Modelling and Analysis of a Re-entrant Manufacturing System

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Abstract

Re-entrant manufacturing systems can frequently be found in semiconductor industries, where the same work systems are used repeatedly for different stages of processing. Due to feedback loops in the material flow, re-entrant manufacturing systems show complex dynamic behaviour making it difficult to predict or control the performance of the systems.

The first part of the paper presents a dynamical model of a re-entrant manufacturing system. This model shows different qualities of dynamic behaviour, depending on the ratio between work load and system capacity. The under-loaded system has the properties of a quasi-periodic driven dissipative dynamical system. The over-loaded system shows dynamics between quasi-periodicity and chaos.

The second part of the paper presents a simulation model based on a dynamical control concept. The simulation model consists of different modules containing the system parameters. The system variables – buffer levels and processing phases – indicate the state of the manufacturing process. This model will be used to develop, test and evaluate dynamic control methods and to investigate the influence of different control policies on dynamics and performance of this re-entrant manufacturing system.

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Introduction

Re-entrant Manufacturing Systems and Models

Re-entrant manufacturing systems are production systems that use the same work systems repeatedly for different stages of processing. This can be found in job shops as well as in flow shops, where the route of a certain type of part through the system is pre-determined, but forms one or more feedback loop. Such re-entrant lines can frequently be found in the semiconductor industry, where wafers undergo a high number of processing stages at a lower number of work systems.

The re-entrant nature of material flow, disparate processing times for different processing stages at a machine, and machine down times make scheduling and control of re-entrant manufacturing systems quite difficult. The situation becomes even more complicated, if the manufacturing system has to process two or more different types of parts. Then the problem of set-ups and lot sizing becomes relevant.

Investigations of re-entrant manufacturing systems aim to stability of scheduling and release policies, optimal control for maximum performance as well as understanding of dynamic system behaviour. For these purposes, different types of models were developed in the past. They can roughly be classified into *flow models*, mostly realised by differential equations, and *discrete models*, realised by a queuing network or event-discrete simulation. At both types of models, events within the system can be modelled as *stochastic* or *deterministic*. A processing time, for example, can vary randomly or be constant.

The most common models of re-entrant manufacturing systems are *queuing networks*, where a machine and its input buffer are represented by a server with a queue in front of it. The discrete part flow through the network is described by formulas of stochastic queuing theory. Such queuing models are good tools for analysing the overall system performance under different release and scheduling policies. This has been done intensively in the past by various authors, especially by Kumar and his colleagues, e.g. in [Kumar 94].

The analytic investigation of queuing models is appropriate for small systems with only a few components. But larger numbers of machines, buffers, and processed parts lead to complex queuing networks that are hard to analyse using the formulas of queuing theory. In that case, it is appropriate to use *discrete-event simulation* for analysing the system. The simulation provides results about stability and performance of the system, plus the chance to analyse its dynamic behaviour. [Beaumariage and Kempf 94] analysed a re-entrant manufacturing system via simulation and showed the sensitive dependence of throughput times and output patterns on initial conditions as well as scheduling and release policies. They postulated that chaotic dynamics were the reason for this unstable behaviour. But for a proper investigation of the dynamics of a re-entrant manufacturing system, a deterministic model based on Nonlinear Dynamics Theory may be essential.

Such a *dynamical model* focuses more on the temporal evolution of the re-entrant manufacturing system than on its performance. The *system state* can be described by *variables* such as “buffer levels” and “processing phases”. These variables span the *state space* of the system. The temporal evolution of the system is represented by *trajectories* in this state space. The state space and the run of the system trajectory can be used for analysing the dynamics of the system. Such dynamical models are used by [Hanson et al. 98] and [Diaz-Rivera et al. 98]. Hanson et al investigated the stability of their model and showed that – contrary to [Beaumariage and Kempf 94] – no chaotic behaviour occurs. Diaz-Rivera et al used a Poincaré map of a re-entrant manufacturing system and proved that only periodic orbits appear. Another dynamical model of a re-entrant manufacturing system, developed by [Katzorke 02], will be presented in part I of this paper.

Control Policies and their Analysis

Control of re-entrant manufacturing systems means an optimal choice and combination of release and scheduling policies to realise high throughput and low work-in-process. The control policies should be robust against uncertainties and must provide good system performance.

A release policy regulates the part input into the system. It determines the points in time at which parts arrive as well as the quantity of any release. Release policies are applicable if the re-entrant manufacturing system is more or less autonomous. If it is organised in a pull-type production line or supply chain, the arrival of parts into the system is determined exogenous and can not controlled by the system.

A scheduling policy regulates the withdrawal of parts from the buffer for processing at the machine. The buffer can contain (i) different types of parts and (ii) parts at different stages of processing. The scheduling policy determines which type of part and which processing stage has the highest priority for processing next. The most common scheduling policies are the *First-Come-First-Served* policy (FCFS), also known as *First-In-First-Out* (FIFO), and the *Last-Buffer-First-Served* policy (LBFS), an implementation of the pull principle. A good overview about scheduling policies for re-entrant manufacturing systems can be found in [Kumar 94].

From a systems perspective, the control policies represent the information sub-system, which generates the dynamics of the physical sub-system (machines, buffers, parts). The release policy generates the material input into the system; the scheduling policy controls the material flow through the system, thus linking the control policies to the system dynamics. This motivates the use of dynamical models, mentioned above, to analyse the system dynamics and to develop control policies based on Nonlinear Dynamics Theory.

Due to the specific features of re-entrant manufacturing systems, the development of appropriate control policies is not trivial. It is well known that, for example, scheduling problems are NP-hard. Therefore, control policies are mostly verified by simulation. It provides results about the *stability* of the chosen control policies as well as *performance* and *dynamics* of the system.

