Energy and material management based on a fuzzy-petri net approach

A. Tuma

University of Augsburg, Dept. of Economics, 86135 Augsburg, Germany
E-mail: Axel.Tuma@WiSo.Uni-Augsburg.de

Abstract: In modern production systems, materials and different forms of energy are provided, converted, stored and transported. Environmental impacts can be identified at any stage of the energy and material flow process. Due to the fact that production units and processes are interconnected with energy and material flows, it is of special interest to implement production control policies, which control the energy and material streams. In this way it is possible that available resources are utilised most efficiently and emissions and by-products caused by the production process are reduced.

Achieving this goal in one step, the input and output streams of a production system have to be balanced. This can be done with input-output models (e.g. unit operation models) or with simulation systems. Due to the requirements of the modelling of real production systems (simultaneous modelling of structure and state of the production system, availability to describe analytical and synthetical production structures, possibility to model different aggregation levels) a petri net approach seems to be adequate to this task. In a second approach, control strategies concerning economic and ecological goals have to be integrated. In accordance with the structure of the available expert knowledge (fuzzy knowledge) a fuzzy petri net approach for an environmental integrated controlling of interconnected production systems is discussed.

Validating this approach an exemplary production system from the textile industry, consisting of a dye house, a hydropower plant, a boiler house, and a flue gas neutralisation facility is analysed.

Keywords: Contract network; ecological production control; fuzzy-petri net.

Reference to this paper should be made as follows: Tuma, A. (2002) 'Energy and material management based on a fuzzy-petri net approach', *Int. J. Environment and Sustainable Development*, Vol. 1, No. 2, pp.160-170.

Biographical notes: Prof. Dr. A. Tuma is chair of the department of environmental management of the faculty for economics at the University of Augsburg. In 1991 he joined the research team of Prof. Dr. Rentz as an industrial engineer at the University of Karlsruhe where he completed his doctoral thesis entitled 'Development of emission orientated production control strategies using fuzzy expert systems, neural networks and neuro-fuzzy-approaches'. From 1994 to 2001 he worked as a member of the Department of Industrial Management at the University of Bremen. Focus of his habilitation thesis was the investigation of economic aspects of production control. Current research topics are the configuration and coordination of supply chain networks under the focus of reverse logistics and different aspects of environmental informatics.

Copyright © 2002 Inderscience Enterprises Ltd.

1 Introduction: modelling and balancing of material and energy flows in production networks

Precondition for the development of environmental integrated controlling strategies for interconnected production systems is the balancing of all input and output streams. This implies an adequate modelling of the interconnected production system. Key-requirements for this process are:

- adequate modelling of the structure of the production system including e.g. production rates, inventory and buffer capacities
- adequate modelling of all energy and material flows
- the possibility to model different aggregation levels (process, segment, factory level).

These requirements recommend the application of petri net models [1]. The petri net concept is used in many disciplines as modelling of business processes, organisation structures and computer systems. From the viewpoint of production science, petri nets are mainly applied in the field of material flow analysis. A new application field is the simulation of environmental orientated production structures [2].

In order to validate the petri net approach an exemplary production system from the textile industry, consisting of a dye house, a hydropower plant, a boiler house, and a flue gas neutralisation facility is analysed [3]. The reasons for the selection of this production system are:

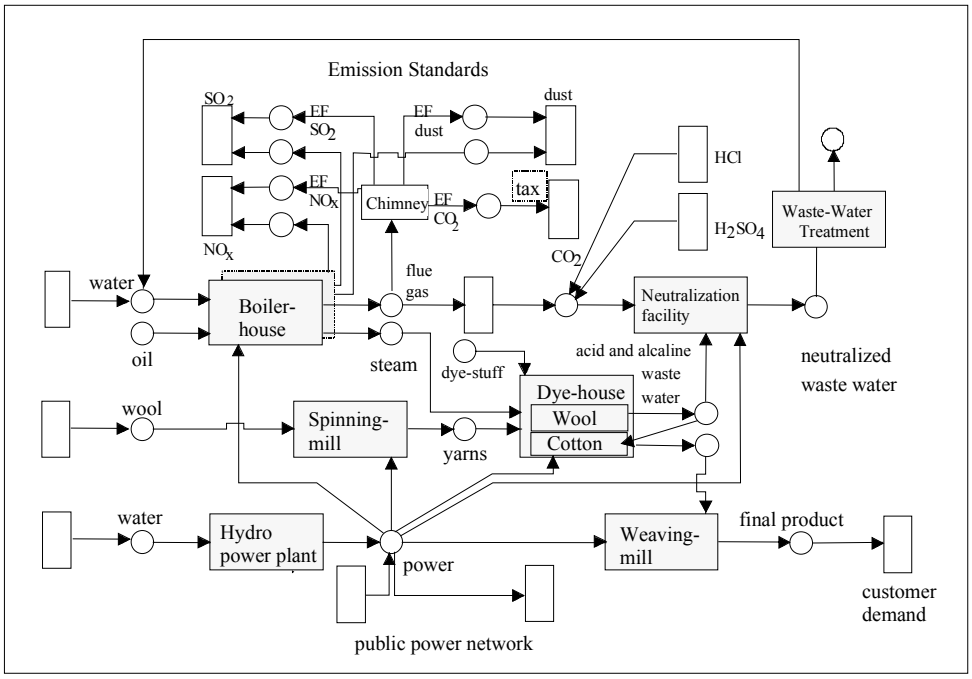
- the interconnected structure of the production system
- the availability of process data
- the environmental impact by such respectively similar production systems.

The production system under investigation consists of a dye house, a boiler house, a hydropower plant, a spinning mill, a weaving mill and a flue gas neutralisation facility. The dye house covers two stages of production, the dyeing process and the drying of the dyed yarns. The two stages of production require steam/hot water and electric power, which are supplied by the preceding power plants. The flue gas of the boiler house is used to neutralise the mainly alkaline waste water of the dye house at the flue gas neutralisation facility. The storage of steam/hot water as well as the capacity of the waste water reservoir is limited. The capacities of all preceding and succeeding production units are variable. Variations can be caused by external factors (e.g. smog, variations of the water level of the inlet of the hydropower plant).

Figure 1 shows a petri net model of the mentioned production system. The single units can be interpreted as follows:

- Transitions (symbolised by rectangles) represent production units (e.g. boiler house, dye house), sources of input-streams (e.g. raw materials, water and electric power from the public power system) and sinks of emission streams and final products.
- Places (symbolised by circles) represent inventory or buffer systems.
- Tokens characterise the state of the production system (e.g. the level of the waste water reservoir).
- Arcs connect transitions and places in a petri net and determine the structure of the production system. Two types of arcs can be discriminated: input and output arcs.

Figure 1 Petri net model of an exemplary production system



From the viewpoint of production theory such models can be interpreted as networks of production functions. In general on that basis the balancing of all relevant material and energy flows is possible. However, the extension of the system from standard flow modelling to ecological production control asks for a distributed, knowledge-based approach with the following requirements:

- the coordination of the autonomous production entities [4]
- opportunistic planning capabilities [5]
- the integration of fuzzy expert knowledge [3]
- modelling and evaluation of alternative policies.

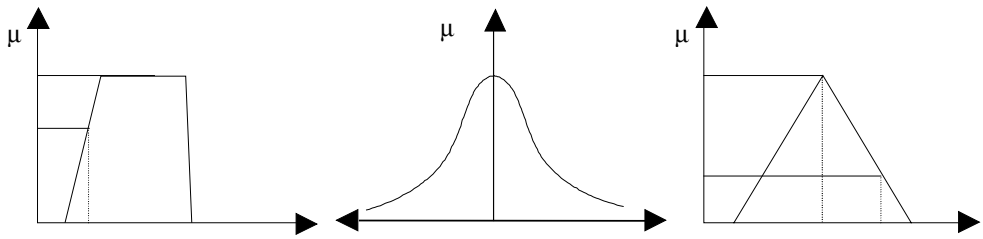
These requirements can be fulfilled by applying a fuzzy-petri net approach [6].

