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Przemysław Różewski
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New Frontiers in Information and Production Systems Modelling and Analysis

Incentive Mechanisms, Competence Management, Knowledge-based Production

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Editors

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Preface

Motivation

Manufacturer of digital products become a driver of the world's economy. This claim is confirmed by the data of the European and the American stock markets. Digital products are distributed in the Internet, serviced by the intellectual property protection solutions and internet payment systems. Online trade platforms support distribution of a variety of products in digital form, which are the result of intellectual work at both conceptual and manufacturing stages. Moreover, the approach to production itself has to be modified to meet demands of knowledge-based production.

The modern information and production system is a complex system since many components have their own goals that determine their behaviour. Moreover, these components are mutually related but can have conflicting goals. The complexity arises from the fact that it strives to satisfy and make use of many different stakeholders and resources: clients, workers, organizations, IT systems, telecommunication infrastructure and information and knowledge resources.

When considering different knowledge-based systems, we see, in addition to various artificial intelligence methods, a strong emphasis on cooperation between knowledge workers. Knowledge workers are the most important source of knowledge for the system and form the core of the intellectual capital of a knowledge-based organization. The quality of their cooperation depends on their motivation, competence and cognitive abilities. In our opinion, it is motivation that makes workers to apply their cognitive abilities to develop new the competencies. In this approach incentive mechanisms become the most important component of management in knowledge-based organizations. They encourage the continuous process of knowledge transfer. Generally speaking, incentive means motivating a subject to perform specific actions. In organizational systems a principal stimulates an agent by exerting an impact on his or her preferences (i.e. the goal function). In the book we shift from individual incentive systems (single-agent organizational systems) and focus on collective incentive systems, which provide incentives for a collective of agents. An agent in a multi-agent organization system can be independent (non-interacting) or collaborative (interacting with other agents). We also have to deal with some level of uncertainty of agents' actions and characteristics. Our goal is to apply incentive mechanisms to the knowledge-based production and information system.

This book consists of 12 chapters, each revised by the editors. The chapters are grouped into three perspectives. The first perspective is focused on theoretical aspects of knowledge-based production and systems. The second perspective goes deep into applications of presented theoretical concepts and approaches in production. The third perspective focuses on applications in information systems. Below we survey the content of all chapters in more detail.

Theoretical Perspective

The first chapter is focused on *Teams: Building, Adaptation and Learning* (Novikov D.A.). A team is a collective ability to achieve a goal in an autonomous and self-coordinated way under the minimum control actions. For many years various aspects of team behaviour (formation, decision-making, coordination, adaptation, specialization, etc.) attract acute attention of psychology, political science, control theory and production studies. This chapter considers game-theoretic models of team building, team adaptation and team learning in multi-agent organizational systems and challenges the problem of inconsistent information of team members while performing the joint activity. It is shown that models of team building and operation described in terms of reflexive games reproduce the autonomy and coordination of team activity. Team adaptation is considered as the process of beliefs' updating under the absence of common knowledge among the agents. In the framework of the joint learning model, the optimal learning problem is stated and solved as the allocation of the work volume performed by agents in certain time intervals.

The second chapter entitled *Incentive Mechanisms for Multi-agent Organizational Systems* (Novikov D.A.), presents a brief (yet comprehensive) introduction to the state of the art in the theory of incentive mechanisms for multi-agent systems under complete information. First, the approach is explained by the theory of financial incentives in organizations, including the game-theoretic grounds and the principal-agent model. Optimal individual incentive schemes are considered as long as collective ones, including the case of information aggregation. Three main principles of optimal incentive scheme design for interacting agents are derived, namely, the principle of compensation, the principle of decomposition and the principle of aggregation. Models of agents' self-coordination in the absence of the central authority are explored in terms of side-payoff games. These models are of great interest in the context of multi-agent approach in distributed control. Finally, the problem of agents' preferences identification in firms is studied in terms of revelation of labour supply curves from electronic surveys.

The chapter *Optimal Organizational Structures for Change Management in Production* (Goubko M.) considers the problem of a rational organizational structure for change management support being an important aspect of the strategic management process in a firm. Recent theoretical findings are combined with experience in strategic consulting to suggest mathematical models of an organizational structure for change management based on the formal representation of a strategy of the firm and of available personnel resources. The model of managers' interactions employs an idea of efforts' duplication.

The problem of an optimal organizational structure is reduced to a complex mixed optimization problem. Then a problem of an optimal organizational form (functional vs. divisional vs. matrix) is considered for a special case of identical and "symmetric" projects of strategic development. It is shown that the span of control should be constant across the levels of an optimal functional, divisional and matrix hierarchy; costs of optimal organizational forms are compared. The matrix organizational structure appears to be optimal when the number of projects and managerial functions are large enough. Ii is also shown that matrix and divisional organizations are robust with respect to the project count increase.

The next chapter is entitled *Knowledge-Based Models of Nonlinear Systems Based on Inductive Learning* (Bakhtadze N.N., Lototsky V.A.). The class of knowledge used today in production process control systems is more extensive than the expert knowledge class. In knowledge-based manufacturing systems (KBMS), artificial intelligence operating with process knowledge along with expert knowledge is widely used. The term "process knowledge" means formalized process operation regularities obtained by means of data analysis. Knowledge management in process control systems enables application of control techniques with intelligent predictive models (automatic control or managerial decision-making support) as well as of network, multi-agent, and multimodal techniques. In this chapter, the predictive model design is carried out using intelligent algorithms of nonlinear dynamic system identification. Those are based on inductive learning: associative search of analogues by intelligent analysis of both archives of system technology parameters (data mining) and the process knowledge base. The chapter examines multimodal plants in process and power industries. For such objects a stability criterion is suggested, which is expressed in terms of wavelet analysis, and a new identification algorithm is proposed based on associative search techniques.

