Modelling and Evaluation of Manufacturing Systems Using Dedicated Petri Nets*

Armin Zimmermann and Günter Hommel
Technische Universität Berlin, Institut für Technische Informatik
Franklinstr. 28/29, 10587 Berlin, Germany
E-mail: {azi, hommel}@cs.tu-berlin.de

Abstract The design of a manufacturing system requires modelling and performance evaluation techniques. To support this process, a modelling method based on Petri nets is proposed in this paper. A new class of coloured Petri nets is introduced, which is well suited for the modelling of manufacturing systems. Using this net class the structure and the work plans of a manufacturing system can both be modelled separately. A library of model templates helps creating large models. The different model parts are merged automatically to create a complete model of the manufacturing system. Measures of interest can be obtained from the model by numerical analysis or simulation, showing its performance and dependability. The usefulness of the approach is shown by applying the proposed techniques to a real-life manufacturing system.

Keywords
Manufacturing Systems Modelling, Performance Evaluation, Coloured Stochastic Petri Nets.

1 Introduction

Modern automated manufacturing systems are complex and require large investments. They consist of machines, transport systems, and manual workplaces. The design process of manufacturing systems is important for an economic success, which is decided by the performance of the system. Without modelling and quantitative evaluation techniques it is often difficult to predict the behaviour of a manufacturing system with adequate accuracy. This is especially the case if resources are subject to failures, thus decreasing the production output.

Therefore, many techniques for the modelling and quantitative analysis of discrete event systems have been developed. One of which are Petri nets, being especially suitable for the modelling of systems characterised by concurrency, conflicts, and synchronization. To study the performance and the dependability of a system it is necessary to include time and probabilities into the model. This is usually done by associating with transitions firing delays or probabilities.

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A Petri net model of a manufacturing system usually includes both the structural information of the system being modelled and the specification of the production routes. Such an integrated model is advantageous for visualization, but the whole model needs to be redefined even if only the production route of a single workpiece changes. The independence of the manufacturing system's structure from the workpieces to be processed should be reflected in the modelling technique.

We have proposed a technique for modelling separately the production routes and the manufacturing system's structure in Zimmermann, Bode, and Hommel [1]. Both model parts use dedicated coloured Petri nets, and are automatically compiled into one unique model. In this paper, we present an integrated modelling and quantitative evaluation technique using those results. It facilitates numerical analysis or simulation for obtaining the desired measures.

2 Related Work

Stochastic Petri nets (SPNs, [2]) and generalized stochastic Petri nets (GSPNs, [3]) are two popular extensions of Petri nets. Both have been widely used in the application field of manufacturing (see, for instance, [4] and [5]). Nevertheless, if more than one product is processed by one machine, due to the lack of distinguishable tokens the machine's model has to be replicated. Zurawski and Dillon [6] proposed a method for constructing those replicated uncoloured subnets in a systematic way. In general, using uncoloured nets leads to models that do not reflect the actual structure, making the model less understandable.

Coloured Petri nets (CPNs [7]) have been applied to manufacturing systems to avoid this problem. Viswanadham and Narahari [8] used coloured Petri nets for the modelling of automated manufacturing systems. Based on these models, deadlocks can be found by analysing the invariants. A coloured Petri net model of a manufacturing cell controller is described by Kasturia, DiCesare and Desrochers [9]. After obtaining its invariants, the liveness of the model is checked. Furthermore, it is "implemented" and "executed". In order to control it and show its current status, the tool exchanges messages with the cell.

Martìnez, Muro and Silva [10] show how the coordination subsystem of a flexible manufacturing system can be described by a coloured Petri net. The obtained model is embedded into the surrounding levels of control (local controllers and scheduling subsystem), while a terminology based upon the Petri net colours is used for the interaction. Analysing the model detects deadlocks, decision problems, and gives performance measures that depend on variations in the system being modelled.