2 Satisfaction calculations based on fuzzy values

To integrate fuzzy controlling knowledge in respect of implementing distinct controlling policies the petri net approach described above is expanded by so-called membership functions. The resulting fuzzy petri net can be interpreted as a set of standard petri nets. Places and transitions in respect of the 'capacity' of a place and the 'production rate' of transitions are described by fuzzy sets. The units of such an interconnected production system and the evaluation of certain strategies can be implemented as follows:

- *Assigning satisfiability (membership value) for potential 'production rates' of transitions:* Potential production rates (v) of single production units can be evaluated by the assignment of membership values (Figure 2a). In a certain analogy to valves the 'production rate' of a transition is a variable parameter. The same model can be applied for sources and sinks of input and output streams.
- *Evaluating potential variations of the 'production rates' of transitions*: By this, the variation of the production rate (Δ v) is evaluated by a membership function (Figure 2b). The reason for this is that production rates of real processes can normally only be manipulated in distinct and limited steps. Additionally these functions play an important role concerning system stability.
- *Assigning satisfiability for potential 'capacities' of places*: The potential capacities of single inventory or buffer systems (c) can also be evaluated by the assignment of membership values (Figure 2c).

Figure 2a Membership function of a transition (static) **2b** Membership function of a transition (dynamic) **2c** Membership function of a place (static)



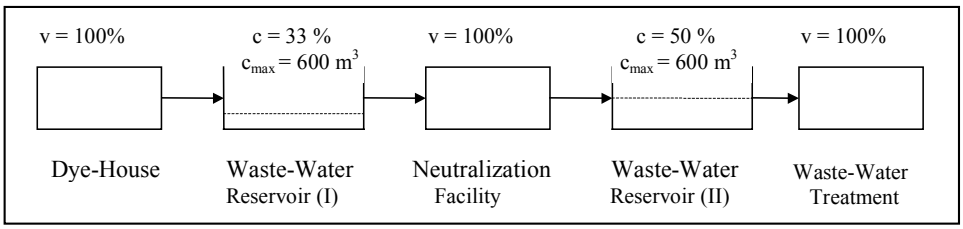
The goal of the coordinating process is to detect the best compromise between all local goal functions. This means especially the detection of crisp production rates, defined input rates of resources and emission levels. In calculating such values the units roughly work as follows:

- To improve the membership value of a place the production rate of at least one of the transitions has to be changed. A broadcast of the change request to all connected transition will result in the most promising transition which could satisfy the request. i.e. the transition with the highest degree of dissatisfaction (defined as a function of the difference between required and actual amount of material/energy) will be selected.
- If the satisfaction of a transition should be improved, the proceeding is similar. However, it must be taken into account that the improvement of the production rate needs information from all neighboured places, which complicates the calculations of the best combination of material/energy providers.

3 Exemplary description of the problem solving mechanism

To illustrate the problem solving mechanism of a fuzzy-petri net orientated environmental production control a simplified sub-system of the described production system is investigated. This sub-system consists of the components: dye house, waste water reservoir (I), neutralisation facility, waste water reservoir (II) and a waste water treatment facility (Figure 3).

Figure 3 Subsystem of the considered production system



For reasons of simplification we assume that in an initial state all productive units (dye house, neutralisation facility and waste water treatment facility) work at their maximal production rate (v_{max} = 100%). According to the defined satisfiability functions these production figures are evaluated with a maximal membership value (Figure 4a, 4c, 4e). The waste water reservoir (II) is filled to 50% (Figure 4d). This means an optimal fill-up level and implies also a maximal membership value. The waste water reservoir (I) is only filled to 33% and gets a satisfiability value of μ = 0.66 (Figure 4b).

