

# Biologically inspired mutual synchronization of manufacturing machines

Erjen Lefeber<sup>\*,a,1</sup>, Herman de Vos<sup>a</sup>, Dieter Armbruster<sup>a,b,2</sup>,  
Alexander S. Mikhailov<sup>c,3</sup>

<sup>a</sup>*Systems Engineering Group, Department of Mechanical Engineering, Technische Universiteit Eindhoven, PO Box 513, NL-5600 MB, Eindhoven, The Netherlands*

<sup>b</sup>*Department of Mathematics, Arizona State University, AZ 85287-1804 Tempe, USA*

<sup>c</sup>*Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany*

---

## Abstract

A biologically inspired manufacturing control system for synchronous delivery of jobs at a batch machine is developed. This control system is based on a synchronization mechanism of enzymes replacing the role of product molecules with kanbans. This manufacturing control system works well, provided the variability in service times is not too high.

*Key words:*

---

## 1. Introduction

? ? ] introduced a simple model of a molecular network formed by a hypothetical enzymatic reaction with allosteric product activation. Depending on the details of an individual molecular cycle, the same population can

---

\*Corresponding author

*Email addresses:* A.A.J.Lefeber@tue.nl (Erjen Lefeber), Armbruster@asu.edu (Dieter Armbruster), Mikhailov@fhi-berlin.mpg.de (Alexander S. Mikhailov)

<sup>1</sup>E.L. was supported by a grant from the Stiftung Volkswagenwerk under the program on Complex Networks and by the Netherlands Organization for Scientific Research (NWO-VIDI grant 639.072.072).

<sup>2</sup>D.A. was supported by a grant from the Stiftung Volkswagenwerk under the program on Complex Networks and by NSF grant DMS-0604986.

<sup>3</sup>A.M. was supported by a grant from the Stiftung Volkswagenwerk under the program on Complex Networks.

form one or several large coherent groups of enzyme molecules. Because the molecular cycles inside a group are synchronized, many enzyme molecules are simultaneously releasing the product and the number of product molecules in the volume shows rapid oscillations (i.e., spiking) at a period controlled by the duration of a single turnover cycle.

In manufacturing, batch machines serve several jobs simultaneously, e.g., heat treatment in a furnace. In order to reduce the average waiting time (including batch formation) in front of a batch machine, it is crucial that jobs arrive to a batch machine simultaneously. It is therefore important to synchronize the machines that deliver their jobs to this batch machine.

The goal of this paper is to translate the enzyme synchronization mechanism introduced in [?] into a decentralized manufacturing control scheme that achieves synchronous arrivals of jobs to a batch machine.

Transferring ideas from biology to logistic and production problems has become known under the name of bio-mimicry. Many papers exist in which ant colony algorithms are used for scheduling, e.g. [? ? ], or for cell-formation, e.g. [? ? ]. Also division of labor [?] and manufacturing control [?] inspired by biological ideas have recently been studied. However, all the above mentioned papers are either using optimization techniques, or routing algorithms. None of these papers are concerned with timing.

Our work starts from [?] in which a biological mechanism is presented that causes many enzyme molecules to simultaneously release their product. We translate this mechanism into a manufacturing control strategy which lets many machines simultaneously release their products to a batch machine. A straightforward translation of the work in [?] would be to translate molecular product into manufacturing product. However, the molecular machines (enzymes) idle for a considerable amount of time, which is undesired in manufacturing. Instead, we translate molecular products into manufacturing kanbans. Next, these kanbans are used for authorizing the start of jobs. This enables us to make a translation in which manufacturing machines can still operate under a sufficiently high utilization.

The main conclusion from our study is that the proposed biologically inspired timing mechanism for the control of manufacturing systems works well, provided that variability in service times is not too high.

The remainder of this paper is organized as follows. In Section 2 the synchronization mechanism of enzymes as introduced in [?] is summarized. Next, in Section 3 we discuss the translation of this mechanism into a control mechanism for manufacturing. Section 4 contains discrete event simulation

results with the bio-inspired manufacturing control mechanism. Section 5 presents a conclusion.