Villaroel, Martìnez and Silva [11] proposed to model separately the production routes and the manufacturing system structure. Using their software tool GRAMAN, a manufacturing system is modelled by a *plant description* and a description of the *work plans*. While for the latter coloured Petri nets are used, the structure of the system is modelled with predefined building blocks. An internal model is generated from these two descriptions: for each building block, a predefined submodel is assigned to the block and parameterized with its structural relations. However, with this method it is not possible to specify machine properties that depend on a processing task. Additionally, submodels are connected by fusing transitions that represent synchronized activities. This implies that those connections have to be already known when the submodel is specified, contradicting the modularity of the specification.

As the approach presented here uses a restricted class of coloured Petri nets, it is not necessary to hide the Petri nets from the modeler. Namely, the complex arc and guard expressions as well as the definition of types and variables are superfluous. Therefore, it is possible to model both the manufacturing system structure and the production routes with the same type of dedicated Petri nets. There is no need for an additional graphical description language. The reader is referred to Zimmermann, Bode, and Hommel [1] for a more detailed comparison of GRAMAN and the approach presented in this paper.

In general, coloured Petri nets allow a higher level of modelling, but contain complex definitions of colours, types and variables. These textual inscriptions are part of the specification of the model behaviour. They spoil the understandability of the graphical Petri net model. However, it is possible to omit most of the inscriptions using a restricted class of coloured Petri nets especially dedicated to manufacturing systems [1].

The remainder of this paper is organized as follows. The following section introduces the manufacturing system example that is used throughout the paper. Section 4 recalls the proposed modelling method, which is subsequently applied to the example. How to obtain a complete model from the two resulting model parts is explained in Section 5. In Section 6 the subsequent derivation of performance and dependability measures is shown. Finally, Section 7 provides some concluding remarks.

3 An Application Example

In order to explain the proposed modelling method in the subsequent sections, the application example is described here. The chosen manufacturing system is operated by a company that supplies car safety equipment and assembles pyrotechnic buckle pretensioners. In case of a collision, which is detected by the airbag sensors, the safety belts are pulled tight.

Figure 1 shows the layout of the system. Most of the 17 stations in the system operate fully automatically, there are only three manual workplaces. The different stations are organized in three circular assembly lines, through which the workpieces have to pass one after another. It should be noted, that due to space limitations the system is presented here with slight simplifications. Bold rectangles denote automated assembly stations. An identification number is associated with each station.

Workpieces are transported on special carriers. The two stations 40 and 120 are responsible for moving the workpieces from one circle onto the carriers of the next one. Each circle consists of several conveyor belts and switches, that connect the different stations and act as buffers. In the figure arrows depict the transport directions of the conveyor belts. Switches are highlighted with dashed boxes. When a carrier arrives at the switch behind station 70, the direction in which the carrier will move depends on the utilization of the subsequent stations 81 and 82. Station 83 supplies additional parts that are fixed on the pretensioners by stations 81 and 82.

The task was to model the described system and to obtain performance measures of some variations. Thus the influence of machine failures on the throughput could be estimated. Furthermore, different possibilities to enhance the performance have been identified.

