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# Optimal distributed real-time scheduling of flexible manufacturing networks modeled as hybrid dynamical systems

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ABSTRACT

The paper considers a class of flexible manufacturing networks. We employ hybrid dynamical systems to model such networks. The main and new achievement of the paper is that we propose a distributed implementable in real time scheduling rule such that the corresponding closed-loop system is stable and optimal. In stable systems the processes converge to periodic ones. The paper gives computing relations for the determination of the parameters of the periodic processes. These are very much suitable for planning purposes. On this basis—and this, we consider, is also a new, significant result—optimal arrival (demand) rates determination method is proposed. Quality characteristics are outlined. Field of application of hybrid dynamical approach for FMS scheduling is analyzed. The results open perspectives for MRP level task planning. Example and simulation results are presented.
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## 1. Introduction

Hybrid dynamical systems (HDS) have attracted considerable attention in recent years (see e.g. [1–3] and references therein). In general, HDS are those that combine continuous and discrete behavior and involve, thereby, both continuous and discrete state variables. In many cases, such systems operate as follows. While the discrete state remains constant, the continuous one obeys a definite dynamical law. Transition to another discrete state implies a change of this law. In its turn, the discrete state evolves as soon as a certain event occurs with both the evolution and the event depending on the continuous state.

The class of HDS introduced in the paper consists of complex switched server queueing networks. This class of HDS was introduced in [4,5] to model flexible manufacturing systems (see also [2,6–10]). A flexible manufacturing system considered in this paper produces several part-types on a network of machines. Raw parts are inputs to the network. Parts arrive at a machine and are awaiting in buffers. Each unit of a given part-type requires a predetermined processing time at each of several machines, in a given order. A set-up time is required whenever a machine switches from processing one part-type to another.

In the theory of flexible manufacturing systems, there is the following important optimization problem: To find the minimal time $T$ and a scheduling policy such that production of part-types over the time interval $[0,T]$ equals the given desired levels. This problem is highly nonlinear and nonconvex, and no constructive solutions implementable in real time are known (see e.g., [11,12]). In this paper, we introduce a slightly modified optimization problem and show that this problem has a constructive and computationally non-expansive solution. For this purpose, we introduce the concept of regularizability. Intuitively, this means that there exists a feedback control policy that meets the following two conditions:

(i) All the trajectories of the closed-loop system are bounded. It means that the buffers of all the machines are guaranteed to be bounded, and the system can thus operate with finite buffer capacities.
(ii) Production of part-types over time intervals $[kT,(k+1)T]$ converges to the given desired production levels as $k$ tends to infinity.

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Then our optimization problem is to find minimal possible value of such time $T$. We obtain a necessary and sufficient condition of regularizability and a simple algebraic formula for the minimal time $T$. For regularizable networks, we find a decentralized control policy implementable in real time which guarantees a regular behavior of the closed-loop system. The case of zero set-up time was considered in [13,14]. The algorithm of [13] asymptotically converge to a limit that is the same as the performance of our method for the case zero set-up times. The paper [14] presents heuristic algorithms. Furthermore, [13,14] did not study the issue of stability. Quite general optimization problems were considered in [15,16]. However, the results of [15,16] lead to computationally expensive algorithms whereas the results of this paper are given in terms of very simple and easily implementable algebraic conditions.

Furthermore, in Section 4, we address the work in progress issue and propose a slightly modified scheduling policy which guarantees that the system will operate with a small quantity or work in progress and production of part-types will be equal to desired levels over any time interval $[kT,(k+1)T]$.

In Section 5, the aspects of practical applications are discussed. Optimal arrival (demand) rates determination method is proposed. The optimal arrival rate coefficient obtained in such a way provides that the excess time of the completion time compared with the global minimum of net manufacturing time will be minimal. The above method is based on the considerations of periodic processes the existence of which got strong theoretical basis in the present article. This Section introduces a term called set-up relation coefficient, which characterizes the given side of the flexibility of manufacturing systems. The smaller this coefficient is the better the results of application of HDS theory to manufacturing scheduling are. The outlined method gives also an opportunity to clear the field of possible application of the above theories in the relation to the numbers of parts.

In Section 6 examples and simulation results are presented. They are especially directed for investigating the periodic processes. The results are surprisingly favorable. They clearly demonstrate the applicability and effectiveness of both the theoretical results and planning issues.

