The Use of Fuzzy Coloured Petri Nets for Modelling and Simulation in Manufacturing*

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1. Abstract

In this paper a kind of Fuzzy Petri Nets is presented - the Fuzzy Coloured Petri Nets (FCPN). They are no new class of Petri Nets, but as the connection between Coloured Petri Nets and fuzzy logic they are a very useful description means. The fuzzy feature of this FCPN is Fuzzy Valuation of transitions used for conflict solving and foresimulation in production planning.
After an introduction main terms of Coloured Petri Nets and the Fuzzy Valuation of transitions are represented. A technological example of the application of FCPN is considered then. Finally a summary and future plans are presented.

2. Introduction

The application of fuzzy algorithms plays more and more an important role for many domains. The software-offers for implementation of fuzzy logic are of a great variety /Feli 93/. But with these tools it is impossible to implement independent concurrent fuzzy algorithms or to test its communications with controlled processes by simulation or analysis. Petri Nets with corresponding interpretation and extension permit design and analysis of control structures of programs for discrete production processes. By use of Coloured Petri Nets all advantages of Place/Transition Nets including analysis are kept but the description power grows /Jens 92/, /Star 91/. It is shown how through a marking dependent data function and Fuzzy-Valuation of transitions the dynamic data flow and the fuzzy algorithms in discrete production processes can be modeled and simulated.

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3. Coloured Petri Nets (CPN)

Coloured Petri Nets are an extension of Place/Transition Nets. They are the result of folding of the net elements. The places or transitions of the Place/Transition Net occur in the Coloured Net as colours in places or transitions (Figure 1). The reversal of this operation, the unfolding, is used for the simulation and analysis in Coloured Petri Nets.

Coloured Petri Nets have the following definition /Jens 92/, /Feng1 93/:
A CPN is a tupel CPN = (P, T, F, C, V, K, m_0) with
P: set of places
T: set of transitions
F: flow relation F = (PxT) ∪ (TxP)
C: colour function
V: multiplicity
K: capacity
m_0: initial marking.

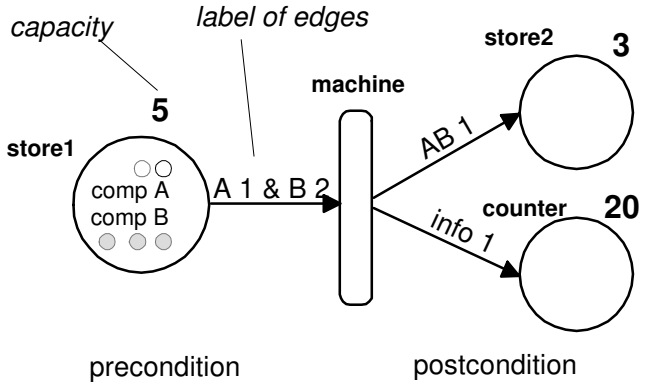

Fig. 1: Coloured Petri Net

An interpretation of Place/Transition Nets for control is, in general, wellknown. In this chapter it is explained how Coloured Petri Nets can be interpreted for control /Feng1 93/, /Wend 94/:
The different colours in the places symbolize local processing states of algorithm, machines and plants or control information about existing and accepted data or buffers for component parts. For instance, a place with two colours may be a store for two various kinds of components (Figure 1, place „store1“). The marking informs about the number of objects available in the store. The capacity per colour shows the maximal number of objects. The total capacity of a coloured place represents the maximal

number of states, information and components in total (5 for the place „store1“ in Figure 1).
Each colour of the coloured transitions symbolizes transitions between local processing states or generation of or waiting for control information or transport and modification of components.
The edges establish the connection - of material or informal kind - between the places and the transitions according to the label of edges (A1 & B2 for example between place „store1“ and transition „machine“ in Figure 1). The multiplicity per colour represents the number of items of information and components that are either necessary or generated.