The chapter *Multiple Criteria Decision Support System for Tender Consortium Building Within the Cluster Organization* (Małachowski B.) covers the multiple-criteria decision support method of contractors' consortium building basing on the analogy to project management methods used to support project team building within project-oriented organizations. The method supports a consortium leader in the process of consortium building. The method is based on fuzzy sets and the graph theory. In real life the decision about the consortium composition relies on many qualitative and quantitative criteria with the qualitative criterion of competence being of significant importance. The main advantage of the discussed approach is the quantitative formal model of competences, which allow precise selection and allocation of consortium members. Moreover, the complexity of the necessary multiple-criteria decision analysis can be reduced sufficiently by introducing a set of company pre-assignment conditions and a set of variant qualification constraints.

The last chapter in this part is entitled *Guideline for MCDA Method Selection in Production Management Area* (Wątróbski J., Jankowski J.) and considers the problems of rationalizing the choice of the multi-criteria decision-aid (MCDA) methods, which are well-suited to solve a given decision problem. Two sources of factors, which influence the choice of the method, are identified: a subject of the decision and the characteristics of the problem description. The technique proposed allows choosing one method from the considered group of methods. Practical verification of suggested decision rules was carried out for referential sets of sample literature applications (over 20 cases) of MCDA in the area of production management.

Applications in Production

In the chapter *Declarative Modelling Driven Approach to Portfolio Prototyping of Production Orders* (Banaszak Z., Bocewicz G.) the problem of production management under the large number of uncertain factors is considered. Using the apparatus of fuzzy logic the authors set the direct problem of job scheduling and the inverse problem of production resources assignment. The suggested solution approach is based on the original concept of the, so-called, "declarative" modelling. In models of this sort only the most important characteristics of the manufacturing process are taken into account. The chapter is equipped with numerous examples to illustrate and confirm the proposed approach.

In the chapter *A Knowledge-Based System for New Product Portfolio Selection* (Relich M.) authors establish a relationship between the success of a new product (NDP—New Development Product) and the key factors of success calculated from the enterprise information system. Effective management of NPD projects is a challenging goal due to numerous factors of complexity, such as intensive research and development investment, long and uncertain development times, low probability of technical success, uncertain market impact and competition. The proposed approach takes into account the data of previous projects that can be retrieved from different modules of an enterprise information system (e.g. marketing and sales, production, project management and customer claim control). Fuzzy neural networks are used to reveal relationships between product success and metrics of the NPD process. The identified relationships are expressed in the form of "if-then" rules. The proposed knowledge-based system uses these rules to estimate net profit for prospective products considered for development and suggests a set of the most promising products according to manager's preferences. The knowledge-based system can also be used for simulation and identification of such changes in the project environment that can increase the chance to develop a successful product. The set of potential products for development is determined with the use of constraint programming taking into account the company's constraints.

The chapter *Knowledge-Based Models for Smart Grid* (Yadykin I.B., Maximov E.M.) represents application of the multi-agent technology to smart grid, unified the grids, consumers and generating facilities. Authors suggest the design technique for intelligent, multimodal, large scale energy networks. Design of the multi-agent control system (MACS) is based on the development of MACS standards and classifications. The authors solve the control stability problem using the method of Gramians to determine the degree of stability. To solve the problem of control stability in time and frequency domain authors apply the method of differential and algebraic Lyapunov equations. Much attention is paid to the development of multi-agent intelligent optimization approach, which allows developing the technology of controlling the degree of MACS stability. This chapter also offers a concept of an intelligent multi-agent system that maintains stability in Russian Smart Grid, which incorporates an active analytical network and new algorithms to determine the degree of system stability using Gramians.

Applications in Information Systems

In the first chapter of this part, *Transformations of Standardized MLP Models and Linguistic Data in the Computerized Decision Support System*, (Becker J., Jankowski J., Wątróbski J.), the authors focus on two complementary issues of DSS. The first one is transformation of the data form and second one is transformation of structures of MLP decision models. The aim of proposition concept in DSS is to deal with multi-stage and multi-criterial nature of the decision-making process, number of decision-makers and experts, scale of the decision problem, flexibility of decision variants and linguistics of data. The information structure of partial mathematical models, reflecting the objects of analysis, are transformed to the form of records of the database and on their connection into a more complex structure, so-called multi-model. Data transformations are based on the use of fuzzy set logic and scoring and linguistic scales are of the ordinal nature.

The second chapter is entitled *New Frontiers and Possibility in the Construction of Learning Systems with Using of the Educational Program Complex "Labyrinth of Knowledge"* (Zapevalina A.A., Troyanovskij V.M., Serdyuk O.A.). The learning process analysis requires the implementation of a set of operating modes: view mode and the transfer of knowledge, controlling regime, account of individual abilities of students, adaptation, development and updating of the knowledge base. Algorithms and software for "labyrinth of knowledge" allow implementing these processes technically by interactive training with use modern gaming methods. Connection of control methods, technical capabilities of computational tools and modern information technology allows to create an effective learning environment with functions of adaptive simulator.

The last chapter *Scenario Analysis in the Management of Regional Security and Social Stability* (Kulba V., Zaikin O., Shelkov A., Chernov I.) represents the methodological and applied issues of development the management processes of regional security. It describes the methodology of diagnosis, structural analysis and evaluation of the major threats to regional security. The problems of countering the destructive information effects based on misinformation and manipulation technologies are examined. The results of the analysis of the main features of the management processes of regional security are presented. There are the mechanisms of the use of scenario analysis in the management of socio—economic development of the region and ensuring its protection against external and internal threats to social stability. A formalized methodology to assess the effectiveness and efficiency of management of regional security is considered. The results of the scenario study investigation of multi-graph management models of regional security are given.