## 2. From biology...

[?] discuss a hypothetical enzymatic reaction with allosteric product activation. An enzyme is considered as a cyclic machine (a stochastic phase oscillator), cf. Figure 1. We scale time such that one cycle takes (on aver-

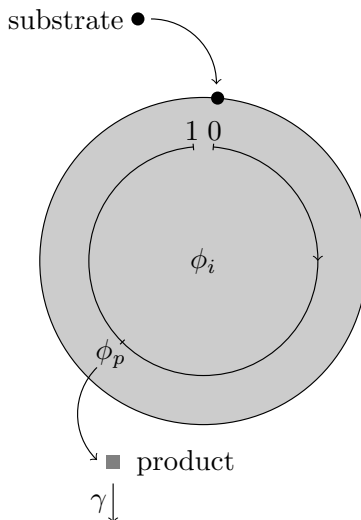


Figure 1: Schematic representation of an enzymatic turnover cycle

age) exactly one time unit. Binding of a substrate molecule to an enzyme  $i$  initiates an ordered internal conformational motion, described by the conformational phase coordinate  $\phi_i$ . The initial state corresponds to the phase  $\phi_i = 0$ . The catalytic conversion event takes place and the product is released at the state  $\phi_p$  inside the cycle. After that, the conformational motion continues until the equilibrium state of the enzyme ( $\phi_i = 1$ ) is finally reached. Product molecules are unstable and decay at a rate  $\gamma$ .

Let  $n(t)$  denote the number of enzymes currently in equilibrium state, waiting to bind a substrate. Let  $m(t)$  denote the number of product molecules. Furthermore, let the probability of substrate binding be given by

$$\nu(t) = \nu_0 + \nu_1 m(t). \quad (1a)$$

If the total number of enzymes in the considered population is large and the change in the number of enzymes in the ground state with a time interval  $\Delta t$  is small, the following continuous description (mean field equations) can be used:

$$\frac{dn(t)}{dt} = -\nu(t)n(t) + \nu(t-1)n(t-1) \quad (1b)$$

$$\frac{dm(t)}{dt} = -\gamma m(t) + \nu(t - \phi_p)n(t - \phi_p) \quad (1c)$$

The steady equilibrium states  $n = n_0$ ,  $m = m_0$  for (1) are given by

$$n_0 = \frac{N}{1 + \bar{\nu}} \quad m_0 = \frac{\bar{\nu}}{\gamma} n_0,$$

where  $N$  denotes the total number of enzymes and

$$\bar{\nu} = \frac{1}{2} \left( \nu_0 + \frac{\nu_1 N}{\gamma} - 1 \right) + \sqrt{\frac{1}{4} \left( \nu_0 + \frac{\nu_1 N}{\gamma} - 1 \right)^2 + \nu_0}.$$

Stability analysis can be performed as described in [? ]. Using the parameters  $\nu_0 = 1$ ,  $\gamma = 20$ , and  $N = 200$  the bifurcation diagram shown in Figure 2 results. At low values of the allosteric regulation intensity  $\nu_1$ , the steady state

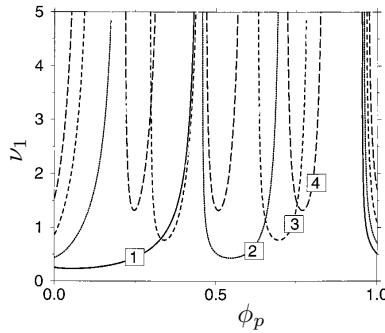


Figure 2: Bifurcation diagram in the parameter plane  $(\phi_p, \nu_1)$ , as presented in [? ], using the parameters  $\nu_0 = 1$ ,  $\gamma = 20$ , and  $N = 200$ .

corresponding to absence of oscillations is stable. Increasing the parameter  $\nu_1$ , going along the vertical direction in the bifurcation diagram, one of the

instability boundaries would be crossed. Above this boundary, the steady state is unstable with respect to development of periodic oscillations.