For the description of environmental influences on the process the nets will be extended with four additional functions (Figure 2). The valuation function w_x is responsible for the influence on the control in the sense of the technological task. The variables or expressions at the transitions represent for example binary sensor signals. The output function w_y allows to determine the current state of the machine or plant. The variables at the places represent for example binary control signals. The time function w_t leads to a more real description of the technological operations. At the transitions a time duration or a time delay can be specified. The action function w_a realizes an assignment of processes to places or transitions by elementary description means, for example commands in a Statement List. All of this is valid per colour.
There is one more additional function (Figure 2). The data function w_d can assign data structures to the colours in the places. It represents per place and colour a cache for additional information (data). The function w_d can be used by the function w_a as well as w_a can file data in w_d. The value of all functions has an influence on switchability, but not the data function.

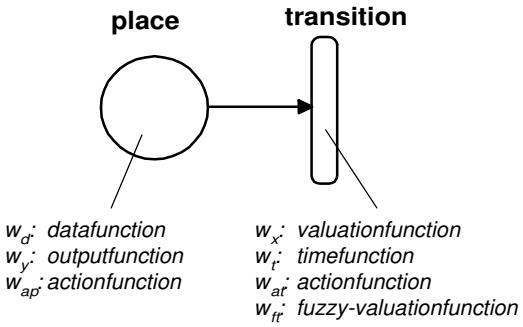

Fig. 2: Additional functions

4. Fuzzy Petri Nets

The application of fuzzy logic became increasingly popular in many domains of computer engineering, control of different processes and decision-making systems. A main reason is the advantage resulting from the use of more efficient algorithms /Zimm 91/.
The use of fuzzy logic has been spreading to traditional non-fuzzy methods and applications. This also concerns the theory of Petri Nets providing simulation and analysis techniques for many domains. Fuzzy logic offers above all lots of advantages in such a traditional field of application as production planning. In real existing production processes that are often modeled with Petri Nets there are typical non-foreseeable events. These events cannot be described exactly with their statistical properties. But it is possible to solve such problems or to formalize algorithms more easily or to reduce calculation time using fuzzy logic.
With the combination of the theories of Petri Nets and Fuzzy Logic concepts for so-called Fuzzy Petri Nets (FPN) could be developed. There are a lot of publications, for example /Chun 93/ or /Dubo 89/ or /Lipp 95/. In this paper the Fuzzy Coloured Petri Nets (FCPN) will be introduced /Feng2 93/, /Wend 95/. These nets are a further development of the Coloured Petri Nets (definition in chapter 2) by extending the coloured transitions with a fuzzyvaluation function w_{ft} (Figure 2) and by connecting fuzzy variables to tokens (markings). It is not a new class of Petri Nets.
The fuzzyvaluation function generates a set of valuation marks for the transition that influences the switchability of single colours. This switchability can depend on the following conditions:

- the number of tokens at input-places, per colour
- the number of tokens at output-places, per colour
- the value of a threshold from which the transition can fire (switch), per colour and
- the values of fuzzy variables of single tokens.

All this information can be combined in different ways in order to make a decision in which colour the transition fires. So FCPN's allow the identification of tokens and the use of complex fuzzy algorithms at transitions for conflict solving and general influence on the switchability. As opposed to /Dubo 89/ the transition fires as in Place/Transitions Petri Nets (non-fuzzy). The tokens leave their places by firing of a transition and don't stay there like in /Chun 93/.
More general expressed a transition with an actionfunction w_{at} can be understood as a fuzzy unit where not only one but several rules can be processed. It is also possible to use non-fuzzy values and to make fuzzification and defuzzification. In general, pre-edges correspond to input variables of a fuzzy unit and post-edges to output variables.
Fuzzy data (data structures of tokens) represent a data flow through the net. The processing of tokens (information) happens independently from each other (asynchronously) at different transitions. Fuzzy units can compete with each other. In such a case one gets real parallelism and independence of fuzzy algorithms.

