A CASE STUDY IN MODELING AND PERFORMANCE EVALUATION OF MANUFACTURING SYSTEMS USING COLORED PETRI NETS*

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KEYWORDS

Model design, Performance analysis, Discrete Simulation, Manufacturing

ABSTRACT

Modeling and performance evaluation techniques play a major role in the design process of manufacturing systems. We recently proposed a modeling method based on colored Petri nets with stochastic timing, which is especially tailored to manufacturing systems. One of its main ideas is the separate modeling of the manufacturing system's structure and the production routes with dedicated colored Petri nets. After an automatic compilation into a complete model, performance and dependability measures can be obtained by simulation or numerical analysis. We demonstrate the advantages of this technique using a rather complex real-life manufacturing system. Additionally, it is shown how a typical failure-and-repair behavior of an automated machine can be modeled with stochastic Petri nets.

INTRODUCTION

Modern manufacturing systems are complex configurations of machines, transport systems, and manual workplaces. It is practically impossible to predict their behavior in the early stages of the design process with adequate accuracy. This is especially the case if one takes into account failures and repairs of the system and their effect on the system's performance. Nevertheless, the system design has a major influence on the economic success of a manufacturing system, which is mostly decided by its quantitative properties (e.g. the throughput).

To overcome this problem, many techniques for the modeling and quantitative analysis of manufacturing systems have been investigated. Among them, Petri nets are now considered as a powerful tool especially suitable for systems that exhibit concurrency, conflicts, and synchronization. To study the performance and the dependability of a system it is necessary to include the notion of time and probability into the model. This is usually done by associating delays or probabilities with transitions. Stochastic Petri nets or SPNs (Ajmone Marsan 1990) and generalized stochastic Petri nets or GSPNs (Chiola et al. 1993) are two popular extensions of Petri nets which have been widely used in the application field of manufacturing; see, for instance, (Al-Jaar and Desrochers 1990) and (Silva and Valette 1991). Nevertheless, if more than one product is processed by one machine in the model, the machine's model has to be replicated due to the lack of distinguishable tokens.

Therefore, colored Petri nets or CPNs (Jensen 1992) have been applied to manufacturing systems (Martinez and Silva 1984, Martinez et al. 1987). In general, colored Petri nets allow a higher level of modeling, but contain complex definitions of colors, types and variables. These textual inscriptions are part of the model behavior's specification, thus spoiling the understandability of the graphical Petri net model. It is, however, possible to omit most of the inscriptions using a restricted class of colored Petri nets especially dedicated to manufacturing systems (Zimmermann 1994).

In manufacturing systems with a certain degree of flexibility in the production program, there is no notion of production line, rather for each product a *production route* is defined (Silva and Valette 1991). A Petri net model of a manufacturing system includes both the structural information of the modeled system and the specification of the production routes. Such an integrated model is advantageous for visualization, but there is a need to redefine the whole model even if the production route of a single part changes. The independence of the manufacturing system's structure from the parts to be processed should be reflected in the modeling technique.

To overcome this limitation, a technique for the separate modeling of the production routes and the manufacturing system's structure has been proposed (Zimmermann et al. 1996). Both model parts use dedicated colored Petri nets from (Zimmermann 1994), and are automatically compiled into one unique model. Simulation or numerical analysis can be employed to obtain the desired performance measures. In this paper we demonstrate the application of this integrated modeling and quantitative evaluation technique using a real-life man-

*This work has been supported by the German Research Council under grant Ho 1257/4-3.

The remainder of this paper is organized as follows. The manufacturing system example is introduced in the next section. Afterwards, the modeling technique is briefly recalled and applied to the example. The derivation of measures from the obtained complete model is shown in the sequel. Finally, concluding remarks are given.

