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Modeling of Manufacturing Systems and Production Routes Using Colored Petri Nets

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Abstract

Modeling and performance evaluation play a major role for the design of today's manufacturing systems. This paper adresses the modeling of manufacturing systems with Petri nets. A new method is proposed, facilitating the independent modeling of the manufacturing system's structure and the production routes of the parts being processed. Both models use the same specialized type of Colored Petri Nets, tailored for the modeling of manufacturing systems. The model parts are automatically compiled into a complete model, which describes the behavior of the whole system.

Key Words

Modeling, Manufacturing Systems, Colored Petri Nets

1. Introduction

Modern manufacturing systems are characterized by a rapid change of the production mix and an increasing amount of automated processes. Due to many different product types the production process becomes more and more complex. Therefore, the design and investment costs for manufacturing systems are rising.

Therefore modeling and performance evaluation of manufacturing systems play a major role in an efficient design of such systems. Starting from a model, the correct behavior can be checked in a first step. Furthermore, the relevant performance measures can be obtained using performance evaluation techniques. Those measures include the system throughput, utilization of the resources, and reliability measures. The comparison of different variations of a manufacturing system leads to an optimized system.

In this paper a new modeling method for manufacturing systems is described. The main contribution lies in the independent modeling of the manufacturing system's structure and the production routes with one specialized kind of Petri net. The resulting model parts can then be compiled automatically into a complete model. This leads to a modeling method, which is much better suited for the design of manufacturing systems than the known types of Petri nets.

Stochastic Petri nets [1] are a powerful tool for the modeling and analysis of manufacturing systems. They represent a graphical description method which has gained increasing acceptance for the modeling of discrete event systems. Petri nets can be used throughout the specification, modeling, qualitative validation and performance evaluation [6].

Manufacturing systems [2], [7] and flexible manufacturing systems [6] have often been modeled in the literature. In the past, different approaches to the modeling of them with specialized Petri nets have been made. For instance, Bruno et. al. introduced *Prot nets* [3] as an extension with marking-dependant arc expressions for the modeling of discrete event systems.

However, uncolored nets have proved to be unsuitable for the modeling of realistic manufacturing systems because of the resulting complex models. Among the main reasons for this are the absence of distinguishable tokens and the impossibility of hierarchical modeling.

Therefore, *Colored Petri Nets* (*CPN*s, [4]) were used to model manufacturing systems [7]. CPNs offer a substantially higher level of modeling, but contain complex definitions of colors, types and variables. Their graphical representation includes many textual expressions. To overcome this problem, a special kind of CPNs has been introduced in [8], which is tailored for the modeling of manufacturing systems. This method is used as a basis for the work presented in this paper.

2. A New Modeling Method for Manufacturing Systems and Production Routes

Opposed to uncolored Petri nets, Colored Petri Nets offer more advanced facilities like distinguishable tokens and hierarchical modeling. The pure graphical description method of Petri nets is, however, hampered by the need to define color types and variables in some kind of a programming language.

To solve this problem, in [8] a new method for the modeling of manufacturing systems is presented, incorporating the benefits of both types of Petri nets. The main idea lies in the pre-definition of two color types (*part* and *state*), which are sufficient for the modeling area of manufacturing systems. Tokens of type *part* model workpieces inside the manufacturing system, and consist of a description of the part's name and current state, e.g. `wheel.raw`. Tokens of type *state* do not have a special color, and are therefore equivalent to tokens from uncolored Petri nets. They are used to model states of resources (e.g. a busy machine) and can be drawn as dots like in uncolored nets.

Places can contain only tokens of one type, therefore they are either of type *state* or *part*. Places of type *part* model the possible locations of workpieces like buffers. To avoid the textual description of the place type as in CPNs, places of type *part* are drawn as thick circles, while places of type *state* are drawn thin. Each input and output arc is connected to exactly one place, and only tokens of the place's assigned color type can "flow through" it. Therefore, arcs are drawn thick or thin as well, corresponding to their associated color type.

Using this method, the textual descriptions needed in

CPNs for the definition of variables and color types can be left out, and the inscriptions describing the types of places and arcs are unnecessary. The modeling process becomes easier and uses more graphical elements. The model of the manufacturing system's structure resembles the real structure, which makes it easier to understand.

To meet the requirements of a modeling technique for manufacturing systems, the structure of the manufacturing system has to be modeled independently of the production routes. Otherwise, the whole model would have to be constructed again for each variation of the product's routes through the system. This problem has not been solved adequatly by the existing approaches to the modeling of manufacturing systems with Petri nets. We present a method to describe the manufacturing system's structure and the production routes seperately with Petri nets. The ideas briefly described above (taken from [8]) are applied to both model parts.

