AUTONOMOUS CONTROL OF SHOP FLOOR LOGISTICS

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Abstract: We investigate methods for implementing highly distributed control of production systems. As a first step we investigate the differences between conventional architectures and fully distributed systems. As a conventional system we understand here a system with a central control entity that plans and optimizes in advance the distribution of work among different work stations. In contrast we consider models of manufacturing systems with a flexible structure that allows parts when they are released to the shop floor to control themselves by means of autonomous shop floor control. The decision layer is transferred to the parts that are being processed. The parts themselves decide which resource they allocate for their processing. Their decisions are based on only local and actual available information and follow simple rules. Exemplary models for autonomous control of a production logistic scenario without any global planning or optimization in advance are presented. Simulation results make these control techniques comparable in terms of performance, through put time and WIP to conventional systems. The results may stimulate a further exploration of distributed autonomous manufacturing

Keywords: Autonomous control, Shop floor oriented systems, self-adaptive control

1. INTRODUCTION

In todays manufacturing systems the production planning and scheduling tasks are of increasing complexity and are aggravated by the necessities to be flexible enough to adapt to outside changes. Due to the dynamic and structural complexity of today's manufacturing systems and networks, traditional central planning and control, that is efficient under steady operating conditions becomes increasingly difficult and is insufficient in the face of dynamic changes, as reported by numerous authors as Zweben and Fox (1994), Baker (1998), Bongaerts *et al.* (2000), Scholz-Reiter *et al.* (2004*b*). To cope with these challenges there is an ongoing paradigm shift from centralized control of non-intelligent items in hierarchical structures towards decentralized control of intelligent items in complex and flexible manufacturing systems (Scholz-Reiter *et al.*, 2004*a*).
First attempts to overcome the problems of centralized architectures through heterarchical control of production systems arose, when the increasing complexity of computer integrated manufacturing was recognized (Havany, 1985), (Duffie and Piper, 1986). During the last decade a number of far reaching new conceptual frameworks for distributed manufacturing control have been proposed, presenting similar concepts but with different origins (Tharumarajah *et al.*, 1996). This includes the fractal factory concept (Warneke, 1993), which focuses mainly on an assumed self-similarity of organizational units, the Bionic Manufacturing System (BMS) (Okino, 1993), (Ueda and Vaario, 1998) which emphasizes biological evolution principles for dealing with dynamic changes, or the holonic manufacturing system (HMS) (Bongaerts, 1998), (Gou *et al.*, 1998). The latter approach identifies key elements of manufacturing, such as machines, factories, parts, products or operators etc. with so called holons, which should have autonomous and cooperative properties. With this identification it compares closely to the main ideas of distributed artificial intelligence (DAI), especially the multi agent systems (MAS) paradigm (Jennings, 1998), (Parunak, 1994).

The mentioned concepts often address the whole spectra of manufacturing planning and control systems, ranging from product and process design to purchase and procurement and represent mainly an systems engineering approach to the development of manufacturing control infrastructure, rather than a solution or evaluation for solving individual manufacturing control problems.
In this paper we focus specifically on the distribution and routing of parts between workstations on the shop floor. The basic idea is, to equip each workpiece with some sort of intelligence, that enables it, to make the routing decisions by itself. This approach has no centralized instance for the allocation of manufacturing resources based on optimalization procedures in advance. Instead, local heuristics are to be applied for the items, which also receive actual information on their environment, to decide which workstation should be used for the next production step. The main advantages of such an autonomous control are a added robustness against unforeseen changes in production times and machinery breakdown and an increased flexibility of the production system. Furthermore, our approach is comparatively simple to implement, since we consider only simple decision making by using decision rules. The challenge in distributed approaches to shop floor control is in achieving optimized global performance. Due to the self-organizing properties of autonomous controlled systems it is at the actual state of the art often impossible to verify these systems by formal methods. We therfore use simulations for evaluating the global performance of exemplary model systems.

The rest of this paper is organized as follows: At first we briefly review the main requirements and challenges for flexible manufacturing systems (Sec. 2). Then the advantages of autonomous control with respect to these requirements are discussed in more detail in Sec. 3. Whereas these discussion is on a more general level we will present simulation results for exemplary production scenarios with decentralized control algorithms in the second part of this paper. For the sake of completeness the used methodologies are introduced in Sec.4. Then simulation results for two basic layouts are discussed in detail in Sec. 5 and Sec. 6 Finally we draw some conclusions for distributed autonomous control mechanisms of shop floor logistics and line out directions of future research.

