UNIVERSITY OF MISKOLC
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SOFT COMPUTING METHOD BASED ON THOM'S CATASTROPHE THEORY FOR CONTROLLING OF LARGE-SCALE SYSTEMS

(with special regard to controlling of a heat power station)

Summary of Ph.D. Thesis

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1. Introduction

Technical development in industry requires a harmony between the controlled process, the control system and the human. This requirement needs to use safe and fast bi-directional communication which is based on the “capabilities” of participants of technological system.

This time, the goal of production development is to achieve a short technological time with a suitable quality. The tool for this goal is the efficient and accurate real-time control. Traditional technical equipments used in real-time process control focus on accuracy, safety, and speed. These requirements do not include the capability to control extremely fast or extremely slow processes.

Extreme technological processes involved by large-scale technological systems require special supervision. Because of extreme features, those processes can occur instability in the operation of large-scale system by the followings:

- extremely fast processes require high-powered data collection and data conversion, high-speed process control system with extremely short real-time cycle, high computational capability, and high memory capacitance,
- extremely slow processes require continuous communication with the process to perceive slow and fine changes, ability to distinguish a finite state of process from any temporary state of process, and capability to recognize and evaluate the relatively faster short-time events occurred during the process.

In my dissertation, I worked out the possibility of controlling the operation of large-scale systems by Thom’s catastrophe theory. The sample system for study the features of large-scale systems has been chosen the system of a heat power station. Heat-energy production is a special task which includes both the extremely fast processes and the extremely slow processes, therefore, the control system must satisfy all the requirements mentioned before.

The first thesis is about the application of Thom’s catastrophe theory applied to large-scale systems as a new tool of soft computing method. There is a description how to make decision if the fuzzy logic control could be applied to control large-scale systems, in particularly, as control system of the steam production technology. It introduces how to divide the large-scale system into large-scale subsystems by the application of soft computing method based on Thom’s catastrophe theory.

The second thesis is about a new method, how to determine the safety integrity level (SIL) of large-scale systems by qualitative method which uses special event of Thom's catastrophe theory, the conditional catastrophe.

The third thesis includes the description of fuzzy logic control system for setting the near-optimum operation of the large-scale system, which control system has the task to distribute the temporary steam load proportionally to the nominal capacities of boilers in the large-scale system.

The fourth thesis includes the description of fuzzy system composed of analogue circuits made of FPAD circuits by the application of the model of reflex course in human nervous system. The operation of reflex course is described by Chomsky’s formal description concerned on the finite-state machines of neural cells, the afferent neural cell, and the interim neural cell, and the moto-neuron.

2. The scientific background

Since the human had begun to use tools to improve vital conditions, the most important activity of human had been *recognition and learning*. Recognition has been focusing on the environment to observe and to study the operation of local environment, and to learn how to apply those the operational rules. That the knowledge, the *learnt knowledge* has been the basis of tool development, technical development, and social development.

Soft computing, an innovative approach to constructing computationally intelligent systems, has just come into the limelight. It is now realized that complex real-world problems require intelligent systems that combine knowledge, techniques, and methodologies from various sources. These intelligent systems are supposed to posses humanlike expertise within a specific domain, adapt themselves and learn to do better in changing environments, and explain how they make decisions or take actions. In confronting real-world computing problems, it is frequently advantageous to use several computing techniques synergically rather than exclusively, resulting in construction of complementary hybrid intelligent systems. The quintessence of designing intelligent systems of this kind is *neuro-fuzzy computing*: neural networks that recognize patterns and adapt themselves to cope with changing environments; fuzzy inference systems that incorporate human knowledge and perform inferencing and decision making. The integration of these two complementary approaches, together with certain derivative -free optimization techniques, results in a novel discipline called *neuro-fuzzy* and *soft computing.*

Soft computing consists of several computing paradigms, including neural networks, fuzzy set theory, approximate reasoning, and derivative-free optimization methods such as genetic algorithms and simulated annealing. Each of these constituent methodologies has its own strength, as summarized in Table 1.

Methodology	**Strength**
Neural network	Learning and adaptation
Fuzzy set theory	Knowledge representation via fuzzy IF-THEN rules
Genetic algorithm and simulated annealing	Systematic random search
Conventional AI	Symbolic manipulation

Table 1. Soft computing constituents (the first three items) and conventional artificial intelligence (Jang et al., 1997, p.2)

The seamless integration of these methodologies forms the core of soft computing: the synergism allows soft computing to incorporate human knowledge effectively, deal with imprecision and uncertainty, and learn to adapt to unknown or changing environment for better performance. For learning and adaptation, soft computing requires extensive computation. In this sense, soft computing shares the same characteristics as computational intelligence.

Application of oft computing in large-scale systems requires a new approach, when the supervision and technological operation have to be composed into a unified system. It means the technology and the control system are “the system” together. The development of complex technological system requires new method in development of process control systems: the technological process will be controlled by the consideration of extreme features of process. The tool to describe the complex technological system is Thom’s catastrophe theory.