Although the Petri net describing the production routes is separated from the structural model, there is a connection between the two model parts in reality, because each of the processing steps of the production routes has to be carried out on a machine which exists in the manufacturing system. Therefore, a production route can be thought of as a path through the manufacturing system. A similar relationship between the model parts exists on the modeling level. Every transition from the production route models corresponds to a transition from the structural model, which means that the production route action is executed by the modeled machine. We introduce the term *associated Petri nets* for the production route models, because they are associated in the above mentioned way to the model of the manufacturing system's strucure.

The application of the predefined color types introduced in [8] makes is possible to avoid the arc expressions and definitions of colors otherwise required in CPNs. The different properties of the transitions, which depend on the markings, are specified in a *transition table* (see Section 2.3). This table contains the set of all possible bindings of each transition together with the corresponding firing conditions and delays. The transition table therefore replaces the guard and arc expressions used in CPNs, and is automatically derived from the associated Petri nets. After enriching the structural model with the transition table, it describes the behavior of the complete manufacturing system.

2.1 An Example

We use the simple manufacturing cell shown in Fig. 1 as an example. Two machines `M1` and `M2` assemble and process parts A and B. Parts of type A enter the system in raw state (`A.0`) via the loading station `LD1`, parts of type `B.0` via the loading station `LD2`, and small parts of type `C.0` are stored in `ST`. Machine `M1` assembles one part of type `A.0` and two of type `C.0`. The resulting parts `A.1` are kept in an intermediate buffer `BF` together with the arriving parts of type `B.0`. The transport system `TR` brings them to the drilling machine `M2`. After having been processed by `M2`, the finished parts of type `A.2` and `B.1` leave the cell via the unloading station `UNL`.

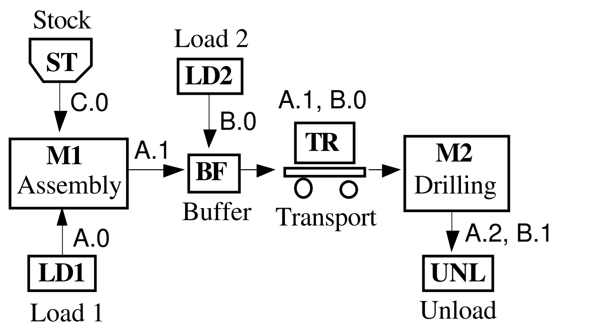

Figure 1: Layout of the manufacturing system

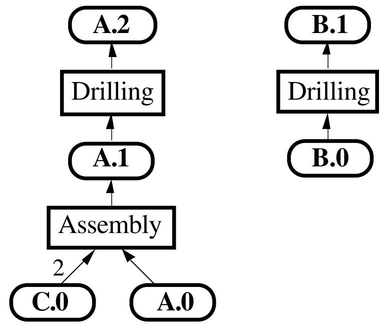

Figure 2: Work plans of the two products

Fig. 2 shows the *work plans* of the two products A and B, describing their processing steps and assembly operations (*what* is to be done). The *production routes* additionally specify the machines, on which the processing steps are carried out (*what* is *where* to be done).

2.2 Modeling the Structure of the Manufacturing System

CPNs consist of *pages*, thus allowing hierarchical modeling. Fig. 3 shows the page `STRUCTURE`, which models the structure of our example. Such a model can be derived directly from an outline of the manufacturing systems layout as it is shown in Fig. 1. Buffers and other possible locations of parts correspond to places of the Petri net, while machines and transport facilities are modeled with transitions. Therefore, there is a similarity

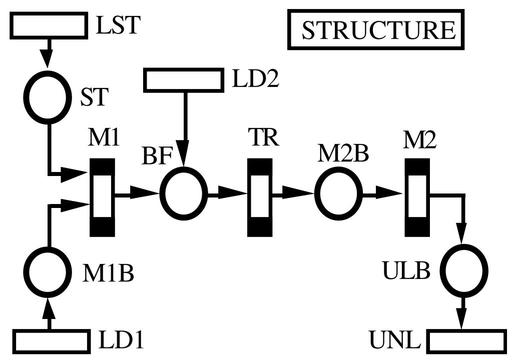

Figure 3: Petri net model of the manufacturing systems structure

between the shape of the Petri net model and the manufacturing systems structure. In Fig. 3 the mentioned model is shown for the example. It describes the modeled system at the highest level of abstraction and is used as a basis for further refinements. Refined transitions are called *substitution transitions* and are depicted as a box with the upper and lower side drawn thick (see transitions `M1`, `TM`, and `M2`). For each substitution transition there has to be a *subpage*, describing the behavior of the modeled resource more thoroughly at a lower level of hierarchy. Fig. 4 shows the subpage `MACHINE2` (corresponding to transition `M2` of the main model) as an example.