2. REQUIREMENTS AND CHALLENGES

The majority of actually used production planning and control systems is based on centralized optimization procedures. Their successful application requires therefore besides a fixed set orders, and (in principle) complete knowledge about the state of the production facility in advance, which is hardly to obtain in realistic systems. Furthermore such a system can not cope with unforeseen downtime of machinery or other outside disturbances and uncertainties.
To adapt to such changing boundary conditions or even for adaption to future alternative use of the same system because of product mix or design changes over time, the planning and control system has to be flexible and convertible. Another point is the robustness of the system which means that it should continue to work even in unpredicted cases of disturbance. To afford these tasks the systems structure has to be convertible and scalable to facilitate the possibility to adapt to different demands.

2.1 Routing Alternatives

A robust manufacturing system requires machines with overlapping capacities. It should be possible to perform every manufacturing step at always more than one machine. In case of breakdown or repair needs this type of redundancy provides the possibility to perform the tasks of the unused machine at an other one. In any manufacturing system a greater number of alternative paths a part can take to be finished indicates therefore a higher degree of flexibility and robustness. However, this flexibility can only be beneficial, if the routing mechanism itself is flexible enough to adapt to changes in the capacities. This is just, what a autonomous control can ensure in a natural way by its design.

3. SELF-ORGANIZATION OF MATERIAL FLOW BY AUTONOMOUS CONTROL

Every part that has to be produced in a manufacturing system is characterized by a sequence of production steps that must be applied until the production is finished.
Our approach is strictly based on spatial and timely local information and decision making. It is assumed that a part knows, when it is released to the production system or a previous production step is finished, which workstations are in principal able to perform the next production step. I.e. a list of routing alternatives is given for each autonomous part. Then in a communication process, that is assumed to be as simple as possible the actual workload of the potential next stations (the sizes of input buffers and the workstations state) are requested. Based on this informations a decision at which workstation it queues is rendered by the product itself, based on simple heuristics called *(decision) rules* in the following. Thus the

routing of a workpiece is organized through a sequence of decisions made by the piece at the end of production steps.

Now we shall consider the behavior on system level that results by this approach. If a workstation breaks down, no further parts visit this station, i.e. the material flow is immedeatly diverted to alternative machines. Even if a workstation has a lower production rate than other alternative stations the work in process is automatically balanced between all workstations that can perform a certain production step. In summary the actual flow adjusts itself to the current situation, even if the product mix or other boundary conditions change.

Thus the topology of material flows is not predetermined. At the one hand side it emerges dynamically from the products and their types respectively, and at the other hand side the available production capacities and their actual load influence the material flow structure. The system may therefore regarded to be self-organizing.

The main advantages of such a self-organization by simplified local feedback mechanisms are the comparatively easy implementation as well as the robustness, which is ensured by the distribution of decisions in many simple and decentralized autonomous units.

The question is, which rule performs best and how to evaluate the performance of such heuristics.

4. NUMERICAL EXPERIMENTS

Generally manufacturing systems can be approached by discrete event simulation (Yao, 1994). The systems dynamics is modeled as a series of events representing the start and end of specific actions. If an action is started, the time of its duration is determined randomly according to a given distribution of inter event times. For demonstration purposes we use Markovian processes and a uniform distribution (U_1) of inter-event-times in the interval $[t_{min}, t_{max}]$ with $t_{min} = 0.8 t_{max}$. Thus uncertainty and disturbances of production are included in the simulation.Because such a system is strongly nondeterministic (whereas the applied rules are) it is necessary to obtain averaged values.