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Part I
Theory

Chapter 1
Teams: Building, Adaptation and Learning

D.A. Novikov

Abstract Game-theoretical models of of team building, team adaptation and team learning are considered for multi-agent organizational systems. It's shown that models of team building and functioning described in terms of reflexive games reproduce the autonomy and coordination of team activity. Team adaptation is considered as the beliefs' updating under the absence of common knowledge among the agents. In the framework of the joint learning model the optimal learning problem is stated and solved as the allocation of the volumes of works performed by agents in certain time intervals.

1.1 Team Building

This section focuses on the model of *team building*, where uncertain parameters are the efficiency levels of agents' activity (see also the basic books and papers Holmstrom 1982; Kim and Roush 1997; Marchak and Radner 1976; Novikov 2008a).

A *team* is a collective (a union of people performing a joint activity and possessing common interests), being able to achieve a goal in an *autonomous* and *self-coordinated* way under the minimum control actions (Novikov and Novikov 2013; Novikov 2013a, b).

The following couple of aspects are essential in the definition of a team. The first aspect concerns *goal* achievement, i.e., the final result of a *joint activity* represents a unifying factor for any team. The second aspect is related to the autonomy and self-coordination of team activity; notably, each member of a team shows the behavior required under specific conditions (leading to the posed goal), i.e., the behavior expected by the rest team members (Halverson and Tirvizi 2013; Novikov 2008a).

Notwithstanding numerous qualitative discussions in scientific literature, today one would hardly find formal models of team building with non-trivial *mutual*

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beliefs. Thus, below we describe the model of team building based on the hierarchies of agents' mutual beliefs (Novikov and Chkhartishvili 2014) about the efficiency of their individual activity.

According to existing beliefs, each agent can forecast the actions to-be-chosen by other agents, the individual "costs" to-be-incurred by them and the total costs of the team. Assume that the actions are chosen repeatedly and the reality observed by a certain agent differs from its beliefs. Then the agent has to correct the beliefs and use "new" ones in its choice.

The analysis of *informational equilibria* (Novikov and Chkhartishvili 2014; Novikov 2013b) shows the following. It is reasonable to consider a team as a set of agents whose choices agree with the hierarchy of their mutual beliefs about each other. As a matter of fact, such definition of a team turns out close to the stability and coordination of *informational control* (both require that the real actions or payoffs of agents coincide with the expected ones).

Moreover, an interesting conclusion is that the stability of a team and self-coordination of its functioning can be ensured under the false beliefs of agents about each other. To disturb a false equilibrium, one should report additional information on agents to them.

Consider the set of *agents* $N = \{1, 2, \ldots, n\}$. The strategy of agent i is choosing an *action* $y_i \geq 0$, which requires the costs $c_i (y_i, r_i)$. Here $r_i > 0$ means the type of the agent, reflecting the efficiency of its activity.[1] In this section, we study the Cobb-Douglas cost functions $c_i(y_i, r_i) = y_i^\alpha r_i^{1-\alpha}/\alpha$, $i \in N$. Let the goal of agents' joint activity (Burkov et al. 2015) lie in achieving the total "action"

$$\sum_{i \in N} y_i = R \tag{1.1}$$

under the minimum total costs:

$$\sum_{i \in N} c_i(y_i, r_i) \rightarrow \min_{\{y_i\} \geq 0} . \tag{1.2}$$

From the game-theoretic viewpoint, for the sake of convenience one may believe that the goal functions of agents coincide and equal the total costs with negative sign.

In practice, this problem possesses the following interpretations: order execution by a production association, performing a given volume of work by a team (a department), and so on. Without loss of generality, set $R = 1$.

Suppose that the vector $r = (r_1, r_2, \ldots, r_n)$ is *common knowledge* (Aumann 1976; Novikov and Chkhartishvili 2014). By solving the constrained optimization problem (1.1) and (1.2), each agent evaluates the optimal action vector

[1] By assumption, the costs of an agent represent a decreasing function of its type.

$$y^*(r) = \left(y_1^*(r),\ y_2^*(r), \ldots, y_n^*(r)\right),$$

where

$$y_i^*(r) = r_i \Big/ \sum_{j \in N} r_j, \quad i \in N. \tag{1.3}$$

Now, discuss different variants of agents' awareness about the type vector (the model considered includes an hierarchy of agents' beliefs about the parameters of each other) (Novikov and Chkhartishvili 2014; Novikov 2008b). We will explore two cases as follows. In the first case, each agent has certain first-order beliefs $r_{ij} > 0$ about the types of other agents; in the second one, each agent has certain second-order beliefs $r_{ijk} > 0$ about the types of other agents, $i, j, k \in N$.

Making a digression, note that there may exist a *Principal* who knows the true types of agents and performs motivational control (see Chap. 2). Consequently, regardless of agents' awareness, each agent would independently choose the corresponding action (1.3), if the Principal adopts a proportional incentive scheme with the wage rate $1/\sum_{j \in N} r_j$ (Novikov 2013b).

Suppose that each agent knows its type. Moreover, the *axiom of self-awareness* (Novikov and Chkhartishvili 2014) implies that

$$r_{ii} = r_i,\ r_{iij} = r_{ij},\ r_{ijj} = r_{ij},\ i, j \in N.$$

According to its beliefs, each agent can forecast the actions to-be-chosen by other agents, the individual costs to-be-incurred by them, and the resulting total costs. Assume that actions are chosen repeatedly and the reality observed by an agent differs from its beliefs. Thus, an agent should correct the beliefs and involve "new" beliefs for the next choice.