Parts located in the machine's input buffer `PRE` can be loaded into the machine, when the transition `MLOAD` fires the token to the place `WORK`. The processing of the part is

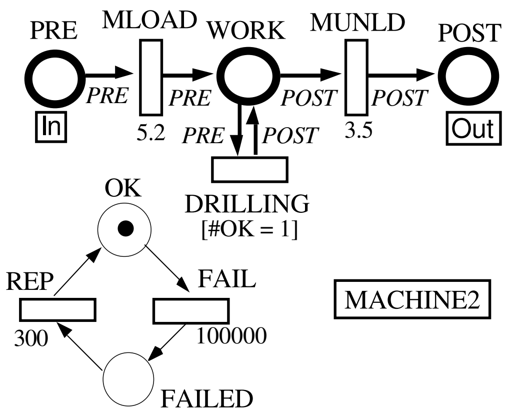

Figure 4: Refined model of machine 2

modeled by the transition DRILLING, changing the state of the token. After finishing this operation, the part is unloaded from the machine (transition MUNLD fires) and leaves the submodel via the buffer POST. At this level of description, for each transition a default firing time can be specified (5.2 and 3.5 units of time for MLOAD and MUNLD, respectively). Later on, this default value can be overridden by a time depending on the actual part being processed.

The names of places written in italics at the arcs (*PRE* and *POST*) are used to describe the modification of the parts. In the example, only the firing of transition DRILLING changes the token type, while all other transitions only move the tokens to other places. After the production routes have been defined, the actual parts being processed by this machine are substituted for the place names. The meaning of *PRE* at an arc is as follows: the type of tokens fired through this arc corresponds to the type of the token when it arrived in place PRE.

The failure and repair of the machine are modeled by the firing of the transitions FAIL and REP, and the delays of them are specified as 100 000 and 300 units of time, respectively. The machine can only work if it is not failed. Therefore, the transition DRILLING has a guard function [#OK=1].

2.3 Modeling of the Production Routes

After having described the structure of the manufacturing system, in this section the modeling of the production routes with Petri nets is introduced. To the best of the authors knowledge, this is the first attempt to model production routes with CPNs. The Petri net models of the production routes are shown in Fig. 5 for the example. They can easily be derived from the work plans.

While obtaining a model of the production routes, an additional step has to be performed: resources have to be assigned to the work plan actions, thus determining the possible paths of the parts through the manufacturing system. Different possible ways to process a part can be modeled using conflicting transitions, but to keep the example easy, we do not consider this case here.

Fig. 5 depicts the *associated Petri nets* of the production routes. An associated Petri net describes a path through the structural model of the manufacturing system, and entirely consists of places and transitions which are also a part of the structural model. Each associated Petri net "starts" and "ends" with a transition describing the system's input or output, or with a change to another asscociated net.

To model the behavior of the manufacturing system while the parts are processed, the associated Petri nets are

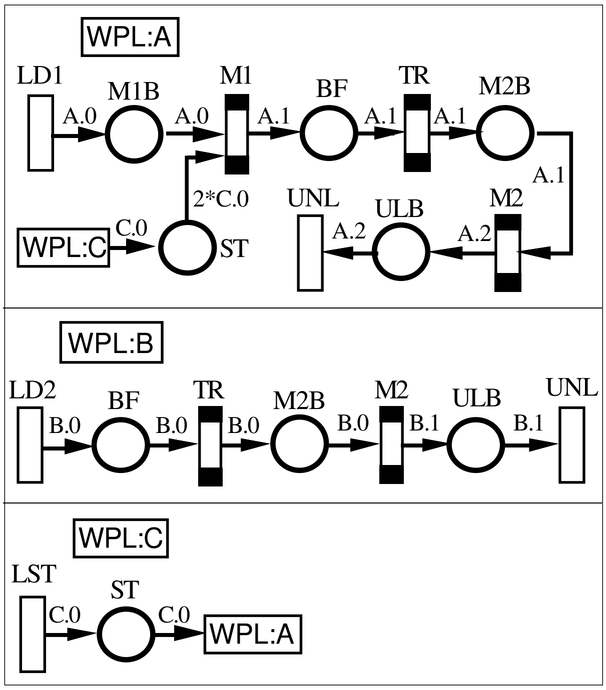

Figure 5: Production route models

automatically compiled into *transition tables*. These tables describe all possible bindings of the transitions of the structural model, and consist of several entries. After the name of the transition, an optional firing guard can be specified in round brackets. The transition is only enabled, if this expression evaluates to true in a given marking. A list of all possible bindings follows in square brackets, each of them describing a possible assignment of tokens to arcs of the transition. Additionally, a firing delay is given for each binding, thus facilitating different processing times of parts at one machine. Arcs are referred to by the name of the place to which they connect the transition, together with their type (e.g. out#WORK).