To any manufacturing system (as a whole as well as to any workstation in the system) we can assign a production rate (service rate) μ. This is just the rate at which the system can produce new parts, given that in every moment a new incoming part is available. For new work, that is released to the system we can also find a arrival rate λ, which gives the rate at which new orders (material) arrives for production. With these rates, the utilization is simply:

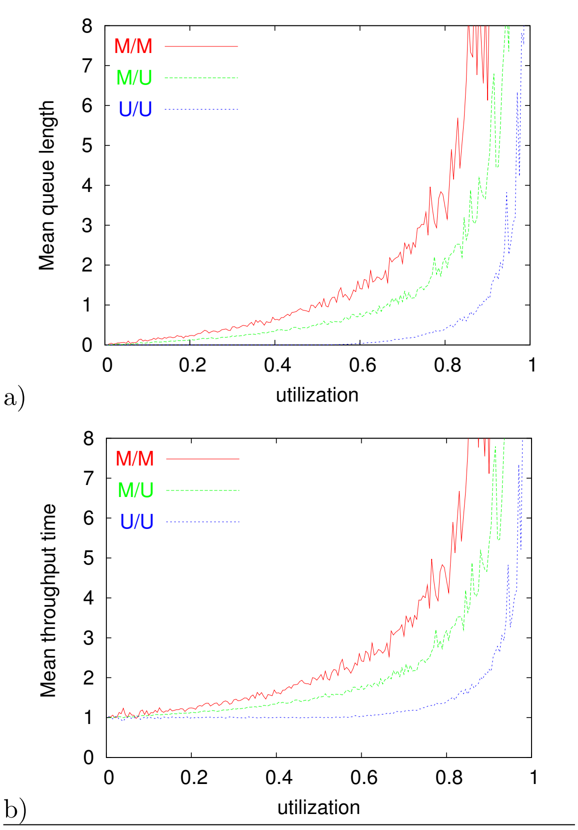

Fig. 1. Curves of performance measures vs. utilization ρ for single server queues for different combinations of inter-arrival time and service time distributions. The production rate is in all cases $\mu = 1$.
a) Shows the mean queue length vs. ρ
b) Shows the mean throughput time vs. ρ
In both plots the dashed curve represents a MM1 system, the solid line a MU11 system and the dotted curve stands for a U1U11 system as indicated inside the figures.

$$\rho = \frac{\lambda}{\mu} \tag{1}$$

$\rho \approx 1$ means a highly utilized manufacturing system working at the border of its capacity, whereas $\rho \approx 0$ implies a manufacturing system that has most of the time nothing to do. As performance measures we apply herein the *mean queue length* which is similar to the work in process, and the *mean throughput time*, i.e. the time a piece of work needs from the moment it is released to the production system to the moment, where its production is finished. Thus a short throughput time gives a good base for due date performance. Usually it is of little validity to obtain results for a single realization of a (at least partially) stochastic production process or to consider a configuration just for a certain workload situation. Therefore we use as a comprehensive visualization a plot of the investigated *performance measures* vs. *total utilization* of the manufacturing system. Fig.1 gives some examples of these also as logistic operating curves known plots (Nyhuis, 1994);(Nyhuis and

Wiendahl, 1999) for a single workstation with a buffer and a machine to produce the part (called single server queue in queueing theory) under different distributions of inter arrival and service times.

5. DISTRIBUTION OF WORK IN ONE PRODUCTION STAGE BETWEEN PARALLEL WORKSTATIONS

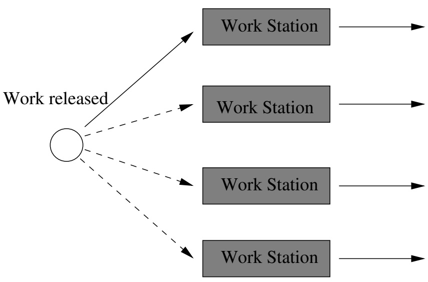

Fig. 2. Visualization of the model used in the first example. Once the workpiece is released, it has to choose one of the workstations to receive its processing.

As a first example for a autonomous control we use a system with four parallel workstations, as depicted in Fig. 2. The processing is done in a single stage step, and all products are of one class. Once a workpiece is released to the production, it should decide which workstation it chooses for processing. We investigate three possible rules for that decision:

Rule A
Just choose the cyclic next workstation compared to the foregoing part. (2)

That rule serves as an example for an inflexible, non autonomous approach, since it does not regard any information of the actual system state. The performance of a system operated with this rule should be compared with systems, where autonomous controlled products that use the following decision rules , which consider the actual input buffer size of the parallel workstations:

Rule B
Choose the first server with the smallest buffer. (i.e. if 2 and 3 have empty buffers use server 2) (3)

Rule C
Choose the first buffer, unless its queue lenght exeeds a certain threshold, then go to the second. If the second also exeeds the the threshold then the next etc. If also the last buffer contains more then the threshold value increase this value. (*In the following we used 5 as increment*) (4)

For the latter rules we imply that a workstation that does not respond to a request for buffer size or indicates that it is down, due to some failure for instance, is not included in the evaluation process. We consider two scenarios: First we assume that all workstations have equal properties (i.e. the same machinery etc.: case I). Secondly we study the situation, that the production at different workstations requires different times, i.e. different production rates are offered by the workstations. The product itself needs no information about this rates, since this information is provided also in the actual buffer sizes in a better way. Typical results of performance evaluation for different distributions of inter event times and these rules applied to the model system are shown in Fig.3.