The set of parameters observed by agent i is said to be its *subjective game history* and denoted by h_i, $i \in N$. Within the framework of the present model, the subjective game history of agent i may include the following information:

1. the actions chosen by other agents (of course, agent i is aware of its own choice):
$$y_{-i} = (y_1,\ y_2,\ \ldots,\ y_{i-1},\ y_{i+1},\ \ldots,\ y_n);$$
2. the actual costs of other agents (and their total costs):
$$c_{-i} = (c_1,\ c_2,\ \ldots c_{i-1},\ c_{i+1},\ \ldots,\ c_n;)$$
3. the total costs of all agents: $c = \sum_{i \in N} c_i$;
4. the actions and actual costs of other agents (and their total costs): $(y_{-i};\ c_{-i})$;
5. the actions of other agents and the total costs of all agents: $(y_{-i};\ c)$.

Table 1.1 The models of team building

Subjective game history	Awareness structure	
	$\{r_{ij}\}$	$\{r_{ijk}\}$
y_{-i}	Model 1	Model 6
c_{-i}	Model 2	Model 7
c	Model 3	Model 8
$(y_{-i};\ c_{-i})$	Model 4	Model 9
$(y_{-i};\ c)$	Model 5	Model 10

Apparently, the stated variants are not equivalent. Variant 4 seems the most "informative," variant 3 is less informative in comparison with variant 2, etc. The choice of an awareness variant is a tool of *informational control* (Novikov and Chkhartishvili 2014; Novikov 2013b) applied by a Principal.

The two cases of awareness structures (beliefs in the form r_{ij} and in the form r_{ijk}) and the five variants of the subjective game history induce Models 1–10 combined in Table 1.1. We believe that the subjective histories and awareness structures of all agents coincide (otherwise, the number of possible combinations grows exponentially).

To proceed, we analyze possible decision-making procedures adopted by agents. Under the awareness structure $\{r_{ij}\}$, agent i can choose its action according to the procedure (1.3):

$$y_i^*\left(\{r_{ij}\}\right) = r_i \Big/ \sum_{j \in N} r_{ij}\,. \tag{1.4}$$

Alternatively, the agent may first estimate the opponents' actions via the procedure (2), then evaluate its action leading to the required sum of actions:

$$y_i^*(\{r_{ij}\}) = 1 - \sum_{k \neq i} \left(r_{ik} \Big/ \sum_{l \in N} r_{il} \right),\ i \in N\,. \tag{1.5}$$

Evidently, the procedures (1.4) and (1.5) are equivalent.

Under the awareness structure $\{r_{ijk}\}$, agent i can estimate the opponents' actions using the procedure (1.3):

$$y_{ij}^*\left(\{r_{ijk}\}\right) = r_{ij} \Big/ \sum_{l \in N} r_{ijl}, \quad j \in N. \tag{1.6}$$

Then the agent evaluates its action ensuring the required sum of actions:

$$y_i^*(\{r_{ijk}\}) = 1 - \sum_{l \neq i} \left(r_{il} \Big/ \sum_{l \neq i} r_{ijq} \right), \quad i \in N. \tag{1.7}$$

Thus, we have described the models of agents' decision-making in the static mode. Now, consider the *dynamics of their collective behavior*.

Suppose that at each step agents make their decisions simultaneously using the information on the previous step only. In other words, the subjective game history includes the corresponding values during the previous period merely. Such assumption eliminates the case when decision-making takes place on the basis of the whole preceding game trajectory observed by an agent. The underlying reason is that these models of decision-making appear extremely complicated and would hardly yield practically relevant conclusions.

Denote by $W_i^t\left(h_i^t\right)$ the current *state of the goal* of agent i during the time period (step) t, i.e., its beliefs I_i^t about the opponents' types that could lead to their choices observed by the agent during this period; here $t = 0, 1, \ldots$ and $i \in N$.

Initially, agents possess the beliefs I_i^t and modify them depending on the subjective game history according to the *hypothesis of indicator behavior* (Novikov and Chkhartishvili 2014; Novikov 2013):

$$I_i^{t+1} = I_i^t + \gamma_i^t\left(W_i^t\left(h_i^t\right) - I_i^t\right),\ t = 0, 1,\ \ldots,\ i \in N, \tag{1.8}$$

where γ_i^t means a vector of real values from the segment [0; 1] ("step sizes").

The beliefs of each agent are described by a finite number of the parameters r_{ij} or r_{ijk}, $i, j, k \in N$. Hence, we will understand (1.8) as the "vector"-form law of independent variations in awareness structure components.

Now, we suggest a rigorous definition of a team. Notably, a *team* is a set of agents whose choices agree with the hierarchy of their mutual beliefs. In the model under consideration, a team is a set of agents with the awareness structure representing a fixed point of the mapping (1.8) provided that the actions chosen by agents according to their awareness structures are given by formula (1.5) or (1.7). The introduced definition of a team is close to the properties of *stability* and *coordination of informational control*; the latter require that the real actions or payoffs of agents coincide with the expected actions or payoffs (see Chkhartishvili and Novikov 2003, 2004, 2005, 2014).

Therefore, in each case the dynamics of agents' mutual beliefs is described by the relationship $W_i^t(\cdot)$ between the current state of the agent's goal and its subjective game history.

Model 1. Suppose that agent i with the awareness structure $\{r_{ij}\}$ observes the actions x_{-i} chosen by the opponents.

For agent i, take the set of opponents' types such that their actions chosen according to formula (1.4) coincide with the observed actions x_{-i}. Denote this set by

$$\Omega_i^1\left\{r_{ij} > 0, j \in N\backslash\{i\} \middle| r_{ij} = x_j,\ j \in N\backslash\{i\}\right\}. \tag{1.9}$$

Next, let $w_{ij}^t(x_{-i}^t)$ be the jth projection of the point belonging to the set Ω_i^1 and being closest to the point $\left(r_{ij}^t\right)_{j\in N\backslash\{i\}}$. Then the dynamics of the beliefs of agent i can be rewritten as

$$r_{ij}^{t+1} = r_{ij}^t + \gamma_{ij}^t\left(w_{ij}^t\left(x_{-i}^t\right) - r_{ij}^t\right), j \in N\backslash\{i\}, t = 0, 1, \ldots, i \in N. \qquad (1.10)$$

And its choice of actions would follow the expression (2).