Thom’s catastrophe theory is based on the classification of critical points. The description of classification is made by Morse’s lemma. Morse’s lemma has been used to describe the critical points of functions, the inflection, the extreme values. These critical points by Morse have stability which means that perturbation does not occur the change of their types. Thom has classified catastrophes into seven groups: inflection catastrophe, peak catastrophe, swallow-tail catastrophe, butterfly catastrophe, elliptic umbilicus, hyperbolic umbilicus, and parabolic umbilicus.

The application of Thom's catastrophe theory for control is introduced by the desription of control for a heat power system. The technological processes of steam production has been described in accordance with Thom’s catastrophe theory. However, this work does not include the physics of steam production process.

The general description of steam production is the function of van der Waals. The surface, set of curves *p-V* depended on the temperature *T* is catastrophe surface. That catastrophe is peak catastrophe, where the bifurcation zone divides the states into three sections. The sections can be featured by the density of water-steam mixture depended on the temperature. The ratio of products can be classified into clusters described by their membership function shown in Figure 1. Clusters are separated by the districts of the bifurcation zone. It seems that homogeneous contents, either water or steam are out of bifurcation zone, only. There are mixture of hot water and steam inside the bifurcation zone.

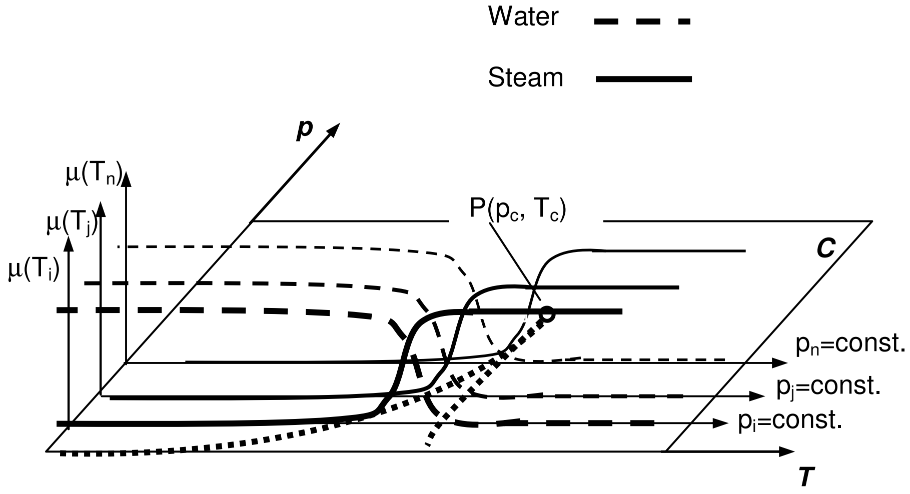


Figure 1. The membership function over the catastrophe space

The composition of mixture can be expressed by the membership function $\mu(T)$, $T=T_1,\ldots,\ T_i\ ,\ldots,\ T_j,\ldots,\ T_n$ while pressure is considered as constant variable by Maxwell. This theory is the base of the new approach applied for control of the steam production system, the fuzzy logic control.

In my work, I focused on the supervisory control of steam production by fuzzy logic system. The chance to apply soft computing methods depended on the controllability of the complex system of heat power station and the technological processes included by the complex technology. The main problem is that function of van der Waals is not analytical function but it is experimental result composed of any critical points of changing density. Therefore, the complex technology of steam production has been decomposed to technological subsystems which were studied if they would have been described as catastrophe events. If subsystems could be described by functions of any catastrophe events then the control of subsystems can be realized by fuzzy logic control. These subsystems require a supervision which can occur the constant quality features of produced steam, and the rated distribution of steam load among the steam production subsystems, the boilers.

Department of Automation at the University of Miskolc has been dealing with soft computing applied for control of extreme slow and extreme fast processes in research for several years led by *Professor István Ajtonyi*.

The Department obtained and completed more projects of TEMPUS, OTKA, MKM, FKFP and other ones successfully. In the project FKFP, I participated in the research works focused on developing new functional fuzzy elements built of analogue circuits and their applicability.

3. Reason of research

The application of fuzzy logic control for supervision of technological processes demands the analysis of technologies by Thom's catastrophe theory, and it requires the method how to compose the hierarchical control by fuzzy logic. The tasks are the following ones:

- examining technological process as large-scale system composed of large-scale subsystems,
- examining if the technological processes are catastrophe events by Thom's catastrophe theory,
- examining large-scale subsystems after decomposition of the complex technology, if the subsystems could be controlled by rule-based fuzzy logic control,
- examining how the number of fuzzy rules could be reduced in the fuzzy logic control systems being either extreme slow or extreme fast processes,
- development of soft computing method to determine the safety integrity level,
- development of fuzzy neurons used in hierarchical control system,
- development of a new fuzzy logic control system for supervising large-scale systems.