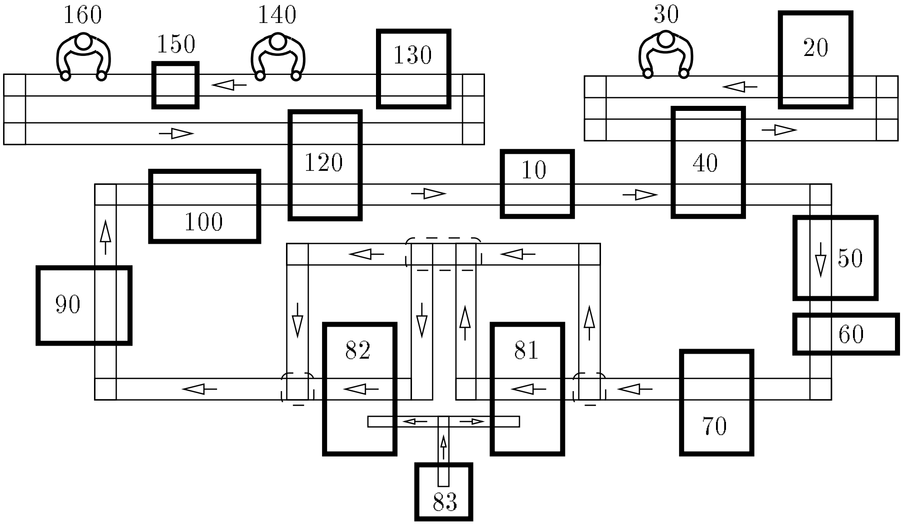

Figure 1: Layout of the manufacturing system

4 Dedicated Coloured Petri Nets

Compared to Petri nets without distinguishable tokens, coloured Petri nets [7] offer advanced modelling facilities like token colours and hierarchical refinement of transitions. Unfortunately, the pure graphical description method of Petri nets is hampered by the need to define colour types and variables comparable to programming languages.

However, for a restricted area of application it is possible to define a class of dedicated coloured Petri nets. Two colour types are predefined, which are adapted to manufacturing systems. *Object tokens* model workpieces inside the manufacturing system, and consist of a name and the workpieces current state. *Elementary tokens* do not have a special colour, and are equivalent to tokens in uncoloured Petri nets.

Places can contain only tokens of one type. *Object places* are drawn as thick circles. They model the possible locations of workpieces, while *Elementary places* represent the status of resources (e.g. a busy machine). The latter are represented by thin circles. Each input and output arc is connected to one place, and only tokens of the appropriate colour type can flow through it. Therefore, arcs are drawn thick or thin as well, corresponding to their associated colour type. Transitions model possible events, i.e. state changes in the system. The structural model of a manufacturing system reflects the layout, which makes it easier to understand. Textual descriptions needed in CPNs for the definition of variables and colour types can be omitted, and the specification of the types of places and arcs are implicitly given.

To meet the requirements of a modelling technique for manufacturing systems, the structure of the manufacturing system has to be modelled independently of the production routes. The structural model describes the abilities and work plan independent properties of the manufacturing system resources, such as machines, buffer capacities, and transport connections. On the other hand, there are several work plan models, one for each workpiece to be produced. Each of the processing steps of the production routes has to be performed on a machine in the manufacturing system. Therefore, a production route can be thought of as a path through the manufacturing system. This relationship