Figure 4a Production rate of the dye house **4b** Capacity of the waste water reservoir (II) **4c** Production rate of the neutralisation facility

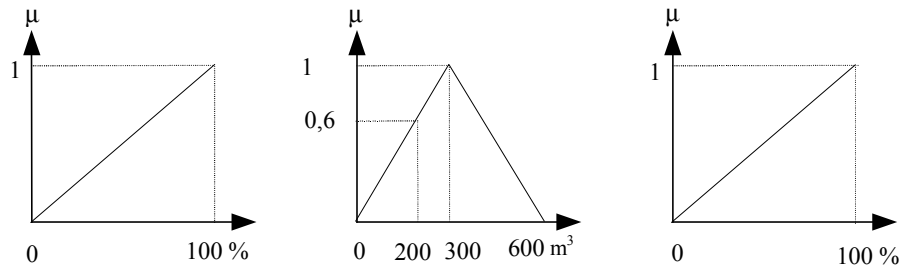


Figure 4d Capacity of the waste water reservoir (II).

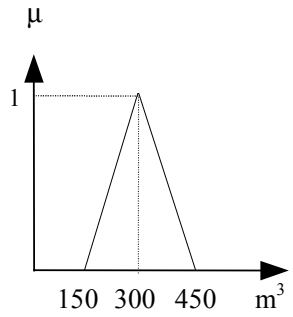
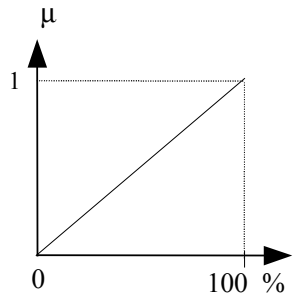


Figure 4e Production rate of water treatment facility



The objective of the production control mechanism is a maximisation of the membership values (satisfiability levels) of all components. To achieve this goal the following problem solving mechanism is applied:

- In a first step the system unit with the lowest satisfiability value is identified. In the considered case the identified unit becomes the place 'waste water reservoir (I)' with $\mu = 0.66$. The following step depends on the type of the identified unit (place or transition).
- Due to the fact that the waste water reservoirs are modelled as places, an improvement of their satisfiability level requires a change of the production rate of one of the associated transitions (dye house or neutralisation facility). The selection of the transition (selection of a negotiation partner) is implemented according to Figure 5a. For each place a linguistic variable 'selection of a transition' is defined. This variable consists of several terms representing possible options for all associated transitions. E.g. the term $t_p^{increase}$ represents the option 'increasing of the production rate of the preceding transition (dye house)'. The term $t_s^{decrease}$ represents the option 'decreasing production rate of the succeeding transition (neutralisation facility)'. The term t represents the option 'no reaction'. This option should keep the system in stable conditions, if the difference between optimal and real production figures is below a certain threshold. The terms are implemented as fuzzy sets. The input variable indicates the difference between the measured and the required fill-up level of the considered place (e. g. the waste water reservoir (I)). This difference is evaluated with a membership value (satisfiability value). The term (option) with the highest assigned value is selected and determines the negotiation partner respectively the required option (increasing or decreasing the production rate of a transition). Analysing the considered application example a membership value of $\mu = 0.66$ for the option 'decreasing of the production rate of the neutralisation facility' and respectively a membership value of $\mu = 0.33$ for the option 'no reaction' can be calculated (Figure 5a). This means that the selected negotiation partner is the transition 'neutralisation facility'. The definition of the terms in respect of the membership functions of the linguistic variable is done by suitable experts.

- After the selection of a negotiation partner in respect of the negotiation option (e. g. decreasing of the production rate of the neutralisation facility) the new production rate of the selected transition must be negotiated. In order to perform this task the satisfiability values of the neutralisation facility (Figure 4c) as well as the membership functions of all preceding and succeeding places are calculated as a function of potential production rates of the selected transition (Figure 5b). These functions are aggregated by the minimum operator. The result of the negotiation process (point of compromise) is the production point for which the minimum function is maximal. Analysing the described example this means a production rate of 83.3% in t + 1 for the neutralisation facility.
- This procedure addresses especially the trade off between the objectives of the 'waste water reservoir (I)' to increase the satisfiability level by a modest reduction of the production rate of the neutralisation facility and the 'waste water reservoir (II)'. Concerning the 'waste water reservoir (II)' the described situation means *ceteris paribus* a decreasing of its membership value.