Data structures can be used for the characterisation of tokens and can influence the choice of the token which will be fired next.
This mechanism of choice of the colour/token to be fired next helps to solve conflicts - in the case if there are more tokens being ready to enter a transition than the transition is able to take. As known the most popular mechanism for solving conflicts is the use of priorities, the probability principle (stochastic PN) or the use of the valuationfunction w_x. The use of the fuzzyvaluation function w_{ft} for conflict solving obviously doesn't affect all possibilities of net analysis. Otherwise the situation looks different if a threshold is used. In that case a transition can be forced not to fire and time characteristics of the net will be changed.
Within the models a locality principle is used for reasons of transparency. That means only the directly connected net elements (the direct pre- and postplaces with their edges) are important for the fuzzy valuation of a transition.
A Fuzzy Petri Net is simulated as follows: The pre- and postconditions are tested with each time clock. If fuzzy algorithms are defined a fuzzy interpreter is started and the fuzzy rules are worked. The result is reflected in a possible change of the fuzzy variables of the tokens or in the decision of conflicts or in an influence of the switchability.

5. Application of FCPN in a technological example

The following example resides in the domain of manufacturing control for single-piece and small-lot series production at a mechanical engineering company. The FCPN's are used to create models to forecast the production. Therefore especially the processes that are not algorithmic definable as well as the not exact definable influences and connections of the production, for example human behaviour, are to considered.
There are two approaches in using FCPN-modelling:

a) The FCPN's are used to determine the production sequence and routing of the jobs. Therefore the fuzzy valuation of the transitions arranges the routing of the parts through the system by the evaluation of the priority of the job or the process times, using fuzzy rules.
b) The production sequence is given by a conventional tool without fuzzy valuation. The FCPN model can be generated from these data and then used for Petri Net based analysis and simulation regarding fuzzy aspects.

Fuzzy Petri Nets can be tested with the use of formal analysis methods if there are inconsistencies or something else. But the main purpose of the model is the foresimulation in order to forecast the future processes in production as exact as possible. Furthermore, the effects of extraordinary occurrences like scheduling of high priority jobs or machine breakdowns may be simulated.

The use of Fuzzy Coloured Petri Nets in manufacturing control will be shown by means of a technological example. It describes a simplified model of a workshop that makes the sales order processing. The job distribution is carried out at the own discretion of the workshop manager. This behaviour is shown in the following as a model.
The illustration of the production happens as follows:

The jobs, which are generated by a production planning system, are represented by coloured tokens (each job has an own colour). The tokens contain job-specific information like latest beginning time or priority of the job. The manufacturing machines are represented by transitions which contain machine data, like performance or susceptibility of disturbances, as well as working parameter, like processing time or tolerances.
Figure 3 shows a corresponding Fuzzy Coloured Petri Net. The workshop consists of a sawing station, a turning machine, a cnc-turning machine, a milling machine, a heattreat station and the checking. The comment of using fuzzy rules confines oneself to the working stations turning and cnc-turning with their connected places p2, p4 and p11.
The tokens in place p2 represent the existence of nonworked parts that are to processed by the turning machine. The job representing by a green token „GR" is an urgent job. They are two operators - one for turning and one for cnc-turning. If they are available then for each of them a corresponding token exists in place p11. After an interview with the workshop manager the following rules for the transitions turning and cnc-turning were put up (a choice):

Rule I: If jobs are very urgent, then they have to be worked as soon as possible.
Rule II: If there are many jobs for the place of work turning and if the operator for cnc-turning has only few jobs then he can help out at turning.
Rule III: The more urgent a job the higher the qualification of the operator has to be. The operator with the best qualification takes the most complicated jobs.