Stability of a manufacturing system is simply a matter of work load versus processing capacity. That means the arrival rate of parts may not exceed the processing rate of the overall system. Unfortunately, in re-entrant manufacturing systems, the total system capacity can not easily be derived from single machine capacities. Here, the re-entrant structure of the system and the chosen scheduling policy create additional capacity constraints, also called virtual bottlenecks [Nielsen 01]. This can lead to an accumulation of parts to infinity despite a low work load – the system turns unstable. This phenomenon has led to the extensive investigation of various combinations of re-entrant flow structures and scheduling policies, especially with respect to their stability properties. The main result was that the LBFS policy was proven stable for any kind of re-entrant manufacturing system [Lu et al. 91].

The goal of controlling re-entrant manufacturing systems is to reach good performance. Common performance measures are the total work-in-process and its costs, the throughput volume and the mean throughput time and its variance. The total work-in-process and the throughput time are related to each other by Little's Law: Work-in-process = arrival rate of parts × throughput time [Kumar 94]. With that, low work-in-process minimises not only costs but also shortens the throughput time of a part. A small variance of the mean throughput time ensures meeting the due-dates, allows better planning of releases into the system, and leads to better coordination of further operations, such as assembly. Maximising throughput volume seems to be a matter of maximising capacity utilisation. But a high capacity utilisation requires high work-in-process which leads to high costs and long throughput times. If the throughput times increase, the throughput volume decreases temporarily. So the throughput volume can not be controlled directly, but is a result of minimising work-in-process and throughput time. All performance measures result from the chosen scheduling and release policies. Some combinations of policies optimise one performance measure but worsen the others. But in general, the LBFS policy is proven to be almost always the best for re-entrant manufacturing systems [Lu et al. 91].

Despite extensive investigations of re-entrant manufacturing systems, there is little research on developing an understanding about their dynamics. The re-entrant structure and a high work load lead to complex dynamic behaviour, while small changes in release or scheduling policies lead to large effects on system performance [Beaumariage and Kempf 94]. These complex dynamics (and possibly deterministic chaos) make it difficult to predict or control the performance of re-entrant manufacturing systems. This motivates an analysis of the system dynamics (i) to decide, whether the system is periodic, quasi-periodic or chaotic, and (ii) to find a mapping of system attractors to performance measures, which will serve as a basis for application of dynamic control methods, derived from Nonlinear Dynamics Theory.

This paper is structured as follows: Part I introduces a specific re-entrant manufacturing system, develops a dynamical model, and analyses its dynamics. Part II introduces a dynamical concept for manufacturing control and presents a simulation platform for an analysis of different scheduling and control policies.

Part I

“2 products – 2 stages” Re-entrant Manufacturing System

The re-entrant manufacturing system considered here consists of a single work system, where two varying types of parts have to pass the system twice for processing. Such a manufacturing system is depicted in figure 1. The two varying parts – labelled A and B – arrive at this work system and enter the input buffer. After the first processing stage, the parts are denoted as A' and B' and return to the input buffer. After the second processing stage, the parts are denoted as A'' and B'' and leave the work system.

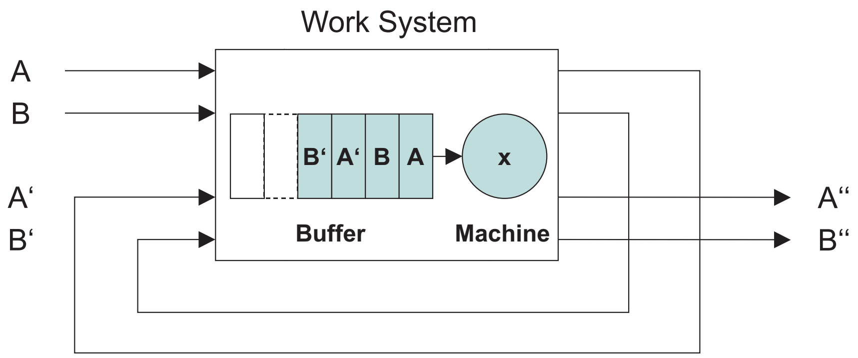

Figure 1: Schematic part flow for the “2 products – 2 stages” re-entrant manufacturing system. Two varying parts A and B have to pass the work system twice until they leave it as A'' and B''.

The parts in the input buffer are organized as a queue according to the FIFO policy. No advanced scheduling rule is applied. In the case of simultaneous arrival of two or more parts, the priority for entering the input buffer is A > B > A' > B'. This means, that at the input of the machine, a series of four symbols A, B, A', B' is encountered, which is transformed to the corresponding series of A', B', A'', B'' at the output. It is assumed that parts A and B arrive at deterministic periodic time intervals t_A and t_B, respectively. Other relevant parameters are the processing times for parts A, B, A', B'. These times are denoted as T_A, T_B, $T_{A'}$, $T_{B'}$, respectively. It is assumed that all these times are constants. For the dynamics of the system it is essential that the times $t_{A,B}$, $T_{A,B,A',B'}$ are arbitrary real numbers. This makes the whole process at least as complex as quasi-periodic. Here, the symbolic characterization of the process will be used to investigate this system.
Depending on its capacity, the machine will be able to process all incoming parts, or not. In terms of the parameters of the system, i.e. of the times $t_{A,B}$, $T_{A,B,A',B'}$, this can be formulated as follows: Let us consider a time interval T, which is large enough for statistical investigations. During this time $N_A = T / t_A$ parts of type A and $N_B = T / t_B$ parts of type B are delivered. The total processing time for these parts is $T_{process} = N_A (T_A + T_{A'}) + N_B (T_B + T_{B'})$.
Thus, the critical processing capacity is described by the parameter τ :

$$\tau = \frac{T_{process}}{T} \quad (1)$$

$$\tau = \frac{T_A + T_{A'}}{t_A} + \frac{T_B + T_{B'}}{t_B} \quad (2)$$

The following types of systems can be distinguished according to the value of τ:

- $\tau < 1$: under-loaded system: the incoming part flow does not exhaust the system capacity;
- $\tau = 1$: balanced system: the incoming part flow fits exactly the processing capacity;
- $\tau > 1$: over-loaded system: the processing capacity is insufficient to process all incoming parts.