Figure 5a Selection of the transition and its required behaviour

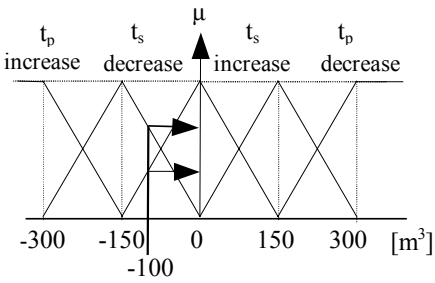
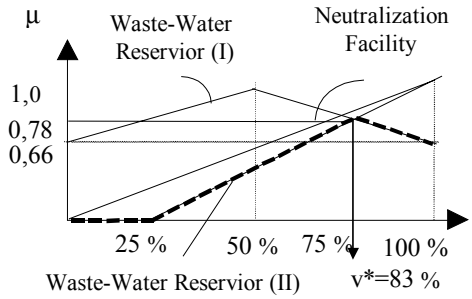


Figure 5b Negotiation and calculation of v* for the neutralisation facility



An adjustment of a production rate of the neutralisation facility to 83.3% implies the following production figures for the other units:

Table 1 State of the production system at t+1

state t +1	*Production rate*	*Fill-up level*	*Membership value (μ)*
Dye house	100%		1,0
Waste water reservoir (I)		233.3 m^3	0.78
Neutralisation	83.3%		0.83
Waste water reservoir (II)		266.7 m^3	0.78
Waste water treatment facility	100%		1.0

In the following step two units (places) with a minimal membership value (satisfiability value) can be identified. An analysis of the unit 'waste water reservoir (I)' shows (Figure 5a) a preference for the option 'no reaction'. In contrast to this an investigation of the unit 'waste water reservoir (II)' (Figure 6a) shows a preference for the option 'decrease the production rate of the succeeding unit' (transition 'waste water treatment

facility'). An analysis of the negotiation process, which means an investigation of the membership value of the units 'waste water reservoir (I)' and 'waste water treatment facility' as a function of potential production rate of the transition 'waste water treatment facility', results in a compromise of an 81 % production rate for the 'waste water treatment facility' in t+2.

Figure 6a Selection of the transition and its required behaviour

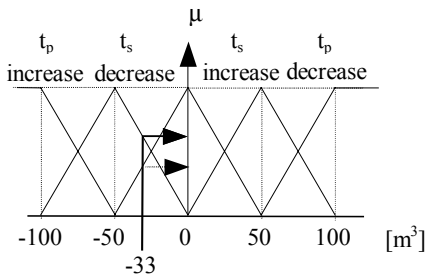
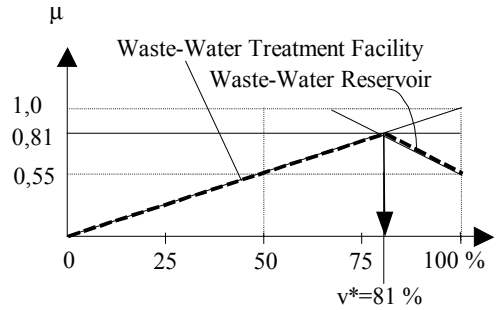


Figure 6b Negotiation and calculation of v^* for the neutralisation facility



Based on this the following production figures can be calculated:

Table 2 State of the production system at time t+2

State t + 2	*Production rate*	*Fill-up level*	*Membership value (μ)*
Dye house	100%		1.0
Waste water reservoir (I)		266.7 m^3	0.89
Neutralisation	83.3%		0.83
Waste water reservoir (II)		271.8 m^3	0.81
Waste water treatment facility	80.8%		0.81

After some iterations the system terminates in stable state. All productive units (transitions) operate at their maximal capacity. Due to the definition of the terms of the waste water reservoirs (especially the option 'no reaction') these units terminate at a non-optimal level.