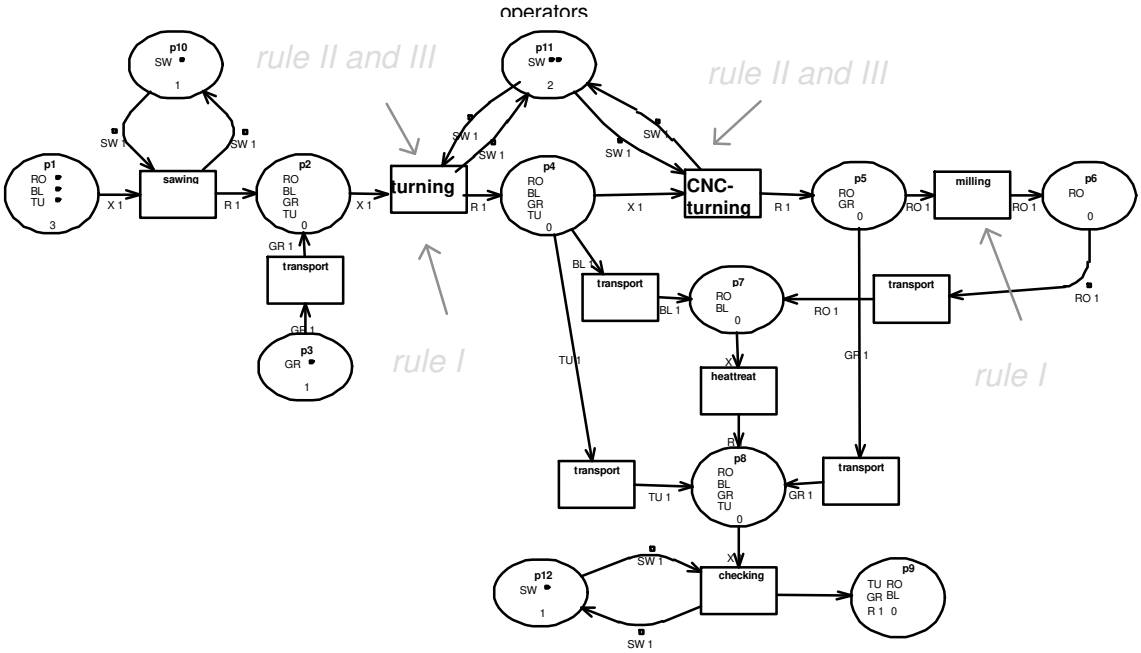

Fig. 3: Technological example

In the following it is explained in detail how fuzzy logic is used in the example of Figure 3.

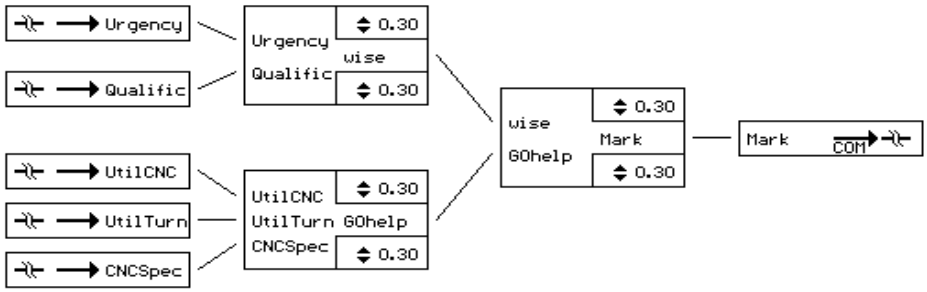

Fig.4: Linguistic variables and rule blocks

After interviews with experts or operators from industrial partners having a lot of experiences in the production processes one finds out by which rules decisions about working priorities are taken. Then the most important criteria for the rules have to be defined. After this, a linguistic variable is generated for every criterion, for example the linguistic variable "Urgency" for the urgency of a job or "Utilization" for the amount of jobs at a machine.
Then the output linguistic variable for making a decision is defined - with the name "Mark" (Figure 4). Usually this variable is fuzzificated in a fuzzyvaluation-function. That can be made by different methods. Two of the most usual are COA - Centre of Area and COM - Centre of Mass /Zimm 91/. The first one is choosen for fine changing results, the second one is used for abrupt changing results. Every variable has some terms (from one to seven, but normal are three or five) . In this case the variable has three terms - "low", "normal" and "high" (Figure 8). The state of a linguistic variable is represented by the grade of the fulfilment of its terms. So for example, the room temperature of 22°C is classified by men with a probability of 0% as "low", with 60% as "normal"and with 40% as "high". If there is one term that is more important than another than the membership function has to be changed. For example, the term "high" of the linguistic variable "urgency" can be made steeper (Figure 8).
From experience it is recommended to use triangular terms. It's also advantageous to keep the sum of all terms equal 1 all the time (Figure 8).
After defining the linguistic variables the second step should be the defining of rule blocks. The linguistic va-