Because of this classification, the queue will disappear, remain, or grow with time depending on the value of τ.

Dynamical Model

The work system modelled here consists of the two sub-systems "buffer" and "machine" (see figure 1). The overall system state thus consists of the current states of the buffer and the machine. The current state of the buffer is described by a sequence of symbols in the queue, namely A, B, A', B'. The current state of the machine is described by a continuous variable x ($0 \le x \le 1$) which can be viewed as the processing phase. The phase x grows linearly in time:

$$\frac{dx}{dt} = \frac{1}{T_S} \quad (3)$$

where S (S $\in$ A, B, A', B') stands for the part which is in process. As x reaches the value 1, the processing of the part ends and the queue is rearranged: the first-in part enters the machine and – in the case S = A or S = B – the corresponding part (A' or B') is added to the end of the queue as soon as the parts leave the machine. Additionally, every time step t_A and t_B, parts A and B are added to the end of the queue. In the general case of incommensurate arriving times t_A and t_B, this latter operation can be considered as a quasi-periodic driving of the system.
The parameters governing the dynamics are the times t_A, t_B, T_A, T_B, $T_{A'}$, $T_{B'}$. The following parameters are used: $t_A = 1$, $t_B = 1+\sqrt{5}$, $T_A = T_{A'} = (2\sqrt{2})^{-1}$, $T_B = T_{B'} = c^{-1}(2-\sqrt{2})(\sqrt{5}-1)^{-1}$. Here the parameter c governs the balance condition. Using the parameters, one obtains from equation (2): $\tau = c^{-1}(1+(c-1)/\sqrt{2})$.

Analysis of Dynamics

Sensitivity to Initial Conditions

The sensitivity of the model to initial conditions is analysed because a sensitive dependence of the system dynamics on small changes in initial conditions is an indicator for a chaotic dynamics. For this purpose, the model is slightly perturbed by a small shift of the arrival times

t_A and t_B. Then, changes in the symbolic sequence in the queue are observed. In the case of a balanced or over-loaded system, the change in the symbolic sequence never disappears, because the queue is never empty and the undisturbed arrival times cannot be restored (see figure 2). In the under-loaded case, the queue is empty from time to time. In these periods, the perturbation of the shifted arrival times disappears, and the unperturbed symbolic sequence is restored (see figure 2). Thus, the effect of perturbation on the under-loaded dynamics is only temporary: it exists only during the time interval $\delta t_1 < t < \delta t_2$ after the perturbation is imposed. Here δt_2 is the time at which the sum of all empty queue states exceeds the perturbation and is inversely proportional to $(1 - \tau)$.

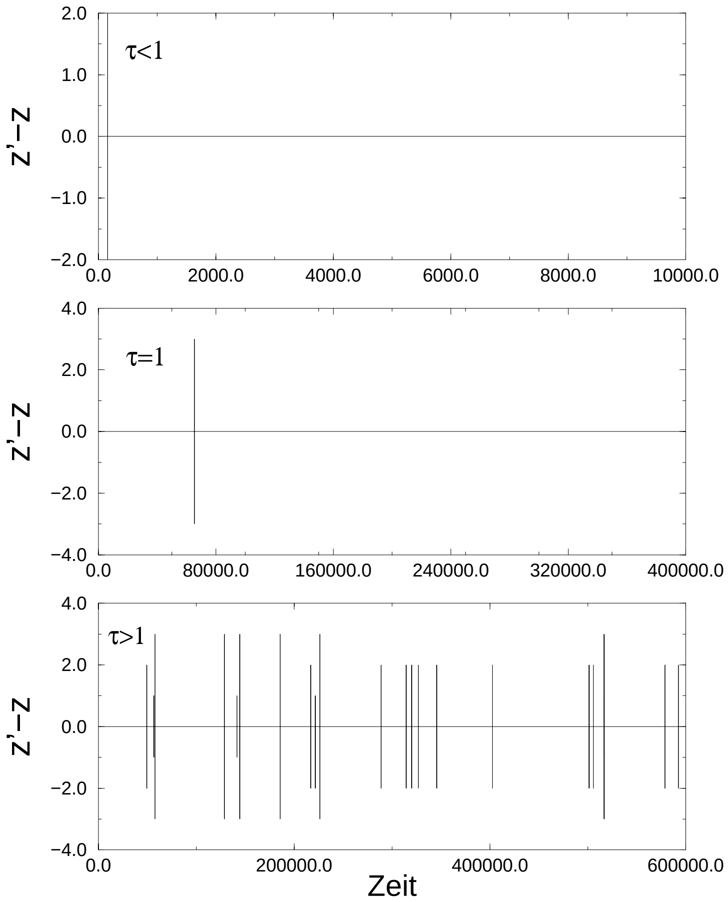

Figure 2: Sensitivity of the symbolic sequences: the difference of the symbols of the perturbed (at time step 4) and the unperturbed sequences. Upper panel: under-loaded system c = 1.1, middle panel: balanced system c = 1, lower panel: over-loaded system c = 0.9. The perturbation is $c_p = c \cdot 1.00001$ in all cases.