4. Objectives of this research

The soft computing method is a tool for create artificial objects with the adaptability to the technical environment and the technical requirement. The dissertation is focused on four main topics which are the following ones:

- description of technological processes by the application of Thom's catastrophe theory,
- description of large-scale system and its division into large-scale subsystem by the method decomposition based on Thom's catastrophe theory,
- near-optimum operation of hierarchical control system by application of Thom's catastrophe theory and Prof. Tóth's cost optimization,
- qualitative method for determining the safety integrity level of large-scale systems by the application of Thom's catastrophe theory,
- composite fuzzy neural system of fuzzy neurons assembled from analogue circuits for fuzzy control systems.

5. The methods of research

It is known that the application of scientific results can be approached in two ways from theoretical point of view:

- on the base of their most important characteristics, the problems have to be grouped and applicable methods have to be allocated to the problems, this is the problematical aspect,
- methods are arranged in according to the tools of solutions, and problems are allocated to the suitable methods as examples, this is the methodological aspect.

Both of two approaches and their combination have been used in my Thesis.

As general methods belonging to the problematical aspect I utilized the following ones:

- the analysis oriented to recognizing and knowing the problem,
- the synthesis targeted to the solving of problem,
- the optimization suitable to achieve the best solutions determined by the given constraints and the valid laws,
- technical description and modeling.

As representative examples to the methodological aspects, application of Thom's catastrophe theory, Chomsky's method for formal description of regular languages, and application of certain MATLAB-tools can be mentioned.

I used a combined approach in the 4th thesis where developing system of ZETEX for FPAD circuit TRAC-20 has been used for making the models of neural cells, and formal description for regular languages by Chomsky were used to describe the operation of neural cells.

6. The new scientific results –Theses

The soft computing method can occur the simplification of process control. Simplification means the structure of traditional control devices can be operated by rules composed into rule-base. Rule-base is the result of human experiences, therefore the operation of control based on human experiences is similar to the process of human problem solving.

Thesis 1: I carried out a new soft computing method for developing the control of large-scale systems by the application of Thom's catastrophe theory.

The new method has been introduced by its application for developing a control system of steam production technology in a heat power station. The description of steam production by van der Waals' rule is based on experimental results. The features of control system for steam production and the efficiency can be increased by the application of Thom's catastrophe theory.

I checked the features of the operating technological system described in Chapter 2, then I worked out the mathematical functions of processes in Chapter 3 which functions has been *catastrophe functions.* These functions can be seen in Figure 2.1.– Figure 2.5. All of elementary catastrophes used to describe the technological processes are low-ordered catastrophes: inflection catastrophe and peak catastrophe.

Since the processes of steam production are catastrophe events, and states of processes can be described by membership functions shown in Figure 1, the system of steam production can be featured by the following fuzzy rules:

- if (p,t) is out of bifurcation zone and t is larger than T_c then there are unsaturated steam,
- if (p,t) is inside the bifurcation zone then there are composition of hot water and saturated steam,
- if (p,t) is out of bifurcation zone and t is smaller than T_c then there are hot water.

where (p,t) are the coordinates of a working point, and (p_c ,T_c) are the coordinates of critical point P, the peak of catastrophe.