4 Discussion

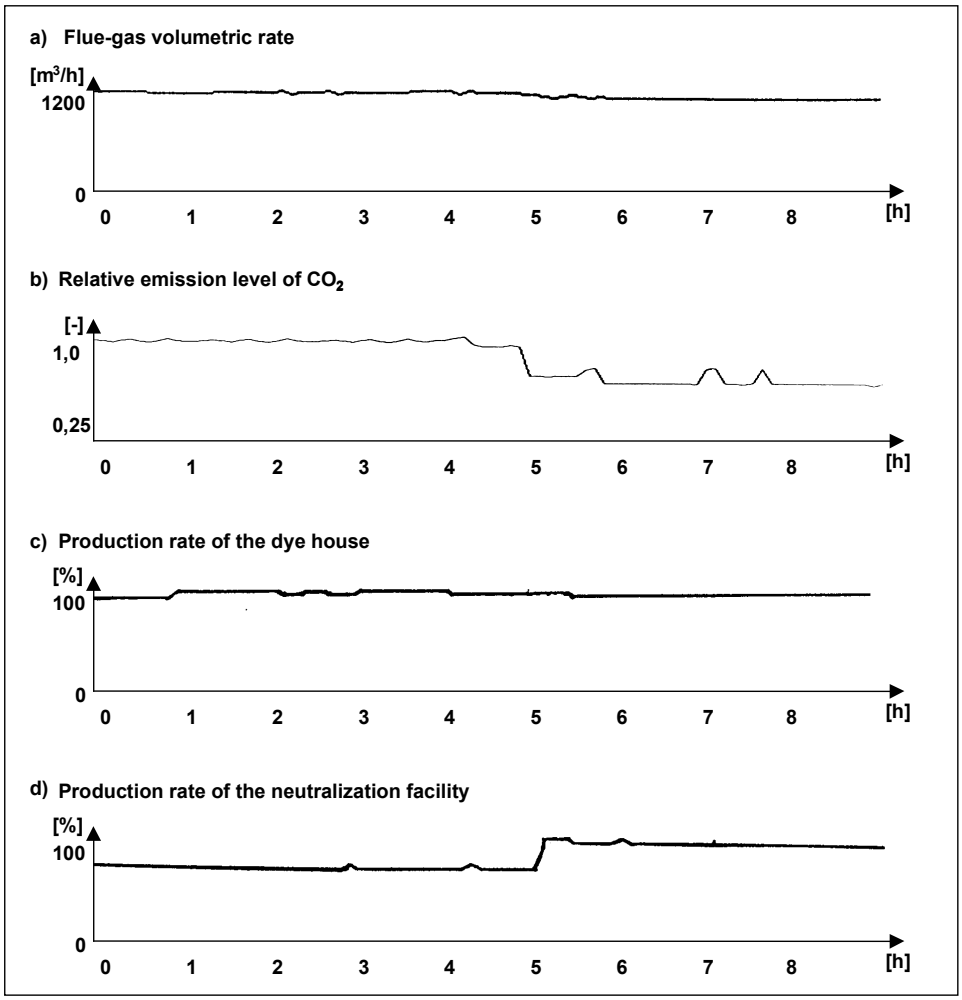
The described approach shows, that in principle an energy and material control system can be modelled on the basis of a fuzzy-petri net. The membership functions (fuzzy sets) characterise the degree of willingness of the individual units to draw compromises taking into account their individual goals (e.g. a required safety stock of a place or a required production rate of a transition). The units in respect of the interactions of them define a cybernetic system. One of the key problems of such a system is the conflict between stability and convergence.