Ergodicity and Stationarity

To test the system for ergodicity, one has to determine how the observed transition probabilities in a time series (i.e. probabilities to find pairs of symbols like AB) depend on the initial conditions. For $c \neq 1$, it is found that the transition probabilities do not depend on initial conditions, while for $c = 1$, such dependence is observed (see figure 3).

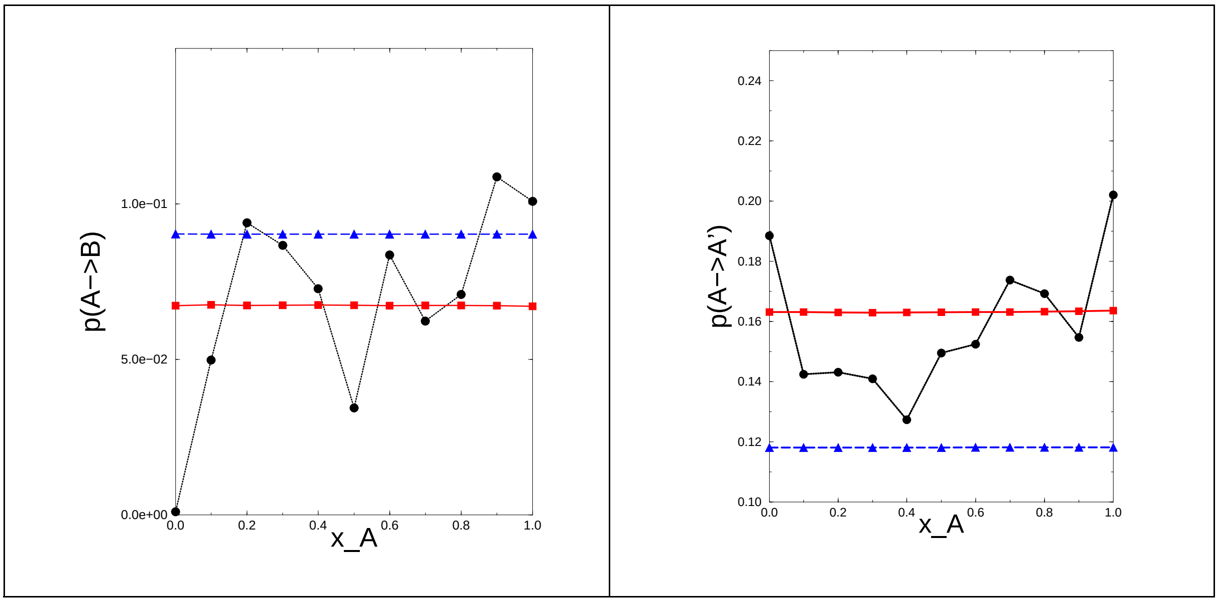

Figure 3: The probabilities of finding a pair (A, B) (left) resp. a pair (A, A') (right) in the queue are shown for the balanced (solid line, filled circles), the over-loaded (dotted line, filled squares) and for the under-loaded (dashed line, filled triangles) systems depending on the initial conditions x_A. Note that only the balanced system exhibits a dependence of p on the initial conditions.

Qualitatively, such a dependence on the balance condition can be understood as follows: in the under-loaded case, the dynamics as shown above are not sensitive to the initial conditions, and are fully determined by the quasi-periodic drive (input flow of parts). Therefore, the system is ergodic. In the over-loaded case, the queue grows, thus any perturbation in the dynamics of the system increases because it affects more and more parts in the queue. As a result, effective "averaging" over all initial perturbations occurs, resulting in ergodic behaviour. In the balanced case, a perturbation in the initial conditions remains roughly constant over time because the queue length is constant. Therefore, different initial conditions do not "mix" and the statistics can depend on them, thus breaking the ergodicity.

Stationarity of the observed symbolic time series is ensured in the under-loaded case, where the dynamics are essentially driven by the quasi-periodic input, and thus follows the stationarity of the quasi-periodic process. The stationarity is tested numerically by the χ^2-criterion

$$\chi^2 = \sum_i^{n_c} \frac{(s_i - q_i)^2}{s_i + q_i} \qquad (4)$$

where s_i is the number of the observed events of a combination, for instance (A, B), from one section of the time series and q_i the number of observed events of the identical combination in another section of the time series. Further n_c is the number of all possible combinations.
For values of the parameter τ not too close to 1, the stationarity hypothesis could always be confirmed. If τ is close to 1 (e.g. $\tau \approx 0.995$), there are difficulties in applying the test because the statistical properties indicate very slow modulations, which would rquire averaging over extremely long time intervals.

Correlations

For the calculation of the normalized autocorrelation function, a time series z_i is used:

$$C(k) = \frac{\langle z_{i+k} z_i \rangle - \langle z \rangle^2}{\langle z^2 \rangle - \langle z \rangle^2} \tag{5}$$

In the under-loaded case, the autocorrelation function demonstrates a pattern typical of quasi-periodic dynamics, returning to a value near 1 at a relatively regular rate. This supports the above conclusion that in this case, the behaviour of the system is completely determined by the quasi-periodic driving. In the case of perfect balance ($\tau = c = 1$), the dynamic behaviour depends on initial conditions, so the autocorrelation function depends on them as well. Two examples are shown in figure 4. In all observed situations, the correlations are close to 1 for some large time shifts k, thus indicating quasi-periodicity. In some cases, the correlations are not close to 1 for small k. This means that the process is more complex than a quasi-periodic one.