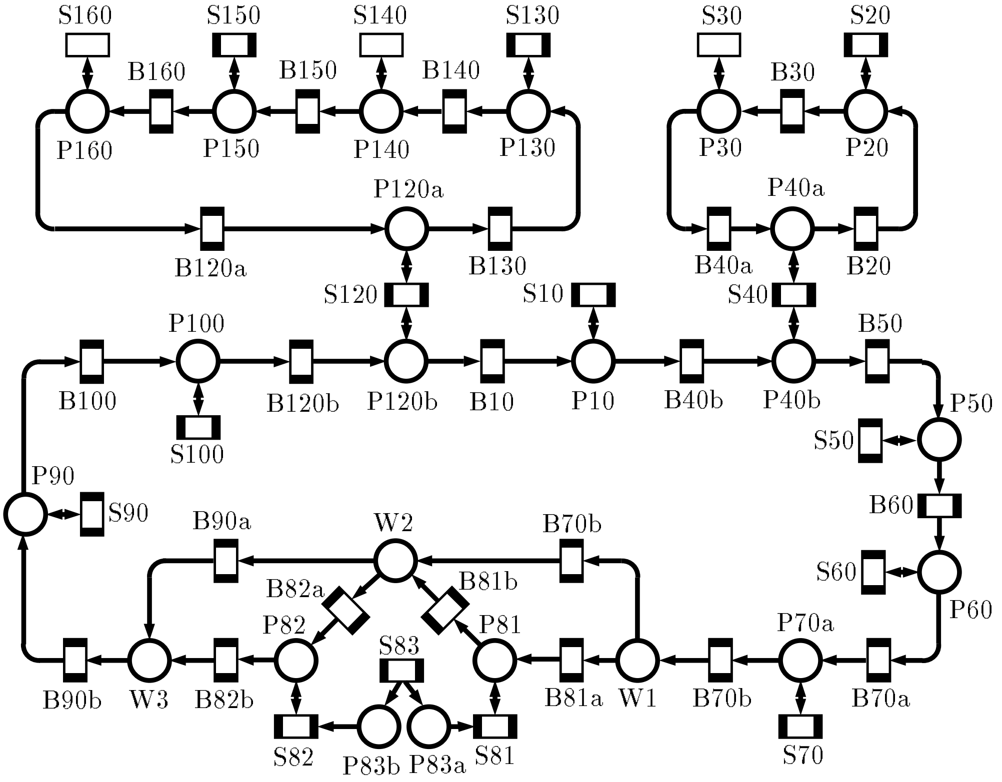

Figure 2: Model of the system's structure

is now reflected on the modelling level. Every transition in a production route model corresponds to a transition in the structural model, indicating that the production step is executed by the modelled resource. Thus the term *associated Petri nets* is introduced for the production route models. Later on, the different model parts are automatically merged resulting in a complete model, which then includes both the resource constraints of the system and the production steps. Analysing this model gives the performance of the manufacturing system or other measures of interest.

4.1 Modelling the Structure of the Manufacturing System

Modelling the manufacturing cell described in Section 3 with a dedicated coloured Petri net results in a concise model. The structural model describes the resources and the properties that are indendent of the work plans. Figure 2 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 behaviour of a machine or a conveyor in more detail. Submodels from a library of standardized building blocks (*templates*) can be parameterized and instantiated while refining the model (see Section 4.3).

Because the model strictly follows the layout of the system shown in Figure 1, it is not only understandable but can be easily derived from a layout sketch of the manufacturing system. Only workpieces to be processed are considered as tokens at this level of abstraction. So no elementary places are used.

The different assembly stations are modelled with a transition and a place holding the actual workpiece being processed. Machines and manual workers are identified by an `S` and the number of the station, while the names of the processing places include a `P`. Stations `S40` and `S120` connect the three assembly circles. Thus they are connected to more than one processing place. The place names have trailing letters `a` and `b` to make them unique. The capacity inscriptions are omitted in the figure. But still they are restricted to one in the example. As each assembly station changes only the processing state of a workpiece and not its location, the corresponding token remains in the same place. The change of state takes place when the transition fires, removing the old token and adding a token with the new processing state instantaneously. Two arcs in opposite directions are therefore needed between a transition modelling a station and its processing place. Drawing them on top of each other results in the double-arrowed arcs shown in Figure 2.

Please note the different transition types that have been chosen for manual workplaces and automated machines. Transitions with exponentially distributed firing times model manual workplaces, while substitution transitions with underlying subnets describe the behaviour of each machine. Please refer to Section 4.3 for a detailed description of the subnets, which include a model of the local failure and repair behaviour. A description of the stations and their processing tasks is omitted here.

Conveyor belts are responsible for transporting the workpieces and are modelled by substitution transitions. The associated submodels include a description of how the workpieces are transported and how many carriers fit onto each conveyor belt. Their names consist of a `B` followed by a number, according to the connected station. If more than one conveyor is connected to a station, a letter has to be appended for unique transition names. Besides that, there are three switching places `W1`, `W2` and `W3`.

4.2 Production Route Models

After modelling the assembly system's structure, a production route model for each workpiece has to be defined. It can be derived directly from a description of where and how the workpieces have to be processed, and which processing states they have to pass through. This set of models is described with the same type of dedicated coloured Petri nets, having some slight differences. Figure 3 shows the top level of this model for carriers with buckle pretensioners in the last assembly circle. Such a model represents a path through the structural model, hence only places and transitions that can be found there are usable. This applies to all levels of hierarchy; the work plan models are refined in the same way as the structural model. If a template submodel is used for the refinement of a substitution transition, a parameterizable production route submodel is taken from the library besides the structural model (see Section 4.3).

Each production route model specifies the sequence of transport operations and production steps of a workpiece. Additionally, it describes the actual parameters of the used resources in each step. The firing delay of a transition in a production route model is set to the time the production step takes for that workpiece. This is only necessary if the delay differs from the default value, which is the firing delay of the associated transition in the structural model. For example, if the processing time for a specific workpiece differs from the machine's default, a particular firing time distribution can be specified in the production route model.