Although the problem of stability cannot be finally discussed, some guidelines for the construction of stable fuzzy-petri net systems can be formulated:

- *Incremental modelling approach:* It is strongly recommendable to begin the construction process with small, relative autonomous sub networks. In an iterative process the membership functions of the single units must be adjusted in order to get stable sub-systems. Finally the sub-systems can be combined.
- *Simple problem solving strategy*: At least in the construction phase (definition of membership functions) parallel problem solving strategies seem to be critical. To investigate the system behaviour it is helpful to start the problem solving process at a defined point (unit with the lowest satisfiability value) and propagate the contract making process from this unit to the sinks of the network.
- *Limitation of the system dynamics:* Furthermore, it is recommendable to allow only relative small variations of production rates per step. To integrate this concept with methodological conformance, membership functions (satisfiability values) for possible variation of production rates can be introduced.
- *Definition of reaction intervals:* An important point seems to be an appropriate definition of thresholds for the initiation of the negotiation process in respect of the maximal tolerable difference between required and actual state values for the single units.

Taking into account these guidelines it was possible to construct a rather stable subsystem of the described production system. The investigated subsystem consists of the boiler house (transition), the flue-gas neutralisation facility (transition), the chimney (transition) and a flue-gas reservoir (place). The experiment documented in Figure 7 investigated the impact of a significant reduction of emission limits to the system. A stronger emission policy for certain pollutants (e.g. CO_2, SO_2) implies a reduction of the pollutant stream leaving the chimney. To handle this situation the system has two options. One way is to reduce the flue-gas stream respective to the capacity of the boiler house. This results normally in a reduction of the capacity of the dye house, which needs the products of the boiler house as inputs for the production process. Another option is to bypass the flue-gas stream to the neutralisation facility. This means to increase the production rate of this unit. As shown in Figure 7 the enforcement of the emission policy leads to a higher production rate of the neutralisation facility (about 8%). This requires a replanning of the production schedule of the dye house. In the investigated case more cotton jobs, which cause mainly alkaline waste water streams, are scheduled. Taking into account the general goal of the production system, to satisfy the customer needs, this strategy harmonises economic and ecological goals. An analysis of the described experiment shows a quite stable system behaviour (Figure 7). The convergence time is quite short. The flue-gas volumetric stream and the capacity of the dye house are also in stable conditions.

Figure 7 System behaviour of the investigated production system



On the other hand it was not possible to achieve such encouraging results for more complex systems up to now. The high number of membership functions hinders an adequate modelling of the system. To handle more complex systems further research work has to be done. A possible approach is to give single units the ability to use meta knowledge (whether it makes sense to start a negotiation process in a certain situation or not) and learn (adapt) their membership functions according to the experience of former runs.

References

1 Spengler, Th. (1998) *Industrielles Stoffstrommanagement, Betriebswirtschaftliche Planung und Steuerung von Stoff- und Energieströmen in Produktionsunternehmen*, Erich-Schmidt-Verlag, Berlin.

2 Rautenstrauch, C. (1997) *Fachkonzept für ein integriertes Produktions-, Recyclingplanungs- und -steuerungssystem (PRPS-System),* de Gruyzer, Berlin u.a.

3 Tuma, A. (1994) *Entwicklung emissionsorientierter Methoden zur Abstimmung von Stoff- und Energieströmen auf der Basis von fuzzyfizierten Expertensystemen*, *Neuronalen Netzen und Neuro-Fuzzy-Ansätzen*, Lang Verlag, Frankfurt.

4 Zelewski, St. (1997) 'Elektronische Märkte zur Prozeßkoordinierung in Produktionsnetzwerken', *Wirtschaftsinformatik*, Vol. 39, pp.231-243.

5 Corsten, H. and Gössinger, R. (1998) 'Produktionsplanung und - steuerung auf der Grundlage der opportunistischen Koordinierung', *Zeitschrift für Planung*, Vol. 9, pp.433-450.

6 Tuma, A., Siestrup, G. and Haasis, H-D. (1997) 'Stoffstrommanagement auf der Basis von Fuzzy-Petri-Netzen', in R. Grützner (Ed.), *Modellbildung und Simulation im Umweltbereich,* Metropolis Verlag, Wiesbaden, pp.87-101.