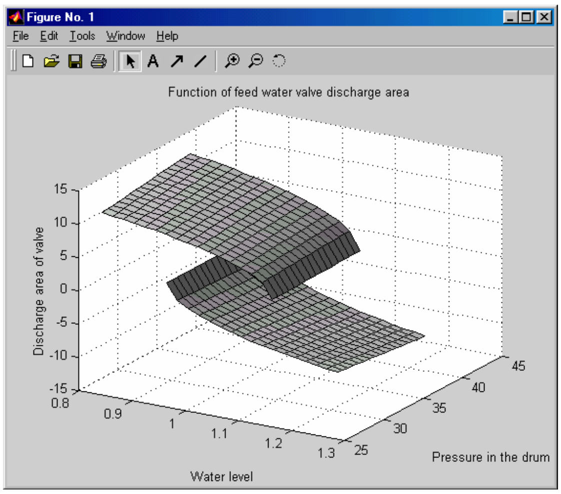


Figure 2.1. Control of feed water valve

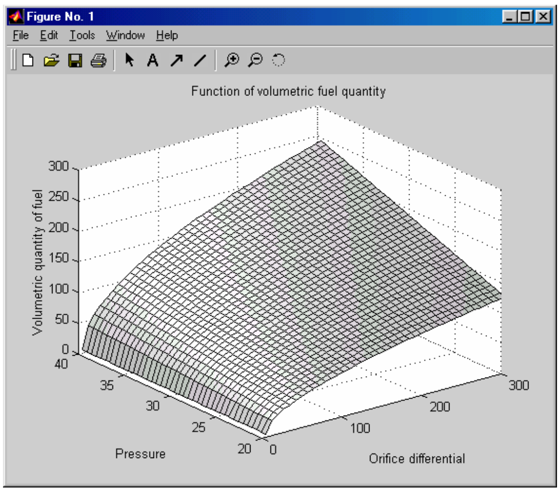


Figure 2.2. Control of fuel quantity

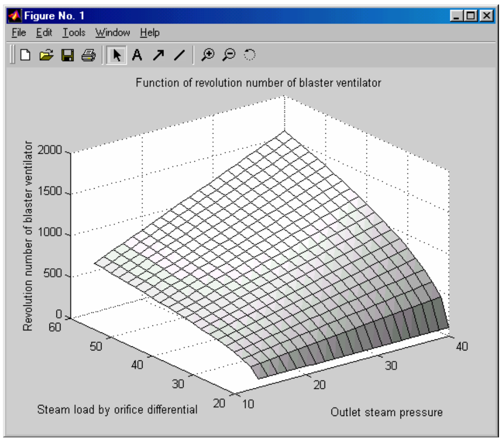


Figure 2.3. Control of speed of blaster ventilator

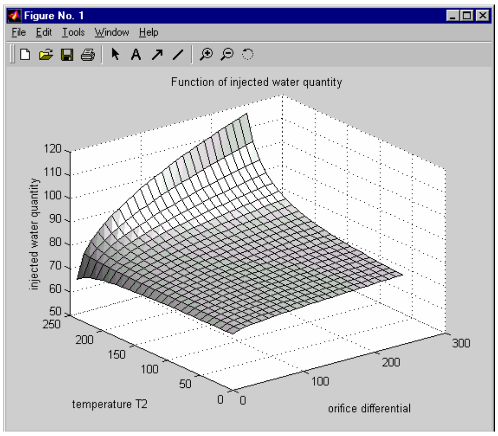
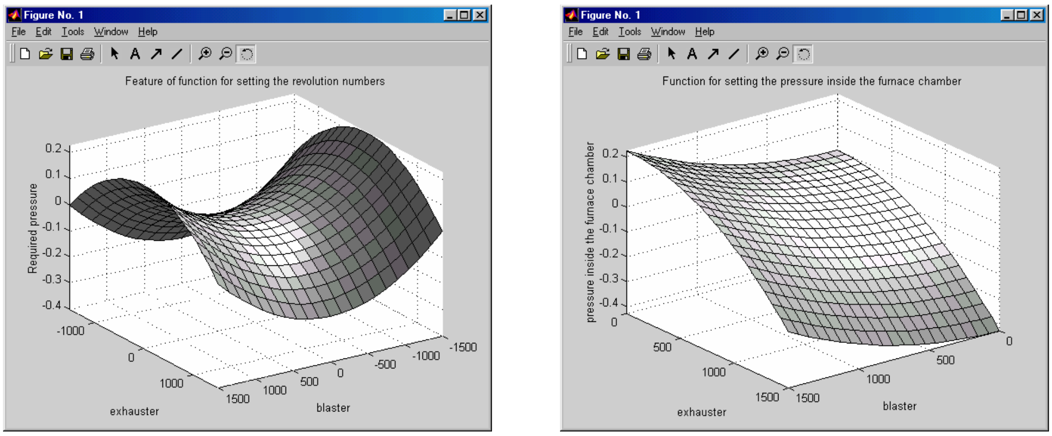


Figure 2.4. Control of injected water quantity



a) b)

Figure 2.5. Control of pressure inside the furnace chamber by controlling the revolution number of blaster and exhauster: a) locus of possible working points; b) applied range for control

Since the pressure p can be seen as constant value by Maxwell's rule because the pressure in the steam production system is set to be constant value, therefore, the linguistic rules of fuzzy control can be simplified, and the fuzzy logic control might be modified where the linguistic description of fuzzy rules are the followings while the pressure p is considered as constant value:

- if t is lower then T_c and the working point is out of the bifurcation zone then there are only hot water in the system, no steam,
- if t is lower then T_c and the working point is inside the bifurcation zone then there are boiling water and saturated steam in the system,
- if t is higher than T_c then there are unsaturated steam only.

The operation of boiler must be controlled in accordance with the second rule, i.e. the working point must be set into the bifurcation zone. The statement of medium is featured by the membership function for illustration the ratio of components in the medium shown in Figure 1. The control system has to be interact when the working point approaches to the district of bifurcation zone, i.e. the membership value is closed to 1.

The elementary catastrophes checked by their functions are stable structurally in accordance with Morse's lemma, and those functions which describe the operation of subsystems are catastrophe functions, therefore they are stable structurally, so the large-scale system consisted of those subsystems is also stable structurally. As the technological processes of steam production could be described by elementary catastrophe functions like inflection catastrophe and peak catastrophe, therefore, those processes are stable structurally.

The number of fuzzy rules had to be reduced for shorten the period of control system without getting worse stability of process. To reach this goal, I applied the decomposition of large-scale system to divide it into subsystems. Decomposition was required to describe technological processes with low-ordered catastrophe functions which resulted lower number of fuzzy rules in the control of subsystems. Relationship between the subsystems are maintained by technological parameters, and the changing of technological parameters in any subsystem occurs the interaction of other control subsystems.