Model 2. Assume that agent i with the awareness structure $\{r_{ij}\}$ observes the costs c_{-i} of other agents.

For agent i, take the set of opponents' types such that their costs incurred by the choice of actions according to formula (1.4) coincide with the observed costs c_{-i}. Denote this set by

$$\Omega_i^2 = \left\{ r_{ij} > 0, j \in N\backslash\{i\} \middle| c_j\left(r_{ij}/\sum_{l\in N} r_{il}, r_{ij}\right) = c_j, j \in N\backslash\{i\} \right\} \qquad (1.11)$$

Again, let $w_{ij}^t(c_{-i})$ be the jth projection of the point belonging to the set Ω_i^2 and being closest to the point $\left(r_{ij}^t\right)_{j\in N\backslash\{i\}}$. Then the dynamics of the beliefs of agent i can be characterized by the procedure (1.10), and its choice of actions agrees with (1.4).

In the sense of informativeness and the feasibility of the corresponding equations (see formulas (1.9) and (1.11)), this case slightly differs from Model 1.

Model 3. Assume that agent i with the awareness structure $\{r_{ij}\}$ observes the costs c of all agents.

For agent i, take the set of opponents' types such that their total costs incurred coincide with the observed total costs c. Denote this set by

$$\Omega_i^3 = \left\{ r_{ij} > 0, j \in N\backslash\{i\} \middle| c_i(y_i, r_i) + \sum_{l\in N\backslash\{i\}} \left[c_j\left(r_{il}/\sum_{q\in N} r_{iq}, r_{ij}\right)\right] = c \right\} \quad (1.12)$$

Similarly, let $w_{ij}^t(c)$ be the jth projection of the point belonging to the set Ω_i^3 and being closest to the point $\left(r_{ij}^t\right)_{j\in N\backslash\{j\}}$. Then the dynamics of the beliefs of agent i can be modeled by the procedure (8), and its choice of actions agrees with (2).

As a matter of fact, this case substantially varies from Models 1–2 (in the aspects of informativeness and non-unique solutions to the equation defining the set Ω_i^3(see formula (1.12)), as well as in the aspect of modeling complexity).

Models 4–5 are treated by analogy to Models 1–2; thus, their detailed treatment is omitted.

Model 6. Assume that agent i with the awareness structure $\{r_{ijk}\}$ observes the actions x_{-i} chosen by the opponents.

For agent i, take the set of opponents' types such that their actions being chosen by the procedure (1.6) coincide with the observed actions x_{-i}. Denote this set by

$$\Omega_i^6 = \left\{ r_{ijk} > 0, j \in N\backslash\{i\}, k \in N \middle| r_{ij} / \sum_{l \in N} r_{ijl} = x_j, j \in N\backslash\{i\} \right\} \tag{1.13}$$

Moreover, let $w_{ijk}^t\left(x_{-i}^t\right)$ be the jkth projection of the point belonging to the set Ω_i^6 and being closest to the point $\left(r_{ijk}^t\right)_{j \in N\backslash\{j\}}$. Then the dynamics of the beliefs of agent i can be defined by

$$r_{ijk}^{t+1} = r_{ijk}^t + \gamma_{ij}^t \left(w_{ijk}^t\left(x_{-i}^t\right) - r_{ijk}^t \right), \; j \in N\backslash\{i\}, \; t = 0, 1, \; \ldots, \; i \in N. \tag{1.14}$$

and its choice of actions satisfies the expression (1.7), i.e.,

$$y_i^{t^*}\left(\left\{r_{ijk}^t\right\}\right) = 1 - \sum_{j \neq 1} \left(r_{il}^t / \sum_{q \in N} r_{ijq}^t \right) i \in N. \tag{1.15}$$

Model 6 appears equivalent to Model 1 in description and analysis techniques. On the other hand, Model 7 is equivalent to Model 2, and so on. Therefore, Models 7–10 are not studied here.

Thus, for each agent Model 1 includes (n – 1) equations with (n – 1) unknown quantities, Model 2 includes (n – 1) equations with (n – 1) unknown quantities, Model 3 includes 1 equation with (n – 1) unknown quantities, Model 4 includes 2 (n – 1) equations with (n – 1) unknown quantities, Model 5 includes n equations with (n – 1) unknown quantities, Model 6 includes (n – 1) equations with n (n – 1) unknown quantities, and so on.

Concluding this section, we consider the simplest model, viz., Model 1, in the case of three agents with the separable quadratic cost functions $c_i\,(y_i, r_i) = (y_i)^2/2\, r_i$.
Model 1 (an example). It follows from formula (1.9) that

$$\begin{aligned} w_{13}(x_2, x_3) &= x_3\, r_1/(1 - x_2 - x_3), \; w_{12}(x_2, x_3) = x_2\, r_1/(1 - x_2 - x_3), \\ w_{21}(x_1, x_3) &= x_1\, r_2/(1 - x_1 - x_3), \; w_{23}(x_1, x_3) = x_3\, r_2/(1 - x_1 - x_3), \\ w_{31}(x_1, x_2) &= x_1\, r_3/(1 - x_1 - x_2), \; w_{32}(x_1, x_2) = x_2\, r_3/(1 - x_1 - x_2), \end{aligned}$$

Set r_1 = 1.8, r_2 = 2, r_3 = 2.2, and take the initial agents' beliefs about their types equal to 2. The objectively optimal action vector (in the sense of the minimum total costs) makes up (0.30; 0.33; 0.37).

