is found in many logistic systems, has facilitated to increase material throughput by 30% and more [1]. The novelty of this paper is to combine the many-particle models of fluid dynamics with the successful concept of SMF. Although this crucial link between synchronous and efficient material flows by time and quantity has generally been acknowledged over many years, it is necessary to reach a finer understanding of these dynamics. This paper will help to bridge this gap. The mathematical tools we are using stem mainly from statistical physics and nonlinear dynamics. This nonlinear and transient modelling of supply chains allows for a better description of real-life behaviour [5]. By treating material items similar to classical multi-particle systems leads to a new, enhanced understanding of logistics processes.

The remainder of the paper is organised as follows. In Section 2, we discuss the empirical evidence of synchronising supply chains. Section 3 describes the continuum material flow model with conservation law, which is derived from discrete parts movement with Newton equations. We proceed with developing different levels of material flow synchronisation, split by internal and external disturbances. In Section 4 the transient behaviour of material flows in a multi-echelon supply chain is analysed through some numerical simulations. Finally, Section 5 is devoted to conclusions.

2. Empirical relevance of synchronised material flow

The main aim of SMF is on the one hand to enable high productivity in manufacturing and logistics and on the other hand to create a source of strategic competitive advantage through low lead times and high stability. In order to prevent local build-ups of inventory, material flow must be synchronised and harmonised so that parts move in a coordinated and highly orchestrated fashion without interruptions between the individual nodes of a material stream [6]. We define SMF as a synchronised and flow-orientated material stream, mainly guided and pull-driven by customer demand. Further it is characterised by stable and time-optimised logistics activities, helping to perform the high productivity of a lean supply chain. Synchronising upstream operations with downstream operations allows response to changing requirements and helps to dampen bullwhip tremendously. Coordination of material flows by both volume and time is aimed at processing the quantity needed by one process from the one that precedes it. Each partner is fed from the next stage up the chain in just the quantity needed at precisely the right time.

Evidence of the empirical relevance of SMF can be found in many industries. The ability to control and synchronise a firm's logistics processes has been critical to operations strategies ever since the start of the twentieth century, when Henry Ford opened the fully vertically integrated River Rouge complex, which included harmonised operations from raw materials to finished cars [7]. Perhaps one of the most significant SMF examples of becoming widely adopted and practised is that of just-in-time (JIT) supply in automotive industry. Synchronous supply is essentially a system where components supplied are matched exactly to the production requirements of the car assembler [8]. The creation of a SMF aims to dramatically reduce inventories while greatly enhancing responsiveness. Complex parts with growing variant number require late configuration and demands that suppliers deliver in sequence to the vehicle manufacture plant. Nowadays sequenced in-line supply (SILS) is a standard delivery approach in synchronous supply. In this concept, the entire vehicle assembly process is dependent upon the timely delivery of components. SILS requires suppliers to deliver customer-ordered components and modules in the same sequence and synchronised with the final assembly process [9]. Resultant orders and call-offs are processed sometimes just hours ahead of when the car is built. Therefore information flows and systems must be synchronised, so that information replaces the need for inventories. Synchronous supply necessitates an integrated information system which can accommodate the time-critical transfer of data and activate the synchronous manufacturing process to deliver zero defect goods, at the right time, at the right place and at the right cost [8]. Transparency of information upstream and downstream maintains the flow of materials in time to the rhythm of the production process.

The higher productivity of SMF processes is mainly generated by improved material flow with higher output and less variation, which is at the heart of Toyota's lean philosophy [10]. This empirical evidence from the automotive industry created a commonly accepted understanding that synchronisation and stability of material flows impact its productivity. Meanwhile, the crucial link between synchronous and stable material flows by time and quantity, to create a supply chain with the highest throughput rates is at the heart of supply chain management in many industries. Hence, this study is not restricted to automotive industry. The Theory of Swift, Even Flow by Schmenner and Swink [11] generalises the crucial relations between material flow, speed and variation. "Thus, productivity for any process – be it labour productivity, machine productivity, materials productivity, or total factor productivity – rises with the speed by which materials flow through the process, and it falls with increases in the variability associated with the demand on the process or with steps in the process itself". The planning issue to ensure harmonised and even material streams is the principle of levelled production. Production levelling by both volume and product mix is aimed at producing the quantity and variety taken by one process from the one that precedes it. It does not process products according to the actual flow of customer orders, which can swing up and down wildly, but takes the total volume of orders in a period and levels them out, so the same amount and mix are made each scheduling period [10]. Schedule stability translates into synchronised material call-offs, which means a smooth material flow pipeline and improved performance in plant operations.