THE MANUFACTURING SYSTEM

The safety of car passengers is receiving much attention in the recent past, and is an important marketing argument for car manufacturers. Our example manufacturing system is operated by a company that supplies airbags and other car safety equipment. The actual production system that we will focus on assembles pyrotechnic buckle pretensioner. They are used to pull the car passengers safety belts tight in case of a collision.

Twenty different parts have to be assembled for a complete buckle pretensioner. Most of the 19 stations in the system operate fully automatic, there are only four manual workplaces. As the final product is safety-critical, very strict quality standards have to be met. Therefore, the buckle pretensioners are checked between the assembly steps by automatic testing stations. If a flaw is detected, the part is transported to a manual workplace, where it may be repaired or sorted out.

The parts are transported on special carriers. The different stations are organized in three circular assembly lines, that the parts have to pass one after another. Two stations are responsible for moving the parts from one circle onto the carriers of the next one. Each circle consists of several conveyor belts and conveyor switches, that connect the different stations and act as buffers. When a carrier arrives at a switch, a decision is made in which direction the carrier will move, depending on the utilization of the following stations and the state of the parts on the carrier.

A more detailed description of the manufacturing system and the model introduced in the following section can be found in (Dalkowski 1996).

MANUFACTURING SYSTEMS MODELING USING DEDICATED COLORED PETRI NETS

Colored Petri nets (Jensen 1992) offer more advanced modeling facilities like distinguishable tokens and hierarchical modeling with respect to uncolored nets. The pure graphical description method of Petri nets is, however, hampered by the need to define color types and variables comparable to programming languages. This is often not well accepted by users without a strong background of computer science. To solve this problem, a method for the modeling of manufacturing systems has been presented in (Zimmermann 1994, Zimmermann et al. 1996).

Two color types are predefined, which are adapted to manufacturing systems. *Object tokens* model workpieces and the current state, e.g. `wheel.raw`. *Elementary tokens* do not have a special color, and are equivalent to tokens from uncolored Petri nets. Places and arcs are drawn thick or thin, corresponding to their associated color type (*Object* or *Elementary*).

With this method, the model of the manufacturing cells structure reflects the layout, which makes it easier to understand. Textual descriptions needed in CPNs for the definition of variables and color types can be omitted, and the specification of the types of places and arcs are implicitly obvious.

To meet the requirements of a modeling technique for manufacturing systems, the structure of the manufacturing system has to be modeled separated from the production routes. We propose a method to describe the manufacturing system's structure and production routes separately, each with dedicated colored Petri nets.

Modeling The Structure Of The Manufacturing System

Modeling the structure of the example assembly system with the proposed method yields a concise and understandable model. Due to space limitations we can only present a small portion of it in Figure 1. The complete structural model consists of about 40 transitions and 30 places at this level of abstraction. Because the model strictly follows the actual structure of the system, it is not only understandable but can be easily derived from a layout sketch of the manufacturing system.