5.1 Discussion

In Fig.3 the mean throughput times for the whole system vs the utilization of the whole system are shown, i.e. every job passing the system, regardless which workstation it uses, is considered for the evaluation.

At first we shall discuss the results obtained by using rule C, since here the differences to *rule A* and *B* are obvious. If *rule C* is used, then even for small utilization a relatively large throughput time is observed. This is caused by the specialty of rule C to imply a type of capacity control. At first the first workstation is highly utilized, whereas all other workstations remain unused. This leads to a large queue for workstation one and therefore to long throughput times. The second workstation comes into processing if the utilization of the first exceeds a certain threshold. Then we have more or less a two parallel server system and with increasing utilization of the whole system further servers are used. Therefore the mean throughput time remains more or less constant for a wide range of utilization. The described behavior is obvious, if we consider Fig. 4, where the successive inset of the buffers with increasing utilization becomes visible. In a nearly deterministic system these effects are much more distinctive, as the strange behavior of the curve in Fig. 3b) demonstrates. If the preferred first workstation offers a relatively low production rate, it is possible that for low utilization the throughput times are larger than for a more utilized system, where more workstations

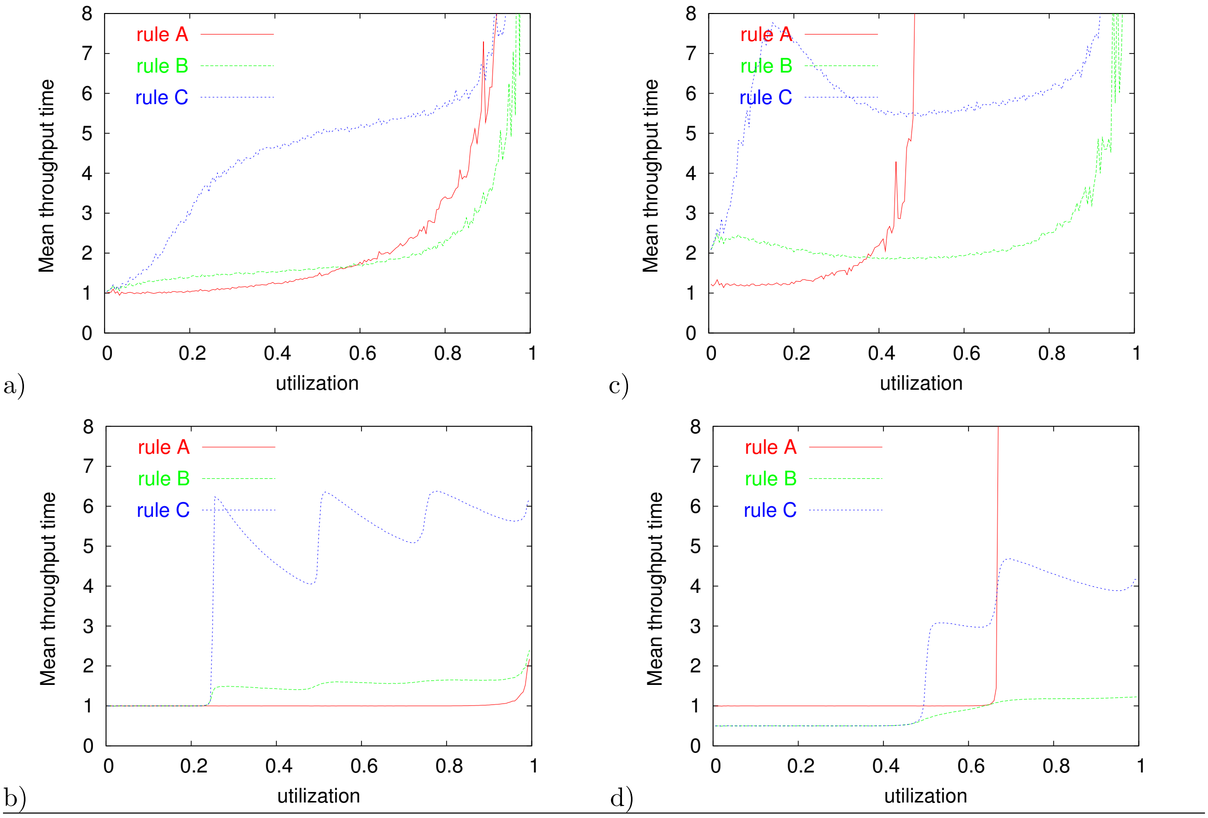

Fig. 3. Typical results of simulations for the model system from Fig.2. The curves show the mean throughput time vs. utilization ρ if decision rules A,B or C (2)-(4) are applied for different systems parameters. the first column contains diagrams for systems (case I) where all servers have a equal production rate $\mu = \mu_i = 1$ whereas the second column depicts the situation for a system (case II) with $\mu_1 = (0.5)^{-1}$,$\mu_2 = (1.5)^{-1}$, $\mu_3 = (0.75)^{-1}$, $\mu_4 = (1.25)^{-1}$

a)t_{trough} vs. ρ, inter-release times and service times are exponentially distributed, all workstations have equal production rates.

b)t_{trough} vs. ρ, inter-release times and service times are U_1 distributed, all workstations have equal production rates.

c)t_{trough} vs. ρ, both inter-release times and service times are exponentially distributed, the workstations provide different production rates (case II).