Suppose that agents act in the following way. Based on their own beliefs about their types and the types of the opponents, agents evaluate the opponents' actions guaranteeing the "subjective" total minimum to the costs sum (i.e., forecast the actions of the opponents). This is done according to the procedure (1.4). Next, agents compare the observed actions with the forecasted ones and modify their beliefs about the opponents' types proportionally to the difference between the observed and forecasted actions; the proportionality coefficient constitutes $\gamma_{ij}^t = 0.25,\ i,\ j \in N,\ t = 0, 1,\ \ldots$

After 200 steps the stated procedure converges to the action vector (0.316; 0.339; 0.345) and the following beliefs of the agents about their types: $r_{12} = 1.93 < r_2$, $r_{13} = 1.94 < r_3$, $r_{21} = 1.86 > r_1$, $r_{23} = 2.01 < r_3$, $r_{31} = 2.02 > r_1$, and $r_{32} = 2.17 > r_2$. Despite the evident mismatches between the reality and the existing beliefs of agents, the outcome appears stable–the expected actions and the observed ones coincide to four digits after the decimal point.

Now, set $r_1 = 1.8$, $r_2 = 2$, $r_3 = 2.2$ and choose other initial beliefs of the agents about their types:

$$r_{12}^0 = 2,\ r_{13}^0 = 2.5,\ r_{21}^0 = 1.5,\ r_{23}^0 = 2.5,\ r_{31}^0 = 1.5,\ r_{32}^0 = 2.$$

Still, the action vector (0.30; 0.33; 0.37) is objectively optimal (in the sense of the minimum total costs).

After 200 steps, the procedure brings to the action vector (0.298; 0.3484; 0.3524) and the following beliefs of the agents about their types: $r_{12} = 2.1 > r_2$, $r_{13} = 2.12 < r_3$, $r_{21} = 1.71 < r_1$, $r_{23} = 2.01 < r_3$, $r_{31} = 1.85 > r_1$, and $r_{32} = 2.16 > r_2$. Again, despite the evident mismatches between the reality and the existing beliefs of agents, the outcome appears stable–the expected actions and the observed ones coincide to four digits after the decimal point.

Under the same initial data, the procedure (1.10) leads to the action vector (0.318; 0.341; 0.341) and the following beliefs of the agents about their types: $r_{12} = 1.93 < r_2$, $r_{13} = 1.93 < r_3$, $r_{21} = 1.87 > r_1$, $r_{23} = 2.00 < r_3$, $r_{31} = 1.05 > r_1$, and $r_{32} = 2.2 > r_2$. Similarly, despite the evident mismatches between the reality and the existing beliefs of agents, the outcome appears stable–the expected actions and the observed ones coincide to six digits after the decimal point.

The phenomenon of informational equilibrium instability (when the mutual beliefs of agents do not coincide with the reality) has a simple explanation. The system of Eq. (1.9) in the beliefs and actions of all agents possesses non-unique solutions. Indeed, in the case of two agents, the system of three equations

$$\begin{cases} \dfrac{r_{12}}{r_1 + r_{12}} = x_2 \\ x_1 + x_2 = 1 \\ \dfrac{r_{21}}{r_2 + r_{21}} = x_1 \end{cases} \tag{1.16}$$

with four unknown quantities $r_{12},\ r_{21},\ x_1,\ x_2$ admits an infinite set of solutions. Really, by expressing all unknown quantities through x_1, one we obtain the family of solutions $r_{12} = r_1\ (1/x_1 - 1)$, $r_{21} = r_2\ x_1/(1 - x_1)$, $x_2 = 1 - x_1$, and $x_1 \in (0; 1)$. Substitution of these beliefs into (1.4) yields identities.

Interestingly, transition to Model 4, i.e., adding information on the opponents' costs may considerably reduce the set of solutions for the corresponding system of equations. In this model, simultaneous observation of the costs and actions of an agent enables unique definition of its type (in one step).

We provide an example. Consider two agents with the types r_1 = 1.5 and r_2 = 2.5. The initial (appreciably "incorrect") beliefs are $r_{12}^0 = 1.8$ and $r_{21}^0 = 2.2$. After 200 steps, the resulting mutual beliefs of the agents make up r_{12} = 1.747 and r_{21} = 2.147, i.e., still being far from the truth.

At the same time, the subjectively equilibrium actions constitute x_1 = 0.4614 and x_2 = 0.5376. The actions observed by the agents form an informational equilibrium–they are coordinated with the individual beliefs of the agents (i.e., satisfy the system of Eq. (1.16)).

For the example above, the set of subjective equilibria is illustrated by Fig. 1.1 (here the circle indicates the initial point, the diamond stands for the actual values of the types, while the arrow shows the direction of variation of the agents' beliefs). The system of Eq. (1.16) implies that stable informational equilibria satisfy the following condition:

$$r_{12}r_{21} = r_1 r_2. \tag{1.17}$$

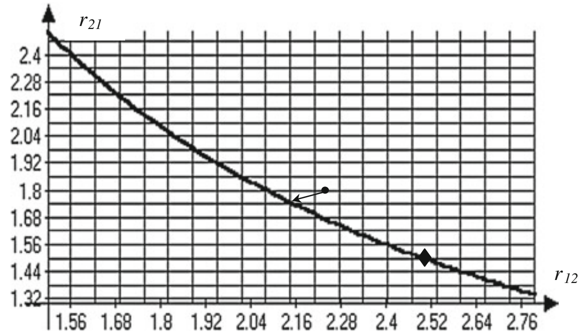
The set of mutual beliefs (r_{12}; r_{21}) meeting (1.17) is a hyperbola on the corresponding plane. Figure 1.2 demonstrates such hyperbola in the case of r_1 = 2 and r_2 = 1.