The mean-field approximation allows for derivation of the bifurcation diagram, which provides the understanding what parameter controls the number of coherent enzymatic groups in the synchronous regimes. However, to derive the mean-field equations, fluctuations have been neglected. These can be added by introducing diffusive phase dynamics, i.e. a Langevin equation for the time evolution of the phase  $\phi$ :

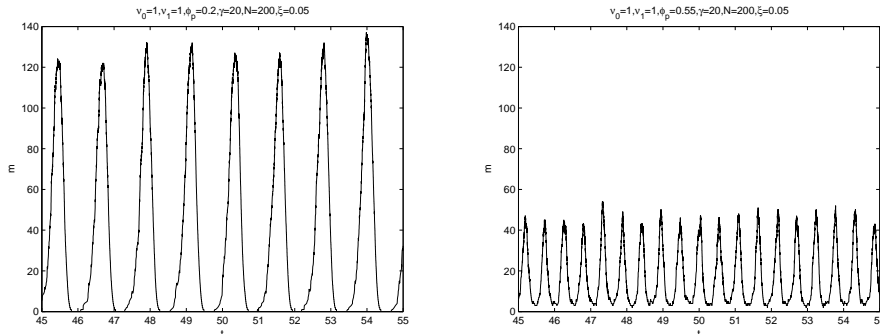
$$\frac{d\phi_i}{dt} = 1 + \eta_i(t)$$

where  $\eta_i(t)$  is a random Gaussian noise with a zero mean value, and noise intensity  $\sigma$ . The relative statistical dispersion of turnover times can be defined as

$$\xi = \frac{1}{\langle \tau \rangle} \sqrt{\langle \tau^2 \rangle - \langle \tau \rangle^2},$$

where  $\tau$  denotes the cycle duration.

For a statistical dispersion of  $\xi = 0.05$ , Figure 3 shows spiking of a single



(a) Spiking of a single enzymatic group (b) Spiking with two coherent enzymatic (i.e. full synchronization) for  $\phi_p = 0.2$ . groups for  $\phi_p = 0.55$ .

Figure 3: Synchronous reaction regimes at statistical dispersion of  $\xi = 0.05$  for the parameters  $\nu_0 = 1$ ,  $\nu_1 = 1$ ,  $\gamma = 20$ , and  $N = 200$ .

enzymatic group as well as spiking of two coherent enzymatic groups, where we used the same parameters as in Figure 2, and  $\nu_1 = 1$ . The two different behaviors have been achieved by taking  $\phi_p = 0.2$  and  $\phi_p = 0.55$  respectively.

From these results, it is clear that the above model explains how coherent enzymatic groups can spike simultaneously, and how parameters can be tuned to obtain certain behavior. This spiking can be achieved, even in the presence of noise.

### 3. ... to manufacturing

Our goal is to translate the enzyme synchronization mechanism of [?] to a manufacturing control scheme that achieves synchronous arrivals of jobs to a batch machine, e.g., heat treatment in a furnace. A furnace typically can hold many parts. These parts arrive to the furnace from upstream workstations. As many parts can be processed simultaneously at the furnace, typically many machines in parallel feed this furnace. One of the key performance indicators of a manufacturing system is the cycle time, i.e. the average time jobs spend in the manufacturing system. Waiting time at a (parallel) batch machine has two important ingredients [?]: wait-to-batch time and queue time. In order to reduce the wait-to-batch time, one should try to reduce the time between the arrival of the first and the last job in the batch. In order to reduce the queue time one should try to reduce the variance of inter-arrival times of consecutive batches. The enzymatic control mechanism achieves both.

The most straightforward extension would be to replace the molecular machine (enzyme) with a manufacturing machine (feeding the batch machine). The binding of a substrate molecule to an enzyme which initiates the catalytic conversion then corresponds with the start of processing a job at the manufacturing machine. The release of the product at the state  $\phi_i = \phi_p$  inside the cycle then corresponds with the completion of a job at the manufacturing machine. The continuation of the conformational motion until the equilibrium state of the enzyme ( $\phi_i = 1$ ) is reached then corresponds with idle time at the machine. There are at least two problems with that approach: i) unstable molecules are removed with a rate  $\gamma$  (the decay rate) which has no equivalence in the manufacturing realm. ii) All of the machines idle from  $\phi_i = \phi_p$  to  $\phi_i = 1$ , and even longer, since substrates do not bind immediately after an enzyme has reached its equilibrium state, but with a probability as described in (1a). In manufacturing it is undesired to have machines idle too long. Typically a utilization of 80% or even 90% is desired implying  $\nu_1 > 0.8$ . As can be seen in Figure 2, for such  $\nu_1$  the system is not

able to achieve stable oscillations with a single group or two coherent groups. Furthermore, the resulting behavior is extremely sensitive to noise.