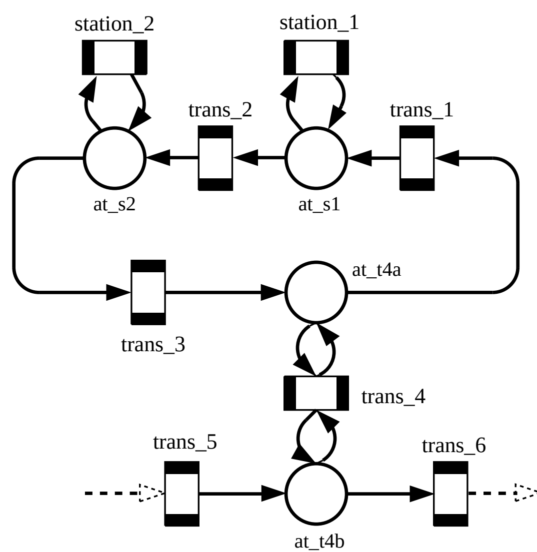

Figure 1: Partial model of the system's structure

The part of the assembly system that is shown in Figure 1 consists of the first circular assembly line and its connection to the second one. At the first station (transition `station_1`), the first two parts are assembled and placed onto an empty carrier. The next part is added to it at station 2 (transition `station_2`). The places `at_s1` and `at_s2` model the buffers where the parts are being processed; they have a capacity of one carrier each. The trans_1, trans_1, and trans_1. Their associated submodels include a description of how the parts are transported and how many carriers fit into them. Station 4 (transition trans_4) takes the belt pretensioners in their current production state from the carrier in line 1 (place at_t4a) and places them onto carriers of the following circular line (place at_t4b). Only the surrounding conveyors of this line are depicted here (transitions trans_5 and trans_6).

As in the definition of colored Petri nets, we allow hierarchical refinements of transitions, thus enhancing the understandability of the resulting models. Figure 1 shows the top layer of the hierarchical model of the assembly line's structure. Each of the so-called substitution transitions (depicted as ▯) is refined by a subpage that describes the behavior of a machine or a conveyor in more detail. Several basic types of machines and transport facilities can be identified, that appear in almost every automated manufacturing system. Submodels from a library of standardized building blocks (*templates*) can be parameterized and instantiated while refining the model (Zimmermann et al. 1996).

Another important part of the modeling process is the determination of the time spent by the machines for each of the production steps and their failure-and-repair behavior. In order to do so, not only the mean values are taken into account, but their distribution as well. Our investigations showed that for most of the machines in our example the same type of behavior could be identified:

- The time spent for one production step varies noticeable for the manual workplaces only. For the automated stations a deterministic time is therefore used, while an exponential distribution is used for the manual workplaces.

- The mean time to failure (MTTF) of a working machine is modeled with an exponential distribution.

- The mean time to repair (MTTR) of a machine denotes the time after a machine failure until it is operational again. In our example, most of the failures are not breakdowns but only short interruptions (e.g. some seconds) which can occur due to a missing part or a temporary malfunction. Only a few failures require a repair by a mechanic, and therefore take longer to recover from. In (Dalkowski 1996) it is shown how this behavior can be modeled with a subnet of transitions with exponentially distributed firing times (cf. Figure 2). This submodel yields a weighted sum of exponential distributions for the MTTR, resulting in a good approximation of the real behavior.

All these considerations are based on large amounts of log data of the system, which were recorded over a rather long period of time. Some measures were taken, however, to verify the exactness of the data.

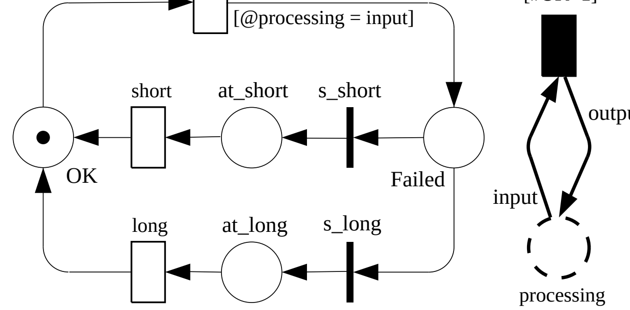

Figure 2: Submodel with failure behavior

In Figure 2 the submodel for a typical automatic machine is shown. The left part of it models the failure-and-repair behavior (see above). It is modeled using elementary net elements, which are drawn thin to visualize the difference to the object places. The machine is operational if there is a token in place OK. If it is working (there is a token of type input in place processing), it may fail (transition Fail fires). The deterministic transition Process models the action that is carried out by the machine. It may only fire if the machine is operational (a token is in place OK). A part that is processed is located in buffer (place) processing with capacity 1. This place may contain object tokens and is therefore drawn thick as well as the arcs connecting it. It is drawn using a dashed line showing that it is a part of the submodels interface to the upper level of the hierarchy. For transition station_2 of the upper level, this place would be merged with at_s2. If transition Process fires, it takes a token of type input from place processing and puts one of type output back. Thus the change in the production status of the part is modeled. The expressions input and output are variables that are set to actual values when the submodel is instantiated.