riables (actually their terms) have to be connected by fuzzy operators. In the described example the MIN-MAX-operator is used /Zimm 91/. In order to keep the rules clearly arranged it's better to connect not more than two input variables by one rule block. So further linguistic intermediate variables are necessary. In Figure 4 it is the connection between the first and the second row of the rule blocks "wise" and "gohelp". Of course, you have to pay attention to the connecting of semantical coherent variables in one rule. One of the variables can get a higher priotity if the terms of the other variables are defined lower than 1.
By combination of terms it was tried to use only a small number of terms (Figure 5). Figure 6 shows a nonsymmetrical array because the value of the variable "qualification" should be equal or higher than the value of "urgency".

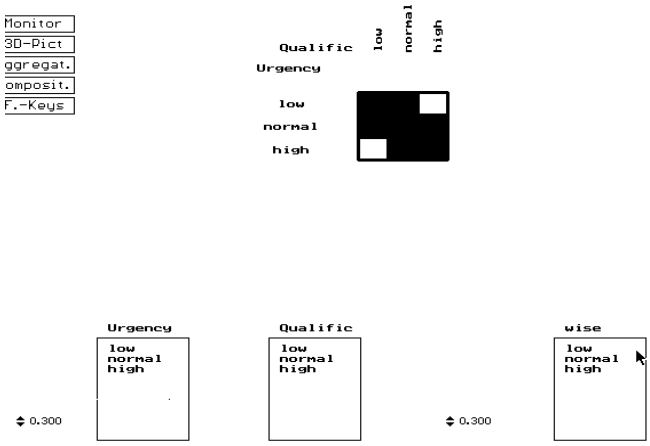

Fig.5: Combinations for "low" of linguistic variable "wise"

After defining and verifying the fuzzy algorithm in a special tool it can be attached to a Fuzzy Coloured Petri Net. In the example of Figure 3 the fuzzyvaluation functions are placed at transitions t1 ("turning") and t2 ("CNC-turning"). Fuzzy data are transported through the net together with the marking (token) flow. So fuzzy data are just a kind of data structures of tokens. So every job represented by token has an "urgency"-value from 0 to 100 written down in the token. The same is valid for every operator with a

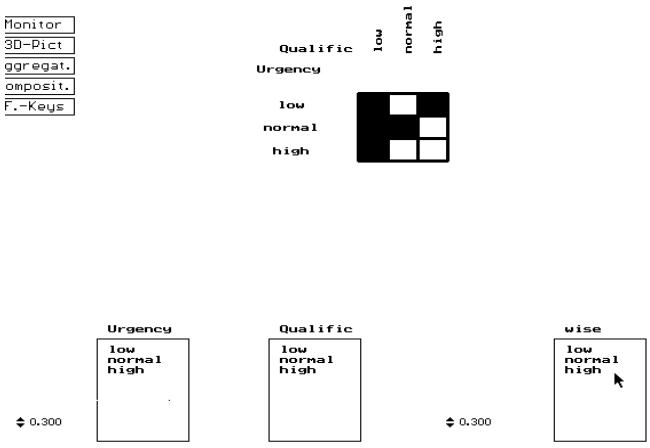

Fig.6: Combinations for "high" of linguistic variable "wise"