The performed analysis makes it possible to define the set of *false equilibria* (1.17), as well as to study the corresponding domains of attraction. It follows from (1.10) that the dynamics of the mutual beliefs obeys the equation

$$\frac{\Delta r_{12}^{t+1}}{\Delta r_{21}^{t+1}} = \frac{\gamma_{12}^{t+1}}{\gamma_{21}^{t+1}} \frac{r_{12}^t}{r_{21}^t}, \; t = 0, 1, \; \ldots \tag{1.18}$$

Hence, under fixed and constant "steps" γ, the trajectories of the mutual beliefs are lines passing through the origin. The slope of these lines (the domains of attraction

Fig. 1.1 The set of subjective equilibria



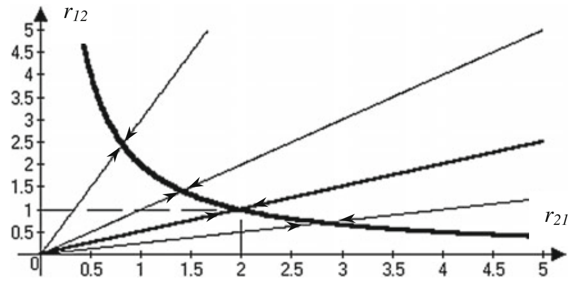


Fig. 1.2 The set of subjective equilibria and their domains of attraction

for the intersection points with the hyperbola (1.17)) depends on the initial point. For instance, any initial point lying on the thick line in Fig. 1.2 ($r_{12} = r_{21}/2$) leads to the true equilibrium.

This fact seems interesting in the sense of informational control. The Principal can easily evaluate the set of initial points (a line) leading to a desired terminal point (agents would definitely reach the equilibrium[2] required to the Principal). Note that the Principal must have adequate information on the types of agents.

The above example leads to the conclusion that the stability and congruence of a team can be achieved under the false mutual beliefs of team members. Disturbing a false equilibrium requires additional information on agents.

Therefore, the models of team building and functioning described in terms of reflexive games reproduce the autonomy and self-coordination of a team. Furthermore, they enable posing and solving control problems for the process of team building.

Indeed, the study of Models 1–10 shows that the most important information on the game history is the one available to agents. Thus, control capabilities lie in

- creating different situations of activity and
- ensuring maximum communication and access to relevant information.

The analysis also testifies that the *speed of team building* (the rate of convergence to an equilibrium) essentially depends on the parameters $\{\gamma\}$ ("step sizes") used in the dynamic behavioral procedures of agents. The impact on these parameters can be treated as control by the Principal.[3]

A natural question arises immediately. Is the outcome of a false equilibrium frequent? We elucidate this issue by stating the general conditions of its occurrence (within the framework of Model 1).

Suppose that the agents' type vector $r = (r_1, r_2, \ldots, r_n)$ is common knowledge, and there exists a unique optimal action vector $y^*(r) = y_1^*(r),\ y_2^*(r), \ldots, y_n^*(r)$.

---

[2] In the case of variable "steps," the problem is to find a trajectory which satisfies (1.18) and passes through a given point of the set (1.18).

[3] Note that increasing the step size improves the rate of convergence; on the other hand, the procedure may become instable for sufficiently large step sizes.

Hence, we have defined n functions $\varphi_i : r \to y_i^*(r),\ i \in N$, mapping the type vector r into the optimal action of agent i (the domains of the functions φ_i include only type vectors leading to a unique vector of optimal actions).

Now, assume that the outcome described above takes place *subjectively*; i.e., each agent *believes* that the type vector is common knowledge. Then the awareness structure of the game is defined by N vectors of the form $(r_{i1}, r_{i2}, \ldots, r_{in})$, $i \in N$. The informational equilibrium $y^* = y_1^*,\ y_2^*, \ldots, y_n^*$ is stable if each agent observes the actions of the opponents expected by it. This means that

$$\varphi_i\left(r_{j1},\ r_{j2},\ \ldots,\ r_{jm}\right) = y_i^*, i,j \in N. \tag{1.19}$$

The equilibrium y^* being arbitrary, formula (1.17) specifies n^2 constraints on the awareness structure. Next, if the type of each agent is fixed (and each agent knows its type), then one should evaluate n $(n - 1)$ quantities r_{ij}, $i, j \in N$, $i \neq j$ in order to guarantee the expressions (1.19).

The system (1.19) is *a fortiori* satisfied by the set of quantities r_{ij} such that $r_{ij} = r_j$ for all i and j. Therefore, under a fixed set of types $(r_1, r_2, \ldots, r_n)$, the issue regarding the existence of a false equilibrium is reduced to the following question. Does the system (1.19) admit non-unique solutions?

One may put the following hypothesis. The outcome of a false equilibrium is rather an exception, and its occurrence in the discussed examples is connected with a specific interaction among agents. This hypothesis is confirmed by some examples in (Novikov and Chkhartishvili 2014) (no false equilibria are found there).

The conducted analysis brings to the following conclusion. The models of team building and functioning described in terms of *reflexive games* reproduce the autonomy and coordination of team activity. Furthermore, they allow posing and solving control problems for team building process. Control capabilities include, first, creating various situations of activity (to identify the essential characteristics of agents–the model of learning) and, second, ensuring maximum communication and access of team members to all essential information.

1.2 Team Adaptation

Problems of team adaptation. This section considers the models of *team adaptation*, i.e., the process of changes in the actions chosen by team members based on current information in varying external conditions of team functioning (Novikov 2008a). In the general case, adaptation also covers the functions and volumes of work performed by team members. We separate out several embedded *levels of adaptation*, namely:

(1) changing of awareness about an external environment;
(2) changing of behavior (actions chosen using available information);

(3) changing of system parameters, which enables implementing more efficient behavior in varying conditions (*learning*);
(4) purposeful modification of an external environment (*active adaptation*).