d)t_{trough} vs. ρ, both inter-release times and service times are U_1 distributed, the workstations provide different production rates (case II).

In all plots the rules that result in the different curves are indicated.

are in use, according to rule C (see Fig. 3b).

If we consider *rule A* and *rule B* the principial differences of a decision made according to local information and a 'blind' routing becomes visible. The information on buffer sizes used for decision in rule B does not contain any information if the workstation is actually processes a product or has finished and can start the production of a new part instantaneously. Thus, in cases where workstations are low utilized and therefore often a production of a new product can start immediately after release, the unintelligent rule A can lead to lower mean throughput times than rule B (see Fig. 3). However, if the utilization is increased and queues are unavoidable due to the uncertainty in production times, rule B clearly leads to a better performance. This is possible because temporarily 'faster' workstations with small buffers can be used for production. The critical utilization, where the mentioned advantage of rule B provides a better overall performance, strongly depends on the systems parameters. We conclude, that for high utilization, the autonomy in routing gives a competitive edge even if the information base (here: actual buffer sizes) is not optimal. Furthermore, in case II, where the offered production rates are different, a 'blind' equal distribution of work for all workstations (rule A) leads to an overloaded system, where the autonomous routing can find the alternative workstations. This behavior is shown in Fig. 3c,d where the throughput times for rule A reaches unacceptable values for moderate utilization whereas the autonomous controlled system provides a good performance.

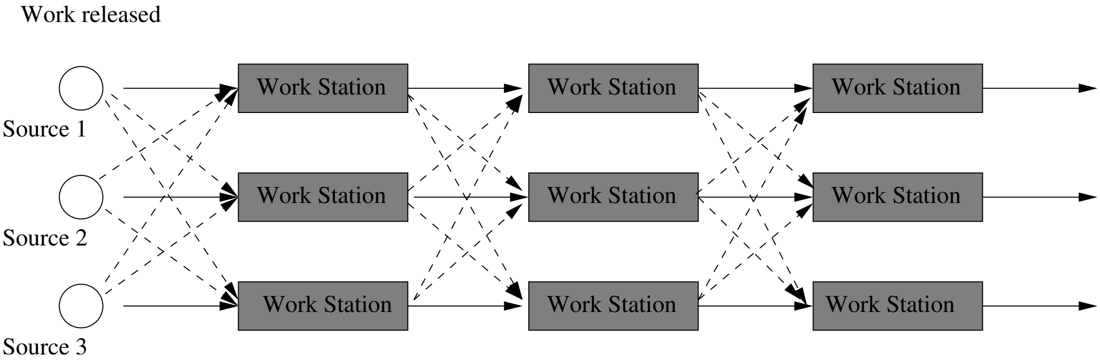

Fig. 5. A simple model of a flexible multistage production system for different classes of products. Depicted is a system where 3 classes of products (labeled with $\alpha \in \{1, 2, 3\}$) are released by source 1-3 to the production system (with rates λ_1,λ_2,λ_3 respectively) consisting of 3x3 workstations providing production rates $\mu_{ij}(\alpha)$ for products of class α . Whereas the solid arrows show the default routes for three separated production lines (one line for each product class) the dashed arrows indicate all routing possibilities in a flexible system that can be obtained by an autonomous self-controlled part.