Modeling Of The Production Routes

Given the model of the manufacturing system's structure, the production routes can be defined. They can be derived directly from a description of where and how the parts have to be processed, and which processing states they have to pass. Obviously, there is one production route model for each production route (each product). This set of models is described with the same type of dedicated colored Petri nets, with some slight differences. In figure 3 a small part of one of the production routes for our example is shown.

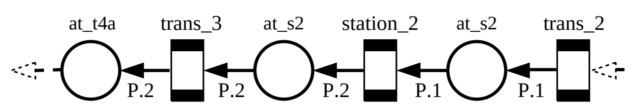

Figure 3: Partial production route model

The production routes represent paths through the structural model, hence the same places and transitions as in this model can be found here, possibly several tokens, showing the changes in their processing state. In figure 3, only transition `station_2` changes the production state from `P.1` to `P.2`. All other transitions model conveyors which only move the carriers from one machine to the next. Alternative routes of workpieces can be modeled using different paths. The processing time of a specific workpiece can be specified here, if it differs from the machine's default.

Compilation Of A Complete Model

Subsequently, the structure and production route nets are automatically merged to create the complete model of the manufacturing cell (Zimmermann et al. 1996). During this process, the informations contained in the production route models are added to the structural model. The transitions are enriched with hidden informations, their *firing possibilities*. This procedure is invisible for the modeler, who only has to construct the model of the cell structure and the production routes for the products.

After the compilation, the structural model together with all (hidden) firing possibilities of the transitions completely describes the behavior of the modeled system and can be evaluated. Please refer to (Zimmermann et al. 1996) for a more thorough description.

EVALUATION

In this section, the example manufacturing system is analyzed and performance measures are derived. The obtained results have been successfully verified by comparing them with the corresponding measures of the real system.

We will now compare different variations of the system and their resulting performance and dependability measures. The aim of this investigation is to obtain a better understanding of the correlations between details of the manufacturing system (e.g. the buffer capacities) and the main performance measures (e.g. the throughput). Proposals can be derived in order to increase the manufacturing system's productivity.

From the complete model explained in the previous section, the *reachability graph* can be generated. Afterwards, numerical analysis techniques (cf. German 1994) can be used to obtain quantitative measures of the model. If numerical evaluation is impossible due to the large state space or limitations in the analyzable firing time distributions, simulation has to be utilized. Fast simulation techniques such as parallelization and control variates (Kelling 1994) speed up the computation.

Currently, the algorithm to calculate the reachability graph directly from the dedicated Petri net model is still under construction. The colored model was therefore unfolded to an uncolored net manually. For the derivation of quantitative measures from the resulting deterministic and stochastic Petri net, the software tool TimeNET (German et al. 1995) has been used.

The influence of the number of available carriers on the Figure 4 shows the throughput measured in parts per hour of the main circular assembly line, if the number of part carriers is varied from 0 to 95.

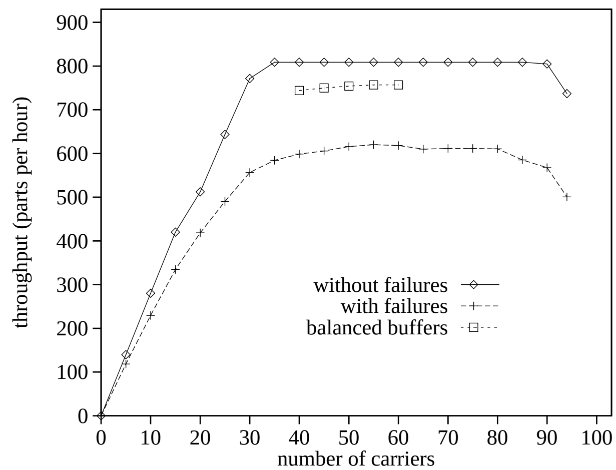

Figure 4: Throughput versus number of carriers

It can clearly be seen that there is an important gain in productivity if the number of carriers is raised in the range up to 40 carriers. If more carriers are added, the system becomes satiated. There is even a range, where the number of produced parts decreases if more carriers are put into the system (all buffers are almost full in that case).