"qualification"-value. The utilization grade of „turning" and „CNC-turning" results from the amount of tokens in the pre-places at the transitions. The most important coherent pairs of criterias are "Urgency" (of a job) and "Qualification" (of an operator) as well as "UtilizationCNC" and "UtilizationTurning" (operations) and "CNCspecial" (operator).
The variable "CNCspecial" (Figure 9) was defined extra to make it possible to use the same fuzzyvaluation function at both transitions (because of time and performance reasons). Normally it can be said "This operator is specialized on CNC-turning." (that's why the array on Figure 7 looks so simple). If fuzzy logic is used one can say "This operator is qualificated for CNC-turning with x%.". So the changing of the working places can be influenced in dependence on the deep of the specialization of the operators.

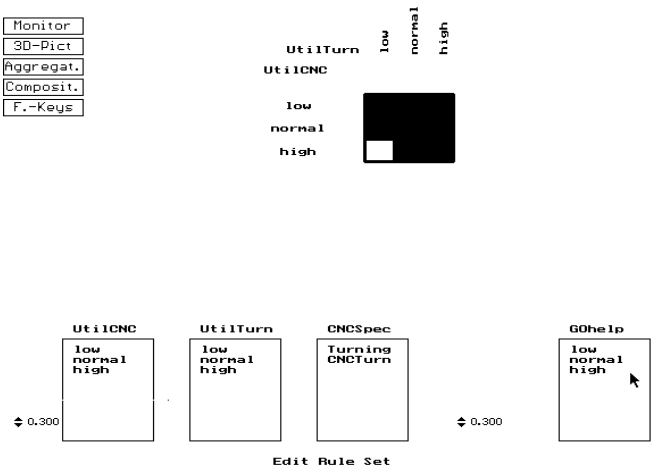

Fig.7: Combinations for "high" of linguistic variable "GOhelp" (CNCSpec="turning")

The intermediate variables are connected again in order to get a decision note. This note fixes from which grade it's meaningful, that the operator of the working place CNC-turning helps at the working place turning. For all pairs job-operator (at both transitions) such notes are computed, so that the settlement of conflict situations in the net becomes clear. This way it is influenced if the operator changes his working place and which job is done first because of its urgency. The pair job-operator must have the highest note. In the described example the notes have relative charakter, their absolut values have no meaning. If other fuzzy operators are used the net could behave in the same way but with other absolut values of notes.
The fuzzyvaluation function will run every time if the transition is ready to fire. In dependence on the amount of tokens at the pre-places (utilization) and the values of data structures of tokens (urgency, qualification) a set of notes is computed and the pair with the best note is choosen and the transition fires.
The input of linguistic variables with membership functions and their combinations can be made with a separate tool, where the fuzzy algorithm can be tested and verified, or in the Petri Net tool, having the same functionality. Fuzzyvaluation functions can be run as exe-programms called during the simulation process (most of fuzzy tools can export fuzzy algorithms as C-functions). They can be written down as commands for an interpreter running parallel to a simulation, too. The last case is the favorite by the authors of this paper.

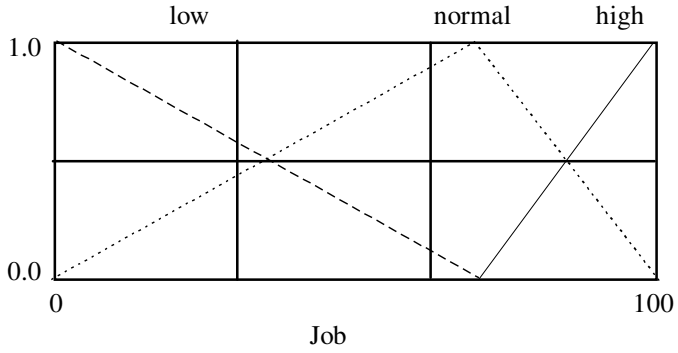

Fig.8: Terms of linguistic variable "Urgency"