It can be declared that *processes featured as catastrophe events can be controlled by fuzzy logic*, because

a) the changing of statement of catastrophe event can be described by membership function drawn over the catastrophe surface,
b) large-scale system described by catastrophe theory can be divided into subsystems which are also catastrophes themselves,
c) large-scale subsystems are stable structurally, and the large-scale system consisted of those subsystems is also stable structurally, in accordance with Morse's lemma,
d) the number of linguistic fuzzy rules depends on the order of catastrophe function used to describe the control process,
e) changing of output parameters occurs the interaction of control subsystems and it results the composition of technology and control into a homogeneous system.

Chapter 5 includes the description of membership functions and catastrophe functions for control of output devices.

* * *

Control of large-scale systems must satisfy the safety rules by standard IEC 61508. The safety of any technological system can be featured by the *safety integrity level SIL.* There are two methods to determine the SIL, the *quantitative method* and the *qualitative method.*

The quantitative method is based on the set of collected *historical data* – frequency of errors, measure of damage of environment, the number of failures of sensors and actuators, – and the value of SIL can be computed with the algorithm by standard IEC 61508.

The qualitative method needs experiences about the operational features of large-scale system – what kind of failures were caused, were they dangerous for human, how much independent safety layers were used, – which gives opportunity to determine the SIL. The standard includes proposals for the application of qualitative method. In my work I carried out a method to determine the SIL based on soft computing method. My method for determination of SIL uses the *severity matrix* by IEC 61508. For solving the task I applied Thom's theory for *conditional catastrophes*.

Thezis 2: I carried out the application of qualitative method for determining the SIL in accordance with the proposals of standard IEC 61508 by using of Thom's catastrophe theory.

The safety integrity level SIL is a measure for feature of technological devices applied in the controlled process which depends on the number of failures caused during a time unit. Table 2 includes the relationship between the SIL and the average value of failures in accordance with the proposals by standard IEC 61508.

SIL	Low demand mode of operation (average probability of failure to perform its design function on demand)
4	$\geq 10^{-5}$ to 10^{-4} [1/year]
3	$\geq 10^{-4}$ to 10^{-3} [1/year]
2	$\geq 10^{-3}$ to 10^{-2} [1/year]
1	$\geq 10^{-2}$ to 10^{-1} [1/year]

Table 2. SIL by IEC61508

I determined the SIL by the application of quantitative method for the subsystems of steam production. The description of computation is the following:

a) furnace chamber

Tolerable flame out frequency: $Ft=2/year$.

Probability of explosion because of an event is not greater then 1/4: $Pe=1/4=0,25$.

Frequency of an explosion: $Pc \leq 1$ *per 5000 years*.

Intolerable risk frequency:

$$Fnp = Ft\,Pe = 2 \cdot 0.25 = 0.5\ [1/year].$$

Protected risk frequency:

$$Fp = \frac{1}{Pc} = \frac{1}{5000} = 0.0002 [1/year].$$

Risk reduction factor:

$$RRF = \frac{Fnp}{Fp} = \frac{0.5}{0.0002} = 2500.$$

Safety availability:

$$SA = \frac{RRF-1}{RRF}\,100[\%] = \frac{2500-1}{2500}\,100 = 99.9\ [\%].$$

Probability of failure on demand:

$$PFDavg = \frac{1}{RRF} = \frac{1}{2500} = 4 \cdot 10^{-4}.$$

The safety integrity level of furnace chamber from Table 2: ***SIL=3***.

b) steam drum (control of feed water level)

Tolerable failure frequency of water level: *Ft=1/year*.

Probability of an explosion because of failure of steam drum is not greater then 1/6 per year: *Pe=1/6 =0.167*.

Frequency of failure: $Pc \leq 1$ *per 5000 years*.

Intolerable frequency:

$$Fnp = Ft\, Pe = 1 \cdot 0.167 = 0.167\ [1/year].$$

Protected risk frequency:

$$Fp = \frac{1}{Pc} = \frac{1}{5000} = 0.0002 [1/év].$$

Risk reduction factor:

$$RRF = \frac{Fnp}{Fp} = \frac{0.167}{0.0002} = 835.$$

Safety availability:

$$SA = \frac{RRF-1}{RRF} 100[\%] = \frac{835-1}{835} 100 = 99.8\ [\%].$$

Probability of failure on demand:

$$PFDavg = \frac{1}{RRF} = \frac{1}{835} = 1.19 \cdot 10^{-3}.$$

The safety integrity level of steam drum from Table 2: ***SIL=2***.

c) water injection (temperature control of output steam)

Tolerable failure frequency of water injection: *Ft=1/year*.

Probability of failure of water injection system is not greater then 1/10 per year: *Pe=1/10 =0.1*.

Frequency of failure: $Pc \leq 1$ *per 5000 years*.