Therefore, we propose a different approach. We still identify keep a molecular machine (enzyme) with a manufacturing machine (feeding the batch machine). In order to reduce the idle time of machines, we consider the service time of jobs to be equal to the entire time of conformational motion. Hence, completion of a job at a manufacturing machine corresponds to the molecular machine returning to its equilibrium state ( $\phi_i = 1$ ). In particular this means that the conformational phase corresponds to the degree of completion of a job. As a result, the idle time of a manufacturing machine corresponds to the time the enzymes spend in the ground state waiting to bind a substrate.

We propose a kanban-controlled manufacturing system. A kanban system is a control algorithm developed by Toyota in the 1950s [?] to limit the growth in the work in progress in a manufacturing line. It is essentially a card that authorizes the start of a new job, stays with the job until it is finished and then is returned to the kanban stack. In the molecular network, the number of product molecules influences the start of a new conformational cycle, as modeled in (1a). In a kanban-controlled manufacturing system the presence of a kanban authorizes the start of a new job. Let  $n(t)$  denote the number of idle machines, and  $m(t)$  the number of available kanbans. Jobs are authorized at a rate  $\nu(t)$  as defined in (1a). When a job starts, a kanban is removed from the kanban buffer and attached to the job. If the degree of completion of a job equals  $\phi_p$ , a new kanban is generated and added to the kanban buffer. Upon job completion, the kanban attached with the job returns to the kanban buffer, and the job continues to the batch machine. In contrast to standard kanban systems, the number of kanbans is not constant since a new kanban is created during processing of a job. To prevent the growth of kanbans, they are removed from the kanban buffer with a decay rate  $\gamma$ . Furthermore, assuming large numbers of machines and kanbans we obtain the description (1) describing the manufacturing system dynamics.

#### 4. Controller tuning and simulation experiments

The proposed bio-inspired kanban manufacturing control system (1) has four parameters:  $\nu_0 > 0$ ,  $\nu_1 > 0$ ,  $\gamma > 0$ , and  $\phi_1 \in ]0, 1[$ . In addition, we have following derived parameters:  $n_0$ ,  $m_0$ ,  $N$  and  $\bar{\nu}$ . For a manufacturing system, typically the number of machines,  $N$ , and the desired utilization

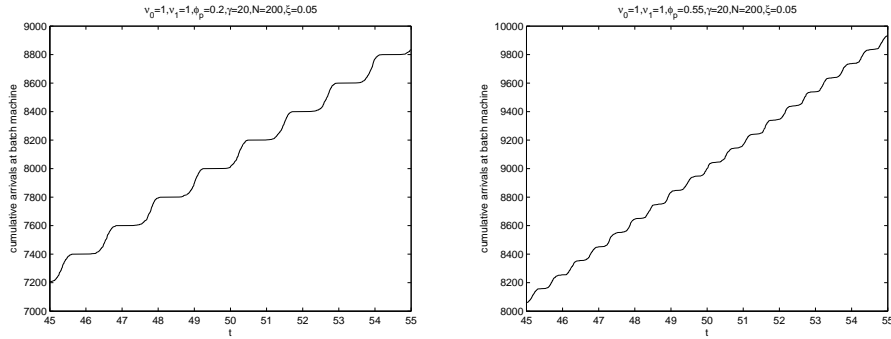
$\rho = \bar{\nu}/(1 + \bar{\nu})$  are given a priori. This reduces the freedom of choice of our parameters.

As we want to keep the parameters  $\phi_p$  and  $\nu_1$  for selecting the resulting system behavior, then for a given number of machines,  $N > 0$ , and a given desired utilization  $\rho \in ]0, 1[$ , we can take

$$\nu_0 = \frac{\rho}{1 - \rho} - \frac{\nu_1 N \rho}{\gamma} \quad \text{with } \gamma > \nu_1 N (1 - \rho). \quad (2)$$

This results in  $\nu_0 > 0$  and  $\bar{\nu} = \rho/(1 - \rho)$ , so  $\bar{\nu}/(1 + \bar{\nu}) = \rho$  as desired. The corresponding steady state equilibrium is given by  $n_0 = (1 - \rho)N$  and  $m_0 = \rho N/\gamma$ .