In Section 7 Conclusions are formulated. The most important is that the theoretical results of the paper provide strong basis for the use of HDS theory for solving manufacturing scheduling problems. When using this, which application field is now already clear, a number of problems still open can be effectively solved. Among them are the following:

- Optimal arrival rate can be determined which guaranties the given small excess time over the global minimum of net manufacturing time
- Automatic lot streaming and overlapping production can be realised
- On-line, real-time, distributed, robust control is possible in a very simple way
- MRP and scheduling level interconnection is easy to realise for task planning purposes

## 2. Problem statement

In this paper, we investigate flexible manufacturing systems described by the following features:

(i) There are $P$ part-types labeled $1,2,\ldots,P$, and a set $\mathcal{M}=\{1,2,\ldots,M\}$ of machines.

(ii) Parts of type $p$ require processing at the machines $\mu_{p,1},\mu_{p,2},\ldots,\mu_{p,n_p}$ in that order where $\mu_{p,i}\in\mathcal{M}$.

(iii) Raw parts of type $p$ arrive to the system at the machine $\mu_{p,1}$ at a constant rate $r_p>0$.

(iv) At the $i$th machine they visit, parts of type $p$ enter the buffer labeled $b_{p,i}$, from which they are eventually processed by this machine at a given constant rate $R_{p,i}>0$.

(v) We also assume that parts of type $p$ incur a fixed transportation delay $l_{p,i}\geqslant 0$ when moving from the machine $i$ to the machine $i+1$.

(vi) The machine $m$ is served from the buffers $B_m:=\{b_{p,i}:\mu_{p,i}=m\}$. A minimal set-up time $\delta_m^0>0$ is required when the machine $m$ switches from processing parts of type $p$ in the buffer $b\in B_m$ to processing parts of another type $p'$ in a buffer $b'\in B_m$. The machine does not work during such a set-up time. The set-up time can be artificially increased to achieve our control goal. In other words, set-up time $\delta_m(t)$ of the machine $m$ is a control variable. However, condition

$$\delta_m(t)\geqslant\delta_m^0 \tag{1}$$

should be satisfied.

In this paper, the flexible manufacturing system under consideration is defined by production paths $\mu_{p,1},\mu_{p,2},\ldots,\mu_{p,n_p}$ of the part-types, machine rates $R_{p,i}$, minimal machine set-up times $\delta_m^0$, and transportation delays $l_{p,i}$. The arrival rates $r_p$ are to be chosen from our control goal.

For such a system, let $x_{p,i}(t)$ denote the level of the buffer $b_{p,i}$ at time $t$. We refer to the contents of buffers as "work": it will be convenient to think of work as a fluid, and a buffer as a tank. However, in applications to flexible manufacturing systems, work represents a continuous approximation of the discrete flow of parts.

The location of any machine is a control variable, and may be selected using a feedback policy.

Furthermore, for any $1\leqslant m\leqslant M$, introduce a symbolic variable $q_m(t)$ to describe the state of the machine $m$. Let $B_m:=\{b_{p,i}:\mu_{p,i}=m\}$ be the set of the buffers served by the machine $m$, and introduce the set of symbols $\hat{B}_m:=B_m\cup\{0\}$. Then the function $q_m(t)\in\hat{B}_m$ is defined for all times $t$ as follows:

$q_m(t):=0$ if the machine $m$ does not work at time $t$, and $q_m(t):=b_{p,i}$ if the machine $m$ works with the buffer $b_{p,i}$ at time $t$.

Moreover, let $y_p(t)$ denote the amount of parts of type $p$ at time $t$ fully processed by the flexible manufacturing system. In other words, $y_p(t)$ is the cumulative output of part-type $p$ from the buffer $b_{p,n_p}$ over $[0,t]$.

**Remark 2.1.** We allow for the possibility that parts may visit any machine more than once ($\mu_{p,i}=\mu_{p,j}$ for some $i\neq j$). Therefore, the class of systems under consideration in this paper includes networks with non-feedforward flows such as, for example, Kumar–Seidman (Rybko–Stolyar) network [17,18] and Dai–Hasenbein–Vande Vate network [19].

**Remark 2.2.** The buffers introduced in the system are virtual ones. For example, in a real-world flexible manufacturing system all parts may be stored in one buffer. The computer control system treats the parts of a certain type as taken from the corresponding virtual buffer irrespective of the fact where they are stored. Such virtual buffers are certainly appropriate if the flexible manufacturing network under consideration is configured with a single buffer that all machines can directly access. A simple example of such a network is the experimental FMS of the Budapest University of Technology and Economics [20,21]. The system contains a central storage buffer and automatically guided vehicles which provide extremely small transportation times.

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