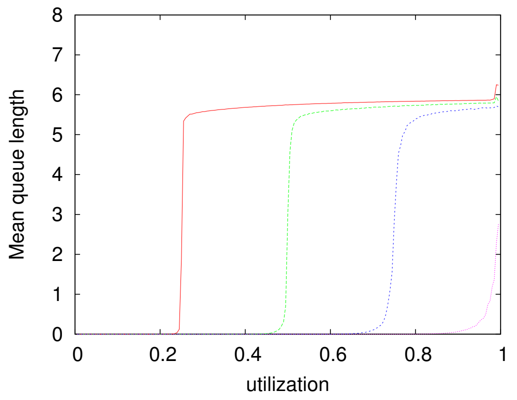

Fig. 4. The figure shows the behavior of the four buffers of the model system from Fig.2 depending on the utilization for rule C (4), if both inter-release time and service time are have a U_1 distribution and $\mu = \mu_i = 1$. Rule C systematically makes a capacity control feasible since the successive buffers become used only with increasing workload. For the nearly deterministic system the transitions are very clear (compare Fig. 3b).

6. DISTRIBUTION OF WORK IN A MULTI-STEP MULTI-CLASS PRODUCTION SYSTEM

As a second model system we use the production system depicted in Fig.5. It serves as an example for a multistage production of different product types in a system, where in every stage three workstations are able to perform the processing for all products assigned to that stage. Thus for every released part there are 3^3 possible routes to complete the processing. For this system we have investigated two situations. The simple example (case III) is a system, where only one product type is manufactured, and all workstations have the same production rate. In this case only the way the routing decisions are made is relevant for the global performance.

Of more interest is the situation (case IV), where three different product classes are manufactured. Each class has a 'line' where the processing of this class products requires a unit time in all production stages. However, it is usefully if a workstation of an other 'line' can take over a product from the preferred line if the corresponding workstation for the stage is overloaded. In that case we penalize the line change by a lower production rate for the part, that can be caused for instance by additional set-up times. The redundancy included in the system is beneficial, if the product mix is variable, and a separated line for one product would be overloaded, where an other product type does not utilize its preferred workstations. In that case not only the routing method is a relevant parameter for the overall performance, but also the product mix has to be considered. It shall be shown in the following, that autonomous control is able to cope with unbalanced product mixes.

We consider again three possible decision rules for control:

Rule A'
Just choose the next server in line. (5)

This rule is the example for an inflexible, non autonomous approach, since the lines are separated and no routing alternatives are available. Also no actual system information is used. The performance of a system operated with this rule should be compared with systems where the routing is organized by autonomous controlled products that use the following decision rules, which consider the actual input buffer size of the alternative workstations in each production stage:

Rule B'
Choose the first of the two following servers with the smallest buffer. (i.e. the rule has a slight preference for the in-line buffer) (6)

Rule C'
Choose the following buffer in line, unless its queue lenght exeeds a certain threshold, then go to the other line. If the the other buffer exeeds the treshold go to the next alternative etc. If all alternative buffers exeed the threshold, then increment the theshold value by fixed amount. (*In the following we used 5 as increment*) (7)

For the rules B', C' we imply that a workstation that does not respond to a request of buffer size or indicates that it is down, due to some failure for instance, is not included in the evaluation process. Typical results of performance evaluation for different distributions of production and release times and these rules applied to the model system are shown in Fig.6.