We performed discrete event simulation studies to validate the working of the proposed manufacturing control scheme. For the first two experiments we considered a manufacturing system consisting of 200 identical machines in parallel. Each machine has a stochastic service time, gamma distributed with a mean of 1 and a standard deviation of 0.05. As in Figure 3 we use  $\nu_0 = 1$ ,  $\nu_1 = 1$ , and  $\gamma = 20$ , which corresponds to a throughput of  $\rho = 0.9099$ . For the first experiment we choose  $\phi_p = 0.2$  and for the second experiment  $\phi_p = 0.55$ . The resulting cumulative amount of jobs delivered to the batch machine is depicted in Figure 4. In both figures we can clearly see a staircase



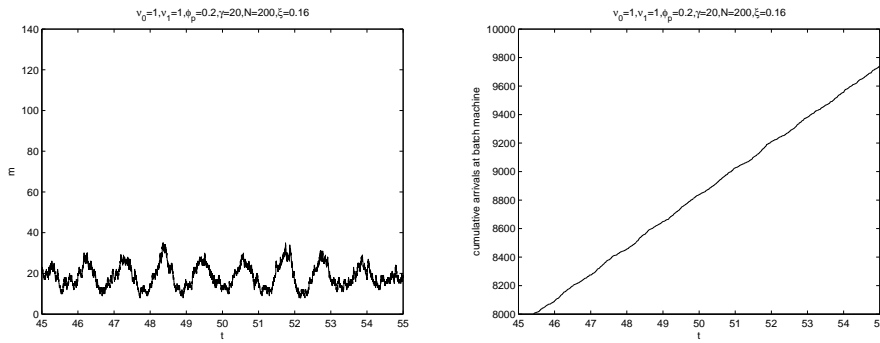
(a) A single group of machines (i.e. full synchronization) for  $\phi_p = 0.2$ . (b) Two coherent groups of machines for  $\phi_p = 0.55$ .

Figure 4: Cumulative deliveries to the batch machine at statistical dispersion of  $\xi = 0.05$  for the parameters  $\nu_0 = 1$ ,  $\nu_1 = 1$ ,  $\gamma = 20$ , and  $N = 200$ .

like graph, which implies that the machines almost simultaneously deliver

their jobs to the batch machine, after which no jobs arrive to the batch machine for a while. By changing the parameter  $\phi_p$  we can achieve either a single group of machines delivering or two groups of machines delivering.

A standard deviation of 5% of the service time is considered low for manufacturing systems. It corresponds with computer controlled operations. Therefore we study the effect of larger disturbances. We repeated the previous two experiments where we increased the standard deviation of the service time to 16%. The results for  $\phi_p = 0.2$  are typical outcomes of our simulation studies and are depicted in Figure 5. We observe that synchronous arrivals to



(a) The number of kanbans still shows period one oscillations (i.e. full synchronization) for  $\phi_p = 0.2$ . (b) The cumulative arrivals to the batch machine for  $\phi_p = 0.2$ .

Figure 5: The number of kanbans and cumulative deliveries to the batch machine as a function of time for a statistical dispersion of  $\xi = 0.16$  and parameters  $\nu_0 = 1$ ,  $\nu_1 = 1$ ,  $\gamma = 20$ , and  $N = 200$ .

the batch machine disappear when the statistical dispersion of the processing times reaches the level of about 16–17% of the batch inter arrival time (Figure 5b). Nevertheless at this level of statistical dispersion the kanbans still show coherent periodic behavior (Figure 5a).

**I don't understand this explanation - can you elaborate?** This observation can be explained as follows. Due to stochastic variations, the service times of jobs vary considerably. When the statistical dispersion of the processing times is about 16-17%, on average about 99% of the jobs are less than 50% too early and more than 50% too late. This makes that jobs of consecutive cycles do not interfere. If the statistical dispersion becomes larger, an early job from the next cycle might have finished earlier than a

late job of the previous cycle, which causes a loss of synchronization at the delivery to the batch machine.

## **5. Conclusions**

We presented a new biologically inspired manufacturing control mechanism which yields synchronous collective machine behavior. This mechanism can be used for a workstation preceding batch processing. Synchronous regimes can be observed when the statistical dispersion of the processing times of single machines are less than 16-17% of the mean batch inter arrival time. This robust synchronization may not be good enough for all types of machines and manufacturing processes. In particular, if variance is generated by machine failure as opposed to variances in transportation time or operator handling time, the variance of the processing times may be too high for synchronization.