Intolerable frequency:

$$Fnp = Ft\, Pe = 1 \cdot 0.1 = 0.1\ [1/year].$$

Protected risk frequency:

$$Fp = \frac{1}{Pc} = \frac{1}{5000} = 0.0002 [1/year].$$

Risk reduction factor:

$$RRF = \frac{Fnp}{Fp} = \frac{0.1}{0.0002} = 500.$$

Safety availability:

$$SA = \frac{RRF-1}{RRF} 100[\%] = \frac{500-1}{500} 100 = 99.8\ [\%].$$

Probability of failure on demand:

$$PFDavg = \frac{1}{RRF} = \frac{1}{500} = 2 \cdot 10^{-3}.$$

The safety integrity level of water injection system from Table 2: ***SIL=2***.

I carried out the fuzzy logic system to determine the SIL by the application of severity matrix and the conditional catastrophe. The conditional catastrophe is a special event of switch catastrophe when the changing of an event depends on any environmental condition, as it described in session 4.11 of dissertation.

The condition in the determination of safety integrity level is the value of the *event likelihood*, which has three linguistic values, low, medium, high. The SIL determined by soft computing method is summarized in Table 3.

Subsystem	Severity	Protection layers	Event likelihood	SIL
Furnace chamber	extensive	single	medium	3
Steam drum	serious	single	high	2
Water injection	minor	single	medium	1

Table 3. SIL computed by soft computing method

By comparison the SIL values computed by the quantitative method and soft computing method, it seems that SILs of the water injection system differ from each other. The reason of this difference is that the severity of failure in water injection system is low and not so dangerous for the full system of boiler, and this feature is not taken into consideration for the quantitative method because this feature can not be evaluated numerically.

* * *

The requirement of near-optimum operation of the system is the minimum cost of operation. The composition of minimum cost method has based on *Prof. Tíbor Tóth's theory* focused on a new approach of cost optimization. The steam production is a continuous process in time, and the base of cost calculation is the ratio of the nominal capacities of individual boilers. The costs of produced steam is computed by the specific costs of the distributed steam load on individual boilers.

Thesis 3: I worked out the supervisory system to satisfy the near-optimum operation when the temporary steam load is distributed between the boilers by the ratio of nominal capacities of the individual boilers, and the minimum of operational costs.

The task of supervisory system is to make the proportional distribution between the boilers. The ratio of steam load distribution depends on the temporary steam load of heat power station and the temporary steam load of individual boilers. Changing the distribution of loading can be occurred by the loading on heat power station, and the modification of distribution can be initiated by the control system of individual boilers. The changing of distribution is initiated by the control unit of boiler when the steam load on any individual boiler is close to the minimum, the critical point of function. In Figure 3 the function of request for changing the distribution is shown. It seems that the steam quantity at the minimum can not be measured by the orifice differential, and then the control system of boiler requests the changing of distribution.

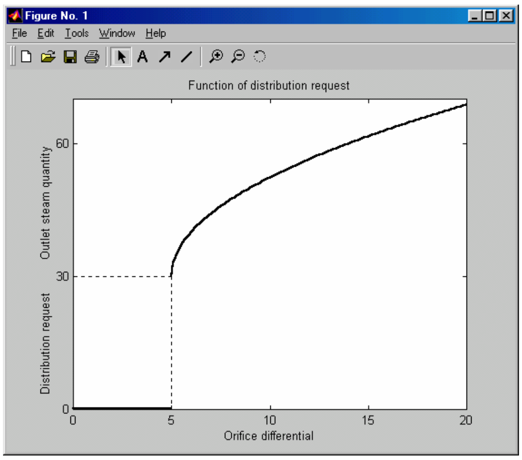


Figure 3. Function of distribution request depended on steam load

The supervisor system is shown in Figure 4 where m_i is the coefficient of steam load, and $\dot{V}=\sum_{i=1}^{n}\dot{V}_i$ is the temporary steam load on the large-scale system. Steam load on the ith individual boiler is computed by the expression $\dot{V}_i=m_i\dot{V}$.