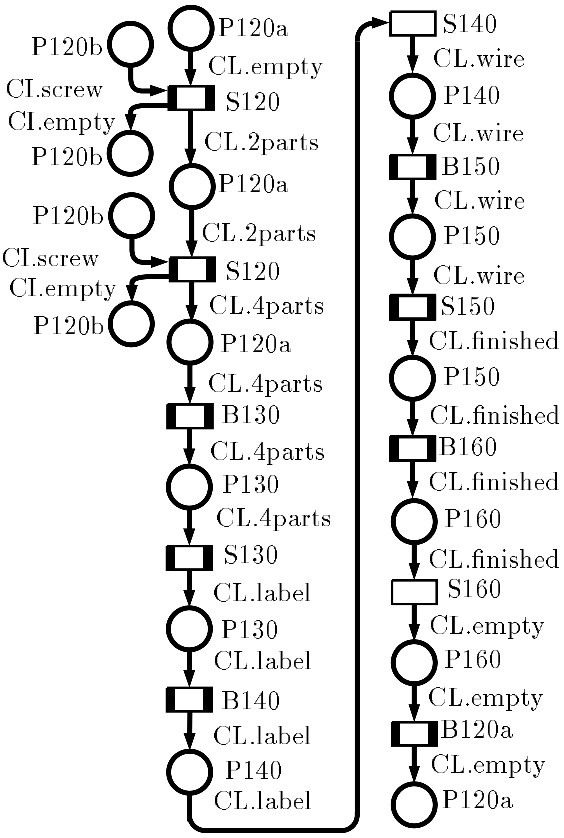

Figure 3: Production route model

The arcs are labelled with the names of object tokens, showing the changes in their processing state. Since the workpieces are transported on carriers in our application example, the model describes their processing states on each carrier. The name of a workpiece is separated from its processing state by a dot. Thus, `CL.finished` describes a carrier of the last circle with finished buckle pretensioners on it.

Alternative routes of workpieces can be modelled by using different paths, with having conditions and probabilities assigned to if needed. However, this was not necessary for the work plan presented here. Conditions decide which path might be chosen, thus allowing the implementation of a scheduling strategy. Usually, a work plan model consists of a simple sequence of places and transitions. Exceptions are — in addition to alternative routes — assembly and disassembly operations, where more than one input and output arc is connected to a transition. In Figure 3, unloading workpieces from carriers of the intermediate circle (`CI`) and loading carriers of the last assembly circle is modelled by transition `S120`. In the intermediate circle, there are two workpieces on each carrier, while the last circle's carriers hold four. Therefore two unloading operations are necessary.

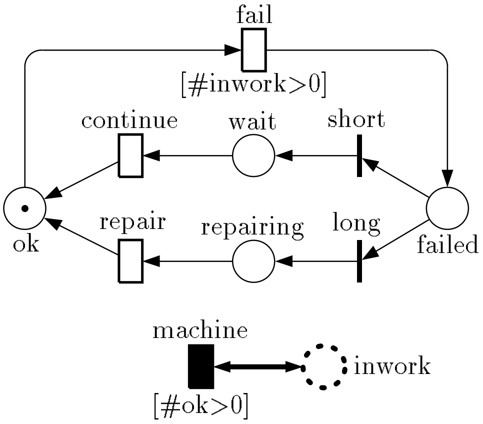

Figure 4: Submodel with failure behaviour

4.3 A Library of Model Templates

Several basic types of machines and transport facilities that appear in many automated manufacturing systems can be identified. It is thus very useful to supply a library of such models. Each of the model templates has a set of parameters such as processing times or buffer capacities. By associating values to the parameters, a class of structurally similar resources is represented. The library models can be used for the refinement of substitution transitions.

There are different models for the structure and the work plans of library templates as described above for the main model. The difference is again the inscription of processing states at arcs in the work plan models. As the actual descriptions of workpieces and their states are unknown during the creation of a library model, they are model parameters that are set to the real values during instantiation.