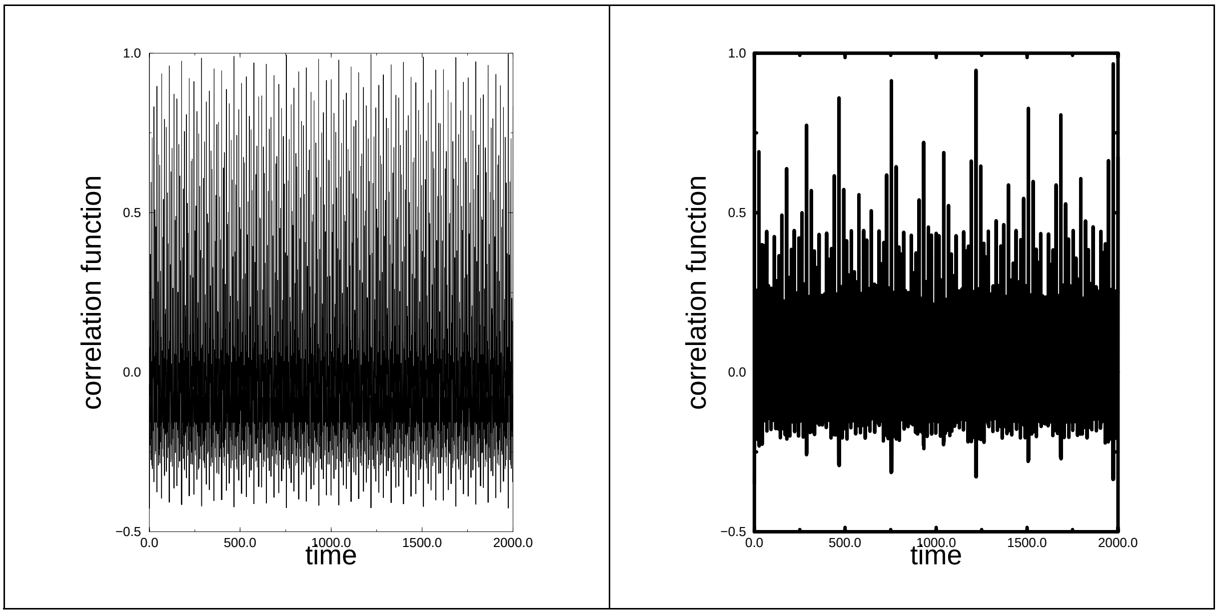

Figure 4: Balanced system: Dependence of the correlation functions on the initial conditions, i. e. the start position of the parts (left side: $x_A = 0$, $x_B = 0$, $x_{A'} = 1$ and $x_{B'} = 0$, right side: $x_A = 0.5$, $x_B = 0.5$, $x_{A'} = 0$ and $x_{B'} = 0$). Sequences (2^{19} symbols) are measured at the output of the work system and consist of all four symbols A, B, A' and B'. The values of these correlation functions return to the value 1 after some time steps. From this, one can assume that the system will be quasi-periodic in all cases.

The largest complexity is achieved in the over-loaded case. Here the value of the autocorrelation function does not return to 1 even for large time shifts k. An example of the autocorrelation function for $0.98 \leq c \leq 0.999$ is presented in figure 5. This function looks like a quasi-periodic one on a small scale, but with a slowly varying envelope with numbers less than 1. This envelope is shown in figure 5 for different values of parameter c, i.e. for different levels of violation of the balance condition. One can see that for larger deviations of τ from 1, the correlations decay faster and to a lower level.

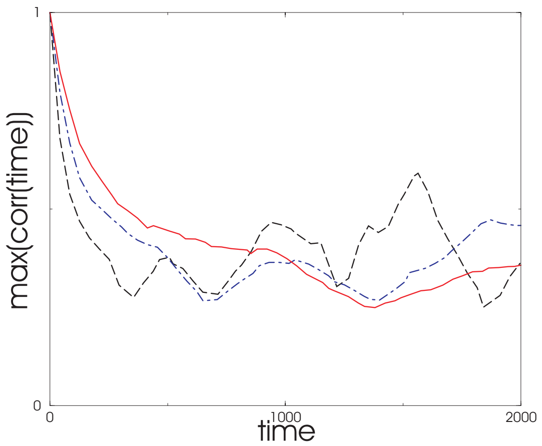

Figure 5: The envelope drawn through the peaks of the correlation function. Parameter values used: c = 0.98 (dashed line), c = 0.99 (dotted-dashed line) and c = 0.995 (solid line).

From the shape of the correlation function it follows that the spectrum is neither discrete nor absolutely continuous. Indeed, it neither decreases to zero nor returns to one. Because the integrated correlation function does not decrease to a value close to zero, the spectrum is apparently not singular continuous. Thus, the situation is quite complicated and it is hardly possible to extract the singular continuous component from the spectrum, because it also has very strong discrete components. Thus, the results described in the last section are of purely conjectural nature. At present, no mathematical descriptions of the spectral measure and the properties of the integrated correlation function exist for this type of system.

Part II

Dynamical Concept for Manufacturing Control

Modern manufacturing systems are highly complex in their structures and dynamics. Even quite simple systems as investigated in part I of this paper can show complex dynamic behaviour. To control such manufacturing systems, concepts from Nonlinear Dynamics Theory could help to manage their dynamic complexity and possibly provide strategies and methods to control the manufacturing process.

This motivates the development of a dynamical concept for manufacturing control. Within this concept, the manufacturing system is considered to be a dynamical system. Such a system has a set of parameters and system variables. The behaviour of the manufacturing system as a whole follows its intrinsic dynamics, which are influenced by the system parameters. As a result of the dynamics, the system variables change over time.

The system variables span the state space of the system. The temporal evolution of the system is represented by trajectories in this state space. The state space and the run of the system trajectory are used for analysing the dynamics of the system and provide possibilities to control the system.

The state of the manufacturing system at any point in time is defined by a point on the trajectory in the state space. It is thus possible to influence and control the state and the evolution of a manufacturing system by manipulation of the system trajectory. For this, several methods for the control of dynamical systems have been developed.