6.1 Discussion

In Fig.6 the mean throughput times for the whole system vs. the utilization of the whole system are shown, i.e. every product passing the system, regardless which specific path through workstation it uses, is considered for the evaluation. For the calculation of the total utilization the largest possible production rate (reached if every product is processed only at its designated line) is used.
For small utilization all three decision rules imply that the three lines are decoupled. Only the distribution of work to the line-heads implies a weak coupling for rules B',C'. Therefore the differences in performance are small if the system is not utilized.
Furthermore, if we consider a more or less *deterministic processing* (see Fig6b), the different rules of exchanging work between lines have practically no impact for case III, where only one product class is produced. The reason is simply, that the line head workstations completely buffer the stochasticity out, and in the following line the system becomes in fact deterministic, which implies vanishing queues, and therefore no reason for a product to change its line.
Contrastingly, even for case III the rules make a difference if the system load is increased and the processing times in the workstations scatter more randomly (Fig. 6a). Then the autonomous control can use unforeseen gaps at alternative workstations for production and provides a better overall performance in terms of mean throughput times (and WIP respectively). Also here rule C' tends to produce larger buffers (and therefore a larger $t_{through}$) if compared to rule B'. Noteless the situation is different to the example rule C discussed in the previous section. Here generally products using all alternative workstations since all 'lines' are feeded by the parallel sources and thus no stepwise utilization as in Fig. 4 is observed.
Now we shall discuss the situation if, case IV applies. Typical simulation results for this scenario are shown in Fig. 6c,d. The most obvious result is, that in the case of an unflexible system according to rule A' the system performance gets worse if one product class overloads its line. In the example the release rate for products of type 1 is two times the rate the 'line' is dimensioned for, and thus the system breaks down for an overall utilization of not more than 50%. In contrast the performance for routing according to rule B' and C' is much better, because the not so frequently visited parallel workstations in every production stage borrow their capacities to the other product class. This happens due to the self-organizing features of the autonomous controlled material flow. Only for heavy utilization the payoff of increased production times if a product is not processed at the designated workstation leads to a higher mean throughput time for the whole system than it would show, if no product has a release rate larger than 1. It is even worth to note that in this scenario (case IV) the scattering of production times is not the most relevant factor (Fig.6 c and d reflect qualitatively a very similar behavior). It is even more important how the system can cope with the asymmetric load of different product classes.
We further remark that the behavior of the system in scenario IV is for other relations for the different product classes very similar to the herein discussed special parameters. This clearly indicates the overwhelming advantages of autonomous control of shop floor logistics. A system where the products schedule themselves by rules like B or C instantaneously adapts itself - without any further changes to any infrastructure or system design - to a changed product mix. It is considerably robust against unforeseen and widely scattering production times an provides an overall performance that is for high utilization better than a system with separated lines for each product type.