Figure 4 shows the refining subpage of a substitution transition modelling an automated station of our example. The behaviour of all non-manual workplaces is the same, they differ only in some delays. Due to this fact, the model shown in Figure 4 has been defined as a model template with parameters for the delays.

The deterministic transition `machine` models the processing step that is carried out by the station. It may only fire if the machine is operational (a token is in place `ok`). The processing place `inwork` is drawn using a dashed line, which indicates that the place is part of the submodels interface to the upper level of the hierarchy.

An important part of the modelling process is the determination of the time spent by the machines for each of the production steps and their failure-and-repair behaviour. In order to do so, not only the mean values have to be taken into account, but also their distribution. Our investigations showed that for all the automated machines in our example the same type of behaviour could be identified.

The upper part of Figure 4 describes the machine's failure-and-repair behaviour. It is modelled using elementary net elements. Thin lines are used in order to distinguish it from the object places. The machine is ready for use if there is a token in place `ok`. If it is working (the number of tokens in place `inwork` is greater than zero), it may fail (transition `fail` fires). The mean time to failure (MTTF) of a machine can be modelled with an exponential distribution. 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 workpiece or a temporary malfunction. Only a few failures require a repair by a mechanic, and therefore take longer to recover from. This behaviour can be modelled with a subnet of transitions with exponentially distributed firing times and immediate transitions as shown in Figure 4. The submodel yields a weighted sum of exponential distributions for the mean time to repair (MTTR), resulting in a good approximation of the real behaviour.

The corresponding work plan model is omitted here. It describes the change in the processing state of a workpiece. Submodels or model templates have to be defined to refine all the substitution transitions. For the sake of simplicity they are not shown here as well as the work plan models for the first and second assembly circle. The complete model for the application example consists of approximately 100 model pages. Most of which could be instantiated from a set of predefined templates.

5 Compilation of a Complete Model

The previous sections described how to construct models of the manufacturing system's structure and the production routes. Subsequently, both model parts are merged automatically to create a complete model that can be analysed. In this section, the underlying algorithm is presented. The information contained in the production route models is added to the structural model during this process. The transitions are enriched with their *firing possibilities*. The procedure is invisible to the modeler, who only needs to construct the model of the structure and the production routes for a given manufacturing system.

In a coloured Petri net, each transition may have several firing possibilities depending on the current model state (the marking). Each is characterized by different values of the arc expressions attached to the transition's input and output arcs. In contrast to other coloured Petri net modelling techniques, variables inside these arc expressions are not needed. Instead, all the different firing possibilities are obtained automatically from the production route models. Please note that all token colours are known a-priori from the arc inscriptions of the production route models. The set of token colours is given by the object tokens used in the inscriptions plus the predefined type of elementary tokens. Each of the production route models describes the production steps of one product. Thus, every occurence of a transition in such a model specifies the use of a resource (machine, transport facility etc.) that exists in the structural model. Identical transition names in both model parts document this relationship.

It should be clear from the different meanings of transitions in the structural and production route model parts, that each occurence of a transition in a production route model describes one possible activity of the resource. In terms of a Petri net, such an activity (or production step) can be described as a firing possibility. The information contained in each one of them is described later. After the compilation, the resulting complete model has to specify all firing possbilities for each transition in the structural model. In order to do so, a so-called transition table is computed for each transition. This table is just a collection of the firing possibilities, organized as table entries. From a more general point of view, this can be thought of as summing up the restrictions imposed by the manufacturing system's structure (the resources and their general capabilities) and the workplans. In some sense the structural model synchronizes the workplan models.