A dynamical system can be controlled by variation of the system parameters to force the system variables onto a desired trajectory. The variables that are usually controlled in a manufacturing system are inventory levels or work-in-process. The temporal evolution of these variables depends on the system dynamics. The idea behind the dynamical concept is to control these dynamics by variation of the system parameters, which are considered flexible and capable of being influenced.

Because of the high number of different parameters of a manufacturing system, they have to be combined into the following functional groups: *structure, capacity, operational rules, release policies, scheduling/queuing policies* [Scholz-Reiter et al 02]. These functional groups generate the dynamics of a manufacturing system, and enable and influence the part flow through the system. They are at first a framework for modelling the manufacturing system and thereafter provide possibilities to control the production process.

Within the dynamical control concept, the variables of the system such as *buffer levels* and *processing phases* are monitored continuously. These variables represent the current system state, which is the basis for controlling the system. Due to the reference to the *current* state of the system, the control takes place continuously and dynamically by an adjustment of the functional groups mentioned above to force the buffer contents and therewith the overall work-in-process to reach a desired level. The goal is a close-to-real-time control of the production process to meet the current requirements of the manufacturing system.

To verify the dynamical control concept, the “2 products – 2 stages” re-entrant manufacturing system – introduced in part I of this paper – is used for developing dynamic control methods. Here, the functional group “structure” is considered constant – the other functional groups can be used for control.

Simulation Model

A simulation platform that provides an event-discrete simulation of the manufacturing process was developed with the objective of developing, testing, and evaluating dynamic control methods as well as investigating the influence of different control policies on the dynamics of the considered re-entrant manufacturing system. An important feature of this simulation platform is the possibility to monitor and record all processes and events so as to capture the dynamics of the system.

The simulation platform is based on the dynamical concept introduced in the last section. The functional groups are implemented in modules. The main module contains the “structure”, here the structure of the “2 products – 2 stages” re-entrant manufacturing system (see figure 1). This main module consists of further modules (sub-systems) which contain the other four functional groups. The sub-system “capacity” contains the capacity of the input buffer (minimum and maximum buffer level) and the capacity of the machine (processing times for every type of part at every processing stage). Thereby, the processing times can randomly vary or be constant. The sub-system “operational rules” controls the buffer input and output. It contains rules such as “stop input if buffer full” or “stop output if buffer empty”. The sub-system “release policy” defines the part input into the system. Parts can arrive at deterministic points in time (constant release periods or inter-arrival times respectively) or randomly.

The sub-system “scheduling/queuing policy” determines the priority of the different types of parts at the different stages of processing (i) for entering the input buffer in the case of simultaneous arriving of two or more parts and (ii) for the withdrawal of parts from the buffer for processing at the machine. The first task of this sub-system is due to the existence of only one main buffer for the different types of parts and processing stages. Here, the type of part or the stage with the lower priority will be shifted from simulation step t to t+1. The second task realises the application of a specific scheduling policy such as LBFS or simply FIFO. But the most interesting feature of this sub-system is the possibility to implement dynamic scheduling policies. In doing so, the policy picks out a type of part and a stage depending on the current system state.

The current state of the system is defined by the system variables. To grasp this system state, the main module “structure” contains monitors for observing the system variables. These are: the buffer levels of the different types of parts and processing stages (A, B, A’, B’) as well as the total buffer content, the buffer input and output patterns and the progress of processing of a part in the machine (processing phase). The temporal evolutions of these system variables represent the dynamics of the system. They will be used for analysis of dynamic behaviour caused by different static or dynamic control policies.

To verify the performance of a chosen control policy, there are routines for calculating the throughput times for every part and the total throughput as well. It should be noted that no mean values are used. The whole simulation model is deterministic. Nevertheless, stochastic influences can be implemented additionally.

Analysis of Scheduling Policies

To demonstrate the functioning of the simulation model, the influence of different scheduling policies on buffer levels, part processing and throughput is investigated. The processing time of every part at every stage is set to 5. The total cycle time of every part including transit times is 13. The inter-arrival times of both types of parts A and B are set to 20. Due to the successive processing of every part and every stage, the system is overloaded by factor 1.3. This overload is used to point out the effects of the different scheduling policies.

The scheduling policy applied first is First-Buffer-First-Served (FBFS). This policy prioritises the buffer that contains parts waiting for the lowest stage of processing. That means in this case, that the parts A and B, which are waiting for processing at its first stage, have a higher priority than the parts A' and B', which are waiting for processing at its second stage.

The second scheduling policy applied is Last-Buffer-First-Served (LBFS). This policy prioritises the buffer that contains parts waiting for the highest stage of processing. That means that the parts A' and B', which are waiting for processing at its second stage, have a higher priority than the parts A and B, which are waiting for processing at its first stage.

In both cases, part type A has always a higher priority for processing then part type B. The following figures 6 and 7 show (i) the buffer levels of the different types of parts and processing stages and the total buffer content, and (ii) the part processing in the machine.