The upper and lower curves in figure 4 show the impact of machine failures on the overall performance, which is actually more than 20 percent less than it would be without failures. It is practically impossible to quantify the influence of failures on a system as complicated as our example without a simulation or numerical analysis. The optimal number of available carriers can be obtained depending on these results and the investment costs per carrier, which are quite considerable in our example.

The capacities of the buffers which are located between the machines differ very much. This stems from the attempt to reduce the space needed by the assembly line. However, balancing the buffer capacities results in a productivity gain of almost 20 percent (see the short curve in figure 4, which has only been calculated for the "useful" range of 40–60 carriers.).

It has been shown now that the machine failures greatly reduce the system performance. If a machine fails, it stops working, and the buffer between this machine and its successor fills up. When there is no space left in the buffer, the successing machine has to stop its work as well, although it is operational. It is clear that this effect is stronger if the buffers are small and the failures take a long time. The failure behavior of the machines in our example are modeled such that we have both short and long failures (cf. figure 2). We will now evaluate the influence of the machine availability and the mean duration of machine failures on the system performance.

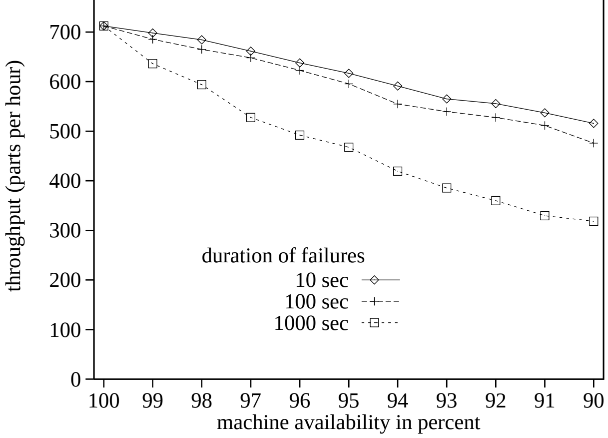

Figure 5: Throughput versus machine availability

Figure 5 shows the results of this experiment. The availability of the machines (the probability that for a given instant of time the machine is operational) is varied from 100 down to 90 percent. Additionally, different durations of failures are considered, while keeping the availability constant. The throughput naturally decreases with a lower availability of the machines. However, it is interesting to see how much this effect depends on the mean duration of each failure. The failure-and-repair behavior of each machine is often known before putting together the assembly system. Based on an examination of a model like the one presented here, it is possible to determine a good configuration of the buffer sizes. The throughput can thus be increased without higher investment costs.

CONCLUSION

In this paper we showed how a dedicated modeling technique for manufacturing systems can be successfully applied to a real-life example. Utilizing this technique, simpler and more concise models are produced that reflect the modeled system's structure. This makes the modeling process easier and less error-prone, and leads to models that are much better understandable.

The hierarchical modeling allows to specify e.g. the failure-and-repair behavior on a lower level and to use parameterizable submodels from a library. We showed that a thorough investigation of machine failures can lead to a very exact failure model. The high impact of those failures is presented in the last section.

We emphasize the separate modeling of the production routes and the system's structure. A modification of the routes does not necessitate a complete redesign of the model, thus reflecting that the manufacturing system is independent of the parts being processed. A complete model is derived automatically by a compilation of both model parts. The complete model can subsequently be used to obtain performance and dependability measures using numerical analysis or simulation. By comparing the performance measures of different model buffer capacities, failures etc. is better understood after the model is evaluated. This technique is therefore valuable especially during the design of a manufacturing system, but can also be used to increase the performance of existing systems.

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