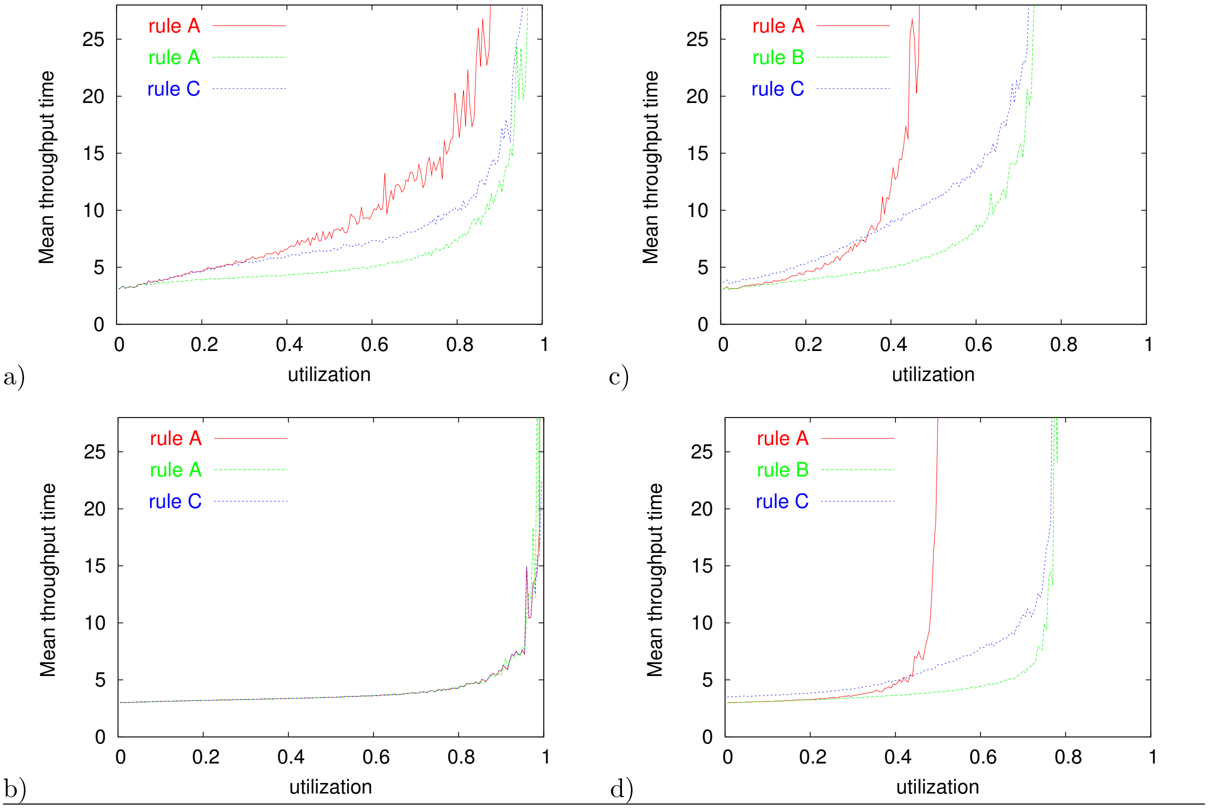

Fig. 6. Typical results of simulations, showing the mean throughput times vs. total utilization for the multistage production system from Fig. 5 with different parameter sets.
The first column shows curves for situations, where only one class of products has to pass the system and all production rates $\mu_{ij} = \mu = 1$ of the workstations are equal $\mu_{ij} = \mu = 1$ for all parts (case III). The second column (case IV) shows results for a system used for the production of three classes of products, released with $\lambda_1 : \lambda_2 : \lambda_3 = 2.0 : 0.1 : 0.9$ (i.e. for the case of separated lines the first line is overloaded, the second in all cases relatively weak utilized and the utilization of third products line is similar to the total utilization). Furthermore in this case different production rates are offered to parts depending if they are in their preferred line or not: $\mu_{ij}(\alpha = i) = 1.0$ and $\mu_{ij}(\alpha \neq i) = 1.5$ otherwise.
a)t_{trough} vs. ρ, inter-release times and service times are exponentially distributed, parameters according to case III, only one product class.
b)t_{trough} vs. ρ, inter-release times and service times are U_1 distributed, parameters as in a).
c)t_{trough} vs. ρ, both inter-release times and service times are exponentially distributed, parameters according to case IV.
d)t_{trough} vs. ρ, both inter-release times and service times are U_1 distributed, parameters as in c)
In all plots the rules that result in the different curves are indicated.

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7. CONCLUSIONS

We have analyzed highly distributed control in form of autonomous routing of intelligent products by means of simulation. By using very simple decision mechanisms we enable individual parts released to the production system to choose a workstation themselves. Different strategies are compared their benefit in terms of throughput time and buffer sizes for the local assignment of jobs to the next production step under a number of distinct stochastic distributions of production times was evaluated. It turns out,that autonomous controls can be more effective than traditional approaches for logistics control and provides additional robustness and flexibility for a production system. The introduced type of local feedback mechanism needs no fixed central planning component, which often is a bottleneck in other systems. The more alternatives for the next production step exist, i.e. the higher the chance to find an un-utilized workstation that can be equipped for the desired production in short time, the better distributed control works. This behavior is most favorable, if large (stochastic) variations of manufacturing times make it impossible to have a good planning and scheduling in advance.
However the design of appropriate systems in detail remains a challenging problem since a evalua-

tion by formal methods provides certain problems. Here the development of analytical models is urgently needed. First approaches for systems with similar properties as discussed here have been recently presented by Dachkovski *et al.* (2004).

Such models will also help to analyze the dynamics of autonomous distributed control systems. This is of interest, since distributed systems can expose a very complicated dynamic behavior, that also may cause performance losses (Diaz-Rivera *et al.*, 2000), (Peters and Parlitz, 2003), (Avrutin and Schanz, 2000). Thus the investigation of decentralized and autonomous control theories is a highly interesting, ambitious and promising research area even in a theoretical point of view.

Future research has also to tackle the question, which benefits a more sophisticated design of local decision making algorithms can provide. This is important due to the fact that such mechanisms will need additional communication and information processing capacities and are not easily to implement. Thus comparative studies of such systems under realistic preconditions will provide informations of great practical relevance.

8. ACKNOWLEDGMENTS

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