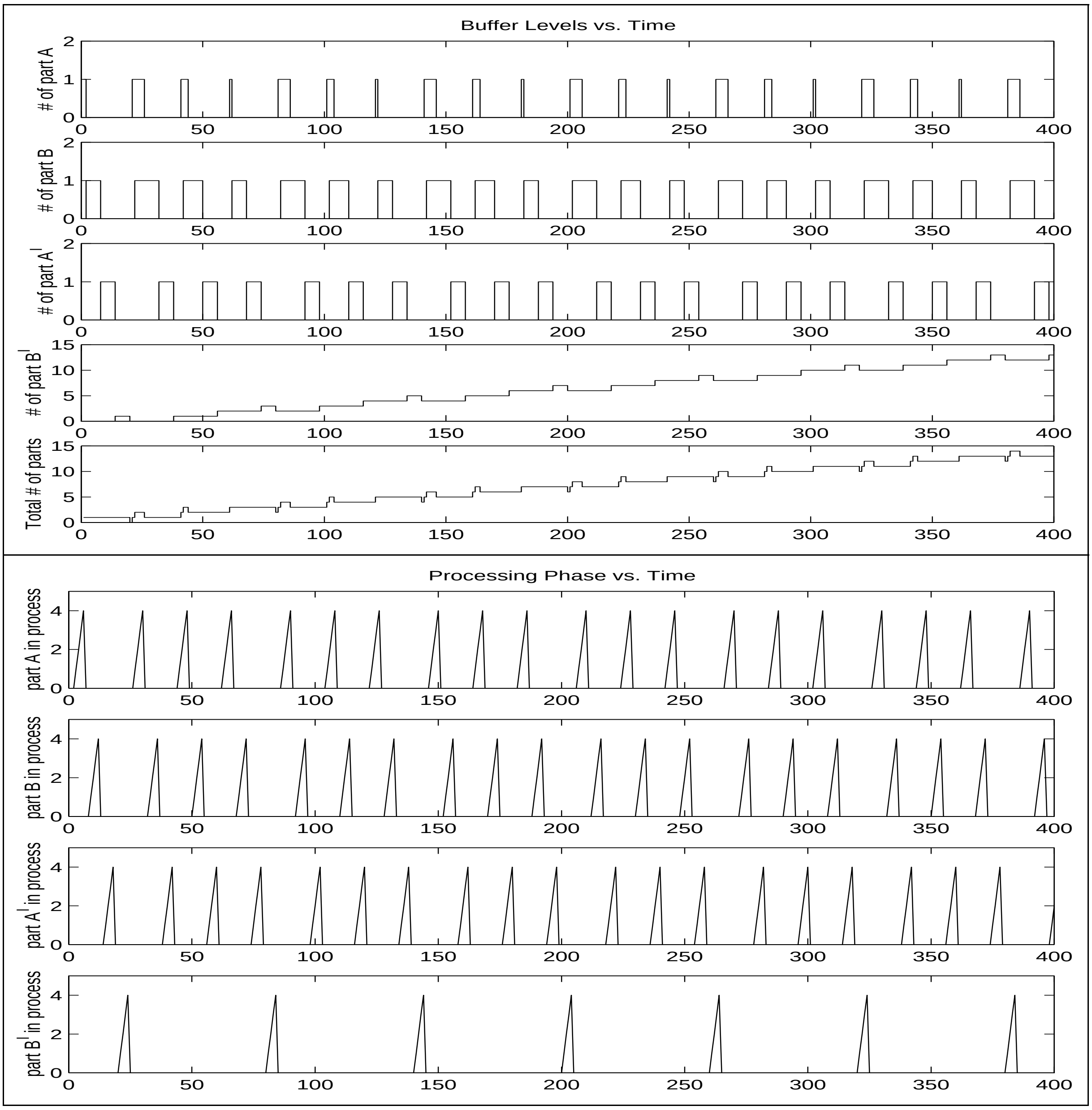

Figure 6: Buffer levels and part processing under the FBFS policy.

Due to the FBFS policy and the general A-over-B priority, parts A have the highest priority and B’ the lowest. This leads to an increasing amount of B’ in the buffer up to a value of 13 (see figure 6, upper panel). All other buffer levels oscillate only between 0 and 1. So the increasing B’ level is responsible for the increasing of the total buffer content up to 14. The direct effect of the FBFS policy can be seen in the lower panel of figure 6. All of the 20 released parts B were processed at its first stage (B) but only 7 parts were processed at its second stage (B’). That means that only 7 of 20 released parts could be finished – the throughput of part B is only 35 % of its maximum.