For substitution transitions a direct transition table cannot be given because the transition itself serves only as a place-marker for the subpage. A substitution transition's entry in the transition table therefore starts with the keyword *substitution*, the name of the subpage, and the *port assignments*, which assign a place (*port node*) of the subpage to a place (*socket node*) of the superpage. The entries for each subpage transition appear afterwards in the transition table. Empty entries are left out.

Workplan A

```
M2[substitution->MACHINE2: M2B->PRE,
        ULB->POST;
  MLOAD[in#PRE=A.1,out#WORK=A.1 ]
  DRILLING[in#WORK=A.1,out#WORK=A.2; 10.3 ]
  MUNLD[in#WORK=A.2,out#POST=A.2 ] ]
```

Workplan B

```
M2[substitution->MACHINE2: M2B->PRE,
        ULB->POST;
  MLOAD[in#PRE=B.0,out#WORK=B.0 ]
  DRILLING[in#WORK=B.0,out#WORK=B.1; 8.8 ]
  MUNLD[in#WORK=B.0,out#POST=B.0 ] ]
```

Table 1: Transition tables for machine 2

The transition tables for the drilling machine and the two workplans are shown in table 1. The first row of the table has the following meaning: transition M2 is substituted by the subpage MACHINE2, while the places M2B and ULB are assigned to the places PRE and POST, respectively. Afterwards, the product-dependent behavior is given for each transition of the subnet.

The line

```
MLOAD [in#PRE=A.1, out#WORK=A.1]
```

means that the transition MLOAD is enabled, if there is a token of color A.1 in the input place PRE. If it fires, this token is moved to the place WORK.

For all non-substitution transitions the entries in the transition table can be derived easily from the Petri net models of the production routes: each time the transition appears in the production route models, one row of the table is generated. The part types and states are taken directly from the production route model. If a delay is given, it is also put into the table.

A little more work has to be done for substitution transitions. Instead of generating transition table entries for the transition itself, the transitions of the subpage are considered. It is known from the production routes, which types of tokens arrive at the places surrounding the substitution transition. These places are assigned to places of the subnet by a substitution (this substitution is part of the structural model of the manufacturing system). The place-marks set in italics in the subpage can than be substituted by the token types entering the subpage via the port nodes. The firing behavior of the subpage transitions together with the token types determines the transition table entry.

Following this method, for each production route one transition table is generated, incorporating informations about all possible bindings of the transitions and their properties.

2.4 Compilation of a Complete Model

To model the behavior of the manufacturing system while processing the parts as defined in the production routes, the Petri net model of the structure is enriched automatically with the informations contained in the transition tables. For this reason, a *combined transition table* is generated for each transition of the structural model. The table for transition M2 from the example is shown in table 2.

```
M2[substitution->MACHINE2: M2B->PRE,
                           ULB->POST;
  MLOAD[in#PRE=A.1,out#WORK=A.1;5.2 |
        in#PRE=B.0,out#WORK=B.0;5.2 ]
  DRILLING (#OK=1) [in#WORK=A.1,
        out#WORK=A.2; 10.3 |
        in#WORK=B.0, out#WORK=B.1; 8.8]
  MUNLD[in#WORK=A.2,out#POST=A.2;3.5 |
   in#WORK = B.0,out#POST = B.0;3.5 ] ]
```

Table 2: Combined transition table of machine 2

All entries belonging to one transition of the structural model are put together. The combined transition table associated to a transition consists of all those rows, connected by a logical OR (”|“ in the table). The last part of each entry is the firing delay of the transition under this binding, which is taken from the transition table of the production route. If a delay is omitted there, the default delay is taken from the model of the manufacturing system’s structure.

The guards of the transitions (specified in the structural model) are also copied into the combined transition table before the different bindings (see DRILLING (#OK=1) in the example).

The generation of the combined transition tables can be done automatically, because no additional informations are required besides the existing model parts. Afterwards, there is a combined transition table associated to each transition of the manufacturing system’s structural model. This table describes the behavior of the transition under its different bindings.

Starting from the automatically derived complete model, qualitative and quantitative properties of the manufacturing system can be obtained with analysis techniques used for stochastic extensions of CPNs.

3. Conclusions

In this paper a new method for the modeling of manufacturing systems is described. CPNs with several restrictions and predefined color types [8] are used for this method, resulting in a more concise way of modeling.

The main advantage of the technique proposed in this paper lies in the independent modeling of the manufacturing system’s structure and the production routes with one specialized kind of Petri net. The term *associated Petri nets* is introduced for the models of the production routes. A modification of them does not necessitate a change of the structural model, thus reflecting that the manufacturing system is independent of the parts being processed.

A complete model can be derived automatically from the model parts. Structural properties and quantitative measures can be computed from the model, using numerical analysis or discrete event simulation.

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