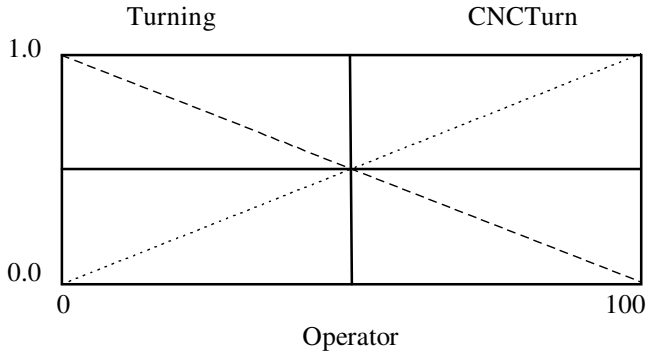

Fig.9: Terms of linguistic variable "CNCSpec"

At real problems, there are often a large number of rules that are partly contradicted. The fuzzy approach seems to be better for this than deterministic or stochastic concepts. So the simulation with fuzzy valuation determines the order of working and the connection of jobs to the machines and operators more precise as it is possible with fixed rules and numbers.

6. Summary and future plans

By means of software-interpreted Petri Nets complicated systems can be modeled. The main advantages are possibilities of analysis and simulation of models.
In the paper, a method for creating and simulating distributed fuzzy algorithms in connection with a process model was introduced. This method is applied in the field of production

planning. Its advantage bases on the simultaneous application of CPN's and Fuzzy Logic used for conflict solving. The method is supported by an FCPN-Tool. Benefits of the method were illustrated by an example of single-piece and small-lot manufacturing.
Further works will deal with a simulation method and the creation of a model library for the application field described in the example. Other goals are the development of a tool for a decision making help system for the manufacturing control and implementation of FCPN-Algorithms as software and the realization of some parts as hardware.

Literature:

/Chun 93/ Chun, M.-G.; Bien, Z.: Fuzzy Petri Net Representation and Reasoning Methods for Rule-Based Decision Making Systems, IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences (June 1993) vol. E76-A, no.6, p.974-83

/Dubo 89/ Valette, R.; Cardoso, J.; Dubois, D. :Monitoring Manufacturing Systems by means of Petri Nets With Imprecise Markings. Proceedings of the IEEE International Symposium on Intelligent Control, 1989, Albany, NY, USA --- Washington, DC, USA: IEEE Comput. Soc. Press 1989 Pages: 233-238

/Feli 93/ Felix, R.: Pacemaker of the Future. Electrical Engineering 2/1993, p. 92-97

/Feng1 93/ Fengler, W.: A Colored Petri Net Interpretation for Modelling and Control in Textile Processing. CSCW-Workshop in Petri Nets 1993, Chicago, USA, June 1993

/Feng2 93/ Fengler, W., Bogoljubow, J.: An Interpretation of Coloured Petri Nets for Modelling of Distributed Fuzzy Algorithms. Workshop "Fuzzy-Systems'93", Braunschweig, 20.-22. Okt.1993

/Feng 95/ Fengler, W.; Wendt, A.; Röhner, U.; Bogoljubow, J.: An Interpretation of Fuzzy Coloured Petri Nets for Modelling of Diskrete Production Processes. Symposium „Anwendungen von Fuzzy-Technologien und Neuronalen Netzen“, Erfurt, 1995

/Jens 92/ Jensen, K.: Coloured Petri Nets, vol.1, Springer Verlag, Berlin Heidelberg, 1992

/Lipp 95/ Lipp, H.-P.: Fuzzy Petri Nets Approaches-A Comparision. 4.Conference „Design of Complex Automatisation Systems“, Braunschweig, June 1995

/Star 91/ Starke, P. H.: Analysis of Petri Net Models. B.G. Teubner, Stuttgart, 1991

/Wend 94/ Development environment for Destributed Controllers. Dissertation. TU Ilmenau, 1994

/Zimm 91/ H.-J. Zimmermann. Fuzzy Set Theory- and its applications. Kluwer Academic Publishers. Boston/Dordrecht/London, 1991