Computing a complete model now reduces to the following algorithm: For each transition t_i in the structural model, scan all workplan models for corresponding transitions

t_2. Such a transition t_2 has the same name and resides on a page that is associated to the page of t_i. For every transition t_2 that is found, add one entry to the transition table of t_i. The information contained in each of the transition table entries is obtained as follows:

- The description of the token input and output behaviour of t_i for this firing possibility is given by the assignment of tokens and their colours to the arcs of t_k. If for instance in the production route model a workpiece `A` is transported from place `P1` to `P2` by the firing of t_k, the transition table entry of t_i would contain the following assignment of token multisets: `in#P1=A, out#P2=A`. The input and output of elementary tokens is given in the structural model and added to every transition table entry.
- Using a marking-dependent guard expression at transition t_k in the production route model expresses that a production step might only be executed if a certain condition is true. This guard expression is copied to the transition table entry. Thus, the firing possibility (the transition table entry of t_i) will later be enabled only if the specified expression evaluates to true.
- The firing time distribution of the transition table entry is normally taken from t_i. This default value can be overwritten by specifying at t_k another distribution for a production step in the production route model. In this case, t_k's firing time distribution will be used for the transition table entry.

Thus, for each transition in a production route model, a new table entry is added to the corresponding transition in the structural model. It contains the input and output behaviour, the firing time distribution and an optional guard expression. For more details about transition tables and their impact on the later analysis see [1]. After the compilation, the structural model together with the transition tables describes the behaviour of the system being modelled and can be evaluated.

6 Performance Evaluation

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

In order to evaluate the performance of a manufacturing system, delays are associated with the transition firings. In SPNs as well as in GSPNs, the exponential distribution is used due to its analytical simplicity. This is often a good approximation of the real behaviour. Zenie proposed coloured stochastic Petri nets [12], while Lin and Marinescu introduced stochastic high-level Petri nets [13, 14].

However, the fixed processing time of a certain workpiece or a transport delay should better be modelled using deterministic times. It has been shown that the results obtained from models with different distributions may vary significantly [15]. To obtain more realistic results, analysis methods for models incorporating non-exponentially distributed firing times have to be used. Techniques for uncoloured nets [15, 16] are adopted here for the analysis of the dedicated Petri net models. This is possible because both model types have the same underlying stochastic process. At the net level of the (reduced) reachability graph they can both be analysed in the same way.

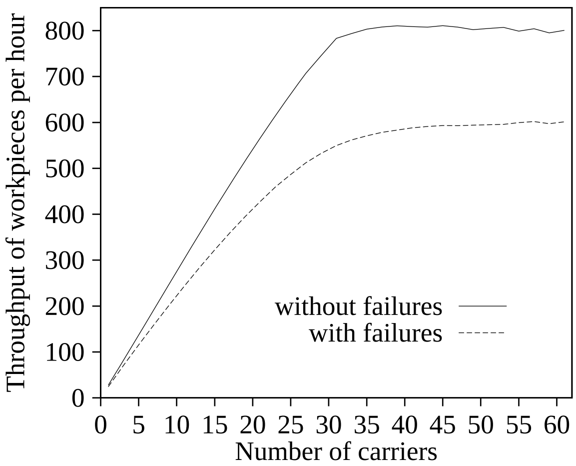

Figure 5: Throughput versus number of carriers

It is possible to numerically analyse models that contain transitions with firing time distributions from a wide class of functions. The firing times may be immediate, exponentially distributed, deterministic or more generally distributed. If no more than one general or deterministic transition is enabled in each marking, a *semi-regenerative stochastic process* underlies the Petri net model. Simulation has to be used if numerical evaluation is impossible due to the large state space or limitations in the analysable firing time distributions. For the derivation of quantitative measures, the software tool TimeNET [16] has been used, in which the described techniques have been implemented.

The aim of the following investigations 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). Suggestions are sought in order to increase the manufacturing system's productivity.

The influence of the number of available carriers on the performance of the assembly system was evaluated first. Figure 5 shows the throughput measured in workpieces per hour of the main circular assembly line, if the number of carriers varies from 1 to 60.

There is an obvious gain in productivity if the number of carriers is increased up to 30 carriers. If more carriers are added, the system becomes satiated.

The same kind of evaluation has been carried out for the other assembly circles as well. In the first circle, there was only a small decrease in the throughput due to machine failures. There only 5 carriers are needed to achieve the maximum throughput. In the last assembly circle the failures have almost no influence on the performance. The throughput increases until about 15 carriers are used.