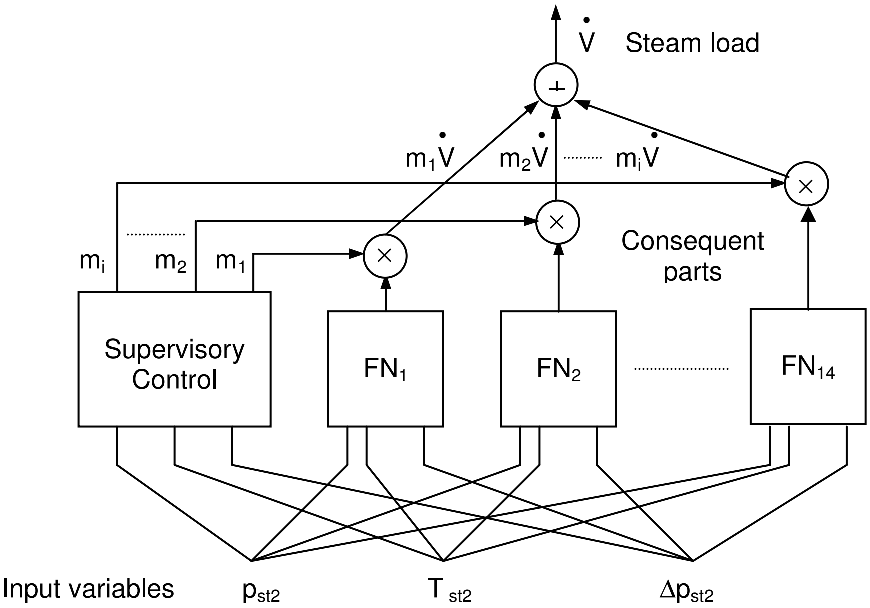


Figure 4. Block diagram of supervisor system for the heat power station

It can be declared, that

a) the operation of large-scale system is near-optimum when the distribution of loading is made by the ratio of nominal loading of subsystems,
b) processes which occur the changing of distribution between boilers are inflection catastrophes,
c) in large-scale systems like heat power stations, changing the distribution of loading is initiated always by the subsystems,
d) the supervisory system for controlling of steam load distribution is neural fuzzy system.

* * *

I developed an analogue neural system operated in accordance with Thom's catastrophe theory. The rules of operation are realized by *synaptic connections* within the network, and operational signals are synaptic voltage pulses. Learning process of neural network built of *fuzzy neurons* means the composition of synaptic connections.

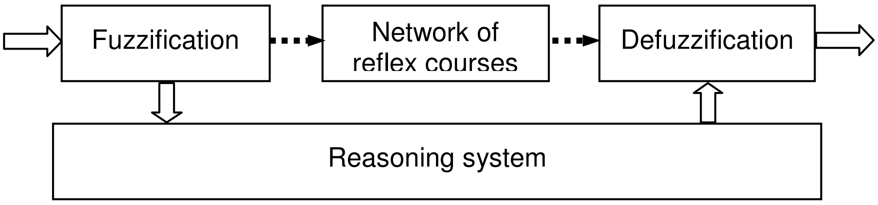


Figure 5. The scheme of catastrophe fuzzy inference system

The control system built of fuzzy neurons consists of vegetative functions and reflex functions. The vegetative functions are provided by the fuzzy system consisted of analogue neural cells the afferent neurons, the interim neurons, and the moto-neurons. Reflex functions are provided by the system of reflex courses, the *"catastrophe bridge"* shown in Figure 3.

The neural fuzzy catastrophe system operates like the human nervous system where the reflex courses provide activities against extreme effects. Rules of normal operation are stored in the reasoning system, the rules of operation occurred by extreme effects are set in the network of reflex courses.

Thesis 4: I carried out an analogue neural fuzzy network consisted of analogue neurons which operates in accordance with Thom's catastrophe theory provided by reflex courses, and these reflex courses are event-controlled, real-time operated neural subsystems, and the neural cells of neural subsystems are finite-state machines.

The reflex course is the basic part of vegetative nervous system which consists of afferent neuron and moto-neuron. Therefore, the reflex course operates fast because stimuli – the excitatory potential or the inhibitory potential – are transferred to the moto-neuron directly.

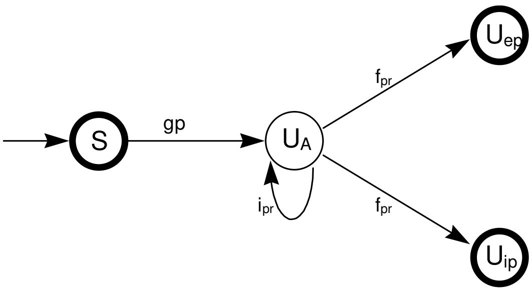
The synaptic connections among neighbored neural cells within a subsystem means the operational rules of neural subsystems. Synaptic connections are circuital connections.

I developed three basic types of neural cells, the afferent neuron, the interim neuron, and the moto-neuron. The functions of neural cells are described by formal description, and the circuital structure of neural cells are similar, and their function depends on their setting in the hierarchy of system.

Neural cells are activated by any environmental events – stimuli or synaptic potentials – and they are operating during the real-time cycle started by events, then the answer, the output resulted by a specific input is always the same, and the output statement of cell does not change during the real-time period, therefore the neural cell operates during the real-time period like a *finite-state machine*. It can be said that operations of the afferent neuron, and the interim neuron, and the moto-neuron are similar to the operation of organic neuron.

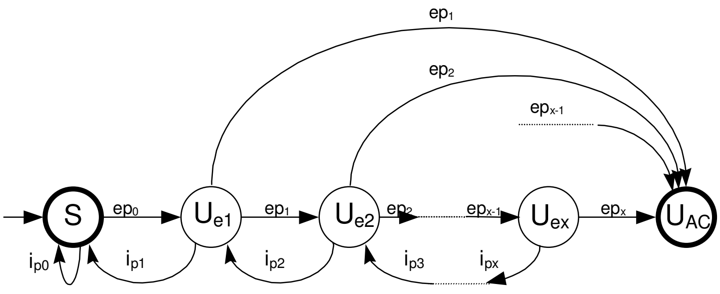
I described the operations of fuzzy neurons composed into analogue fuzzy system by mathematical objects in accordance with Chomky's description rules for formal description of regular languages. The graphs and formal descriptions of their operations are in Figure 6, Figure 7, and Figure 8.