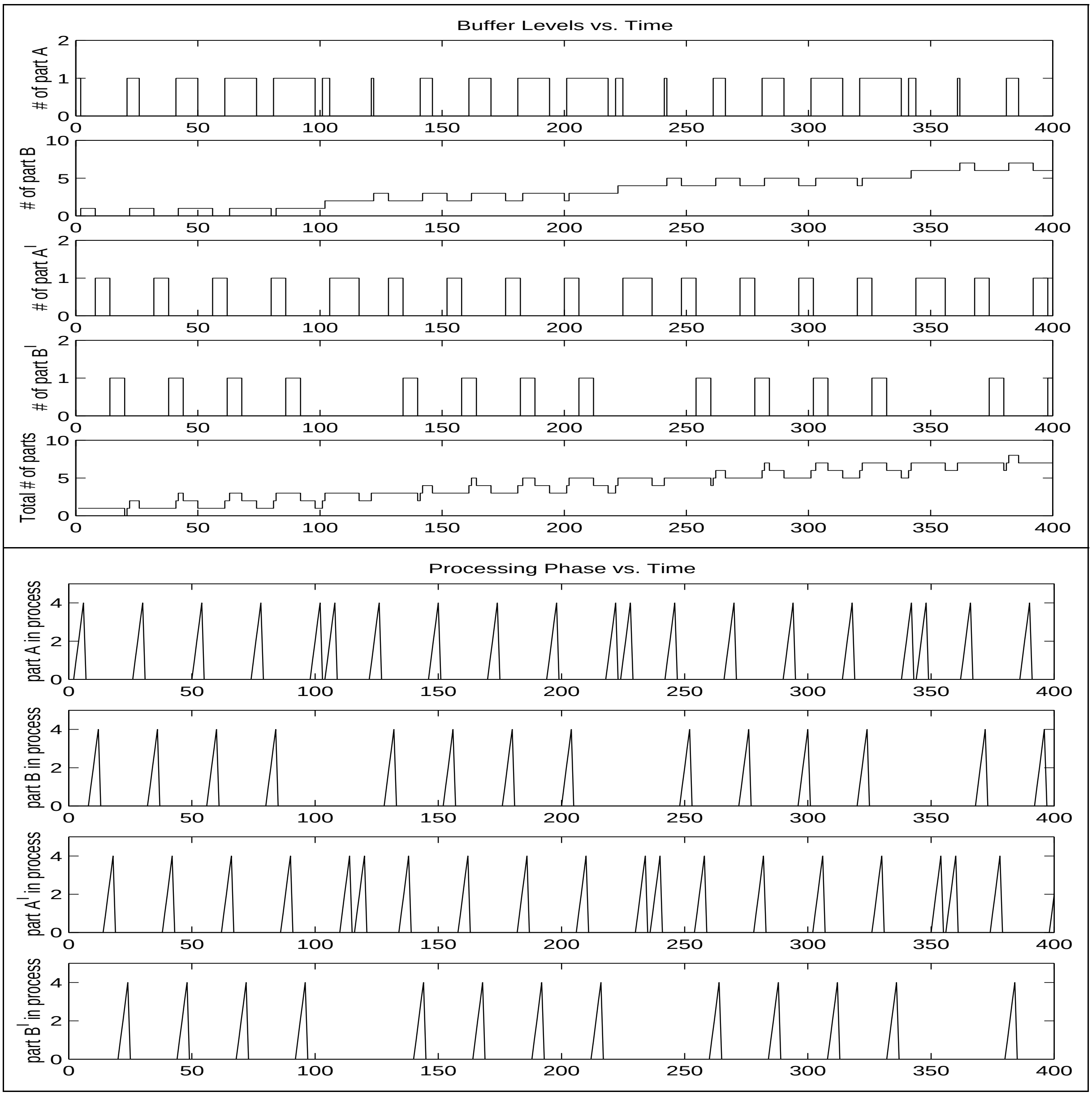

Figure 7: Buffer levels and part processing under the LBFS policy.

In the case of the LBFS policy and still the general A-over-B priority, parts A’ have the highest priority and B the lowest. This leads to an increasing amount of B in the buffer up to a value of 7 (see figure 7, upper panel). All other buffer levels oscillate only between 0 and 1. So the increasing B level is responsible for the increasing of the total buffer content up to 8. It should be noted that the maximum buffer level is only about 57 % of the maximum buffer level in the FBFS case. The reason for this fact can be seen in the lower panel of figure 7.

Only 14 of 20 released parts B were processed at its first stage (B) but 13 of these 14 parts were processed at its second stage (B'). That means that 13 of 20 released parts could be finished – the throughput of part B is 65% of its maximum. That means that in comparison with the FBFS policy, the LBFS policy leads almost to a doubling of the overall throughput and almost to a halving of the maximum buffer level or the overall WIP respectively.

The scheduling policies FBFS and LBFS, which have been analysed here, are static priority rules. But in spite of their static nature, such advanced scheduling policies lead to a better performance then the widely used FIFO policy in the majority of cases. Furthermore, the development of dynamic scheduling policies, which change their priority scheme depending on the current system state, is in process. This will provide a dynamic control of the processing and completion of parts.

Conclusion and Outlook

This paper (i) introduced a dynamical model of a re-entrant manufacturing system and analysed its dynamics and (ii) presented a simulation model based on a dynamical concept for manufacturing control.

Part I of this paper described a "2 products – 2 stages" re-entrant manufacturing system and developed a dynamical model of this system. The dynamics are governed by the ratio of work load to system capacity. If the system capacity is larger than the work load, the system is under-loaded and has the properties of a quasi-periodically driven dissipative dynamical system. One can relate this to the fact that for large production rates, the queue disappears and the idle time intervals damp out perturbations.
When the system is balanced (work load = system capacity), the dissipativity is no longer given. In this case, the queue is never empty and the perturbations do not decay. Moreover, the dynamics depend on the initial state. This can be related to the fact that the perturbations do not grow either.
In the third case, when the system capacity is less than the work load, the queue grows continuously and the dynamics become more complex than in the quasi-periodic case. One can understand this as an effect of the growing queue which leads to an effective growth of the perturbations. This growth is, however, not fast enough to yield chaos. The correlations in the over-loaded case neither return to one nor decay to zero.
Further investigations need to be devoted to the classification of the particular kind of system that seems to be neither periodic nor chaotic. In addition, suitable controlling methods have to be developed for an optimisation of such systems.

Part II of this paper introduced a dynamical concept for manufacturing control. Within this concept, the manufacturing system is considered to be a dynamical system. The *buffer levels* and the *processing phases* were defined as system variables. The general parameters of a manufacturing system were combined into the functional groups *structure, capacity, operational rules, release policies, scheduling/queuing policies*.
This dynamical concept was realised in a simulation platform and a simulation model of the "2 products – 2 stages" re-entrant manufacturing system. All functional groups were implemented in specific modules that can be used to control the system variables. The functioning of the simulation model was exemplified using the functional group "scheduling/queuing policies" for control of the processing and completion of parts. It was shown that the LBFS scheduling policy leads to a much better system performance than the FBFS scheduling policy.
Moreover, the dynamical concept and its implementation in the simulation platform provide a dynamic control of the manufacturing process using all functional groups. E.g., the module "release policy" can be used for a part release depending on the current system state, the module "capacity" can be used for a dynamic adjustment of the buffer or machine capacity and so on. Consequently, the developed simulation platform is a useful tool for further work regarding dynamic control of manufacturing systems.

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