The degree of utilization of the stations and their mean availability due to failures and repairs has been obtained from the model. This shows the bottlenecks of the system. In our example, stations `S20` and `S160` have the highest utilization. This is according to their processing times for one workpiece, which is very high compared with the others. The slowest machine in the second assembly circle is station `S83`, due to its high percentage of down times. Stations `S81` and `S82` are slowed down because of missing parts that are supplied by `S83`. As a result of these investigations it is clear which machines should be improved and whether one should concentrate on avoiding failures or decreasing the

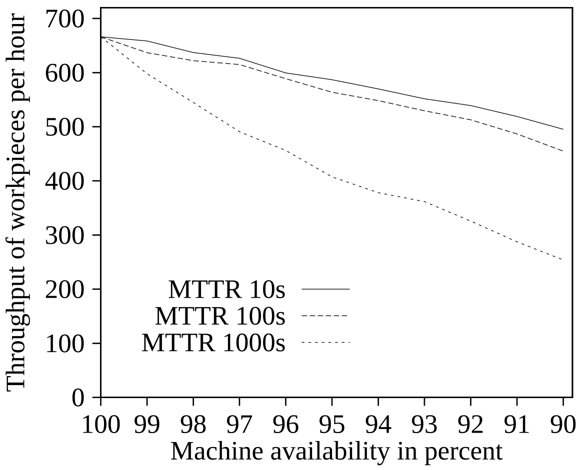

Figure 6: Throughput versus machine availability

processing times.

The upper and lower curves in Figure 5 show the impact of machine failures on the overall performance, which is actually more than 30 percent less than it would be without failures. It is impossible to quantify the influence of failures on a complex system 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.

If a machine fails, it stops working, and the buffer between this machine and its predecessor fills up. When the buffer is full, the previous machine has to stop working 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.

Figure 6 shows the influence of the machine availability and the mean duration of machine failures on the system performance. The availability of the machines (the probability that for a given instant of time the machine is operational) varies from 100 down to 90 percent. Additionally, different durations of failures are considered, while keeping the availability constant. The throughput of course 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.

Based on an examination of a model similar to the one presented here, it is possible to determine a good configuration of the planned system. The bottlenecks can be identified by comparing the degree of utilization of the stations. During the further analysis of model variants, propositions for system changes could be made, that lead to a higher output. For the example presented, the buffer space should be distributed equally among the conveyor belts by adjusting their length. It is clear from the examination of the failure's influence and the importance of the buffers that this improves the throughput without higher investment costs. The number of carriers has been set to the values that are necessary to maximize the output. Afterwards, the distribution of the workers among the manual workplaces has been optimized by evaluating the performance for different possibilities. The slowest stations are accelerated in such a way that they fulfill the initial requirements of the assembly line's stations. This means that they have an isolated throughput equal to the planned output of the whole assembly line. It is obvious that no higher throughput can be achieved. In the final experiment, the performance of the improved assembly system has been evaluated. The modelling and analysis technique showed that the overall throughput increases by 22 percent with the mentioned small changes. This proves the necessity of modelling and analysing a manufacturing system during the design process.

7 Conclusion

This paper describes a new modelling technique for manufacturing systems. A dedicated modelling method based on coloured Petri nets is introduced for this application area. Simpler models are created that reflect the system's structure and are better readable than models using general-purpose net classes. In addition to immediate and exponentially timed transitions, non-exponentially distributed firing times of transitions are allowed. Thus, the timing behaviour can often be modelled more realistically. Hierarchical refinement allows for the specification of the failure-and-repair behaviour on a lower level and for using model templates from a library.

Furthermore, modelling separately the production routes and the system's structure is now possible. The routes can be modified and no complete redesign of the model is necessary. A complete model is derived automatically by a compilation of both model parts. This model can subsequently be used to obtain performance and dependability measures by using numerical analysis or simulation. Optimization is possible by comparing the performance measures of different model variants. The introduced modelling technique has been applied to a real-life problem, successfully showing its usefulness. It is implemented as an extension of the software package TimeNET [16].

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