Mathematical objects in formal descriptions are the following: Q is the set of statements of finite-state machines, Σ is the set of input signals, δ is the set of rules, and F is the set of finite-states.



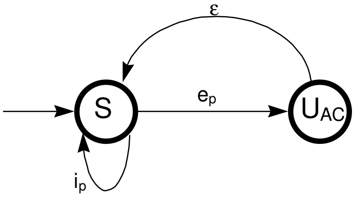
$Q=\{S,\ U_a,\ U_{ep}, U_{ip}\}$,
$\Sigma=\{gp,\ i_{pr},\ f_{pr}\}$,
$\delta=\{(S,\ gp)=U_a,\ (U_a,\ i_{pr})=U_a,\ (U_a,\ f_{pr})=U_{ep},\ (U_a,\ f_{pr})=U_{ip}\}$,
$F=\{U_{ep},\ U_{ip}\}$.

Figure 6. Graph and formal description of afferent neuron



$Q=\{S,\ U_{e1},\ U_{e2},\ \dots,\ U_{ex},\ U_{AC}\}$,
$\Sigma=\{ep_0,\ ep_1,\ \dots,\ ep_x,\ ip_0,\ ip_1,\ \dots,\ ip_x\}$,
$\delta=\{(S,\ ep_0)=U_{e1},\ (S,\ ip_0)=S,\ (U_{e1},\ ip_1)=S,\ (U_{ej},\ ep_j)=U_{e(j+1)},$
$,(U_{ej},\ ep_j)=U_{AC},\ (U_{ex}, ep_x)=U_{AC},\ (U_{ej},\ ip_j)=U_{e(j-1)}\}$,
$F=\{U_{AC}\}$.

Figure 7. Graph and formal description of interim neuron



$Q=\{S,\ U_{AC}\}$,
$\Sigma=\{e_p,\ i_p,\ \varepsilon\}$,
$\delta=\{(S,\ i_p)=S,\ (S,\ e_p)=U_{AC},\ (U_{AC},\ \varepsilon)=S\}$,
$F=\{U_{AC}\}$.

Figure 8. Graph and formal description of moto-neuron

These neural cells have particular operations described by formal descriptions and they have the following features:

a) operations of the afferent neuron, and the interim neuron, and the moto-neuron are similar to the operation of organic neurons,
b) all the neurons have specified operations, and they can be used for those operations only,
c) neural cells operate like *finite-state machine*s during the real-time period,
d) the afferent neural cell is a non-determined, fully specified finite-state machine,
e) the moto-neuron is a determined, fully specified finite-state machine,
f) the interim neural cell is a non-determined, not fully specified finite-state machine.

These neural cells can be composed into neural networks, similarly to the human nervous system. The technical features and operations of artificial neural cells are described in Appendix 2, Appendix 3, and Appendix 4.

7. Application of new scientific results

Scientific results can directly be used in the supervision of heat power stations. The application of fuzzy logic control for supervision of a large-scale system can be realized by stages. It means every large-scale subsystem can be operated individually, too. Therefore, supervisory subsystems can be implemented into the hierarchical system where the hierarchy is built by communicational network.

The hierarchical control built of fuzzy neurons is dedicated for the control of modeled process, only. The fuzzy rules are learnt by the synaptic connections between the neural cells. Synapses between neural cells can be realized either by software in digital systems or real connections in systems built of analogue circuits.

The results of my scientific research can be applied if

- the operation of technological system could be describe by Thom's catastrophe theory,
- the technological system could be decomposed into individual subsystems which may be either large-scale subsystems,
- the technological features of a dedicated large-scale system have to be learnt and used,
- the errors occurred at the output propagate backwards across the supervisory system to influence the states of controlled subsystems and the plant.

The large-scale system control operated by Thom's catastrophe theory can be used in

- *real-time process control* where large-scale subsystems are operated by their individual supervisory subsystems, and subsystems are involved into a large-scale system by the supervisory system of hierarchical control which decides the relationship between the individual subsystems and the goal(s),
- technologies where the *cost of production depends on the capabilities of subsystems*, and the economical control of large-scale system requires fast interventions to change the distribution of loading by the ratio of capabilities of individual large-scale subsystems, like a heat power station involved more boilers, electric power station involved more generators, metallurgical technologies in blast furnace, processes in nuclear reactors,

- control systems to control *extreme slow or extreme fast processes* like the steam production technology, or the stability control of high-speed aircraft, or operation of nuclear power station,
- *supervisory manager systems where the human ability is not enough to control safety* the processes of large-scale systems, like power stations, blast furnaces, nuclear reactors, airport traffic control.

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