Particularly, it is demonstrated that *teams possess the following specifics*. Each agent corrects its beliefs about an uncertain parameter based on the observations of an external environment and, moreover, the observations of the actions and results of other agents (endeavoring to "explain" their choice Novikov 2008a). In other words, if the result of joint activity depends on the actions of all agents, each agent operates (at most) four "sources of information" on the external environment:

(1) the a priori individual information possessed by each agent;
(2) the actions of other agents (by observing them and assuming the rational decision-making of opponents, an agent may perform reflexion, i.e., assess the information on the external environment leading to exactly these rational choices of the opponents);
(3) the payoffs of agents (using this information, agents make conclusions on the states of the external environment, under which the observed result leads to the observed payoffs);
(4) the set of states of the external environment, under which the observed vector of agents' actions leads to the observed result).

We introduce the notion of *adaptation time* in a team; this is the time required for the unambiguous identification of the state of an invariable external environment by team members based on observed information. As a matter of fact, adaptation time decreases if team members observe more parameters and increases in the case of growing a priori uncertainty.

The models of team adaptation explored in this section reflect the effects of accommodation, readjustment, etc. to varying external conditions. A series of examples illustrate the processes of team adaptation to abrupt and gradual changes in external conditions.

Recall that a fundamental difference between teams and organizations is that the former possess no formal hierarchy (even despite the presence of an informal leader). For instance, consider organizations (a hierarchy makes an indispensable attribute of almost any organization, perhaps, except network organizations Novikov 2013b). Here the "readjustment" problem of the principles and conditions of functioning to any variations in external conditions or other essential parameters is solved at higher hierarchical levels and the solution is subsequently "translated" to lower levels. The current section deals with the models of independent adaptation of teams to varying conditions.

Adaptation. Let us introduce a series of basic notions. Adaptation has a close correlation to self-development and self-organizing. *Self-development* is self-motion connected with transition to a higher level of organization (Novikov and Novikov 2013). Next, *self-motion* is a change of a certain object under the influence of its internal contradictions, factors and conditions. In this case, external actions play the modifying or mediating role.

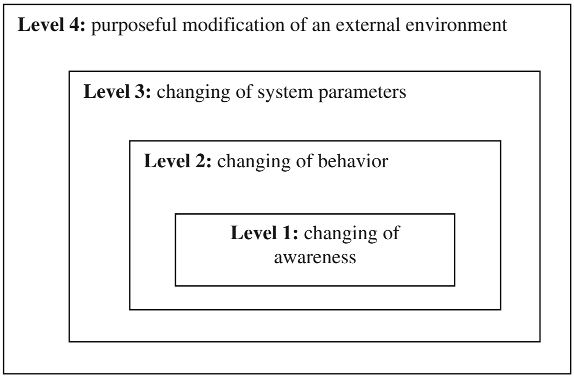


Fig. 1.3 The levels of adaptation

The notion of *self-organizing* (Novikov and Novikov 2013) (as a *process* leading to creation, reproduction or perfection of a complex system organization) seems more general. The term “a self-organizing system” was pioneered by Ashby (1956).

Interestingly, the independent choice of functions, volumes of works, etc. by agents (see the models of teams in the previous section) can be viewed as *team's self-organizing* (in contrast to the centralized organization of activity by a Principal in hierarchical organizational systems).

Adaptation (from Latin *adaptatio* ‘fit’) is adjustment to the conditions of existence and habituation to such conditions; (in social systems) a type of interaction with an external environment, used to agree the requirements and expectations of its participants (Novikov and Novikov 2013; Novikov 2013a). Within the framework of the models of teams, we will comprehend adaptation as the process of changes in the actions chosen by team members based on current information in varying external conditions of team functioning (in the general case, including the functions and volumes of works).

One would easily identify several embedded levels of adaptation in any system (see Fig. 1.3), namely:

- changing of awareness about an external environment;
- changing of behavior (actions chosen using available information);
- changing of system parameters, which enables implementing more efficient behavior in varying conditions (*learning*);
- purposeful modification of an external environment (*active adaptation*).

This section discusses levels 1 and 2 (level 3 of adaptation, known as *learning*, will be studied in the next section).

Control theory possesses broad experience in solving adaptive control problems for “technical” systems. Nevertheless, little knowledge has been accumulated in constructing dynamic adaptive models for socio-economic systems to date (in this context, we refer to close directions of research, viz., evolutionary games and Bayes models of learning, see the surveys in, Camerer 2003; Novikov and Chkhartishvili 2014; Weibull 1996 etc.).

Team members appear rational (their interests are described by goal functions, and the rational behavior of each agent presupposes maximization of its goal function). However, at each instant team members make decisions–choose their actions–under the conditions of incomplete awareness. With the course of time, they accumulate information on uncertain parameters. Different "strategies" of agents' behavior are possible depending on the goals they have.

The first variant consists in choosing at each instant such actions that facilitate rapid accumulation of maximum information on uncertain parameters (identification of their values). The *identification* stage being completed, agents then easily choose actions maximizing their goal functions. The described "behavioral strategy" agrees with the tradition of *identification theory*.

The second variant is choosing at each instant such actions that maximize the agents' payoffs within a current period, with "parallel" accumulation of information on the state of nature. We model exactly this "behavioral strategy" below.

And finally, in the third ("synthetic") variant agents choose such trajectories (sequences of actions for a given horizon) that maximize their cumulative payoff with due account of the identification effects. The corresponding models form a promising topic of future investigations.

The specifics of teams is that each agent corrects its beliefs about an uncertain parameter based on the observations of an external environment and, moreover, the observations of the actions and results of other agents (endeavoring to "explain" their choice). Figure 1.4 demonstrates the general structure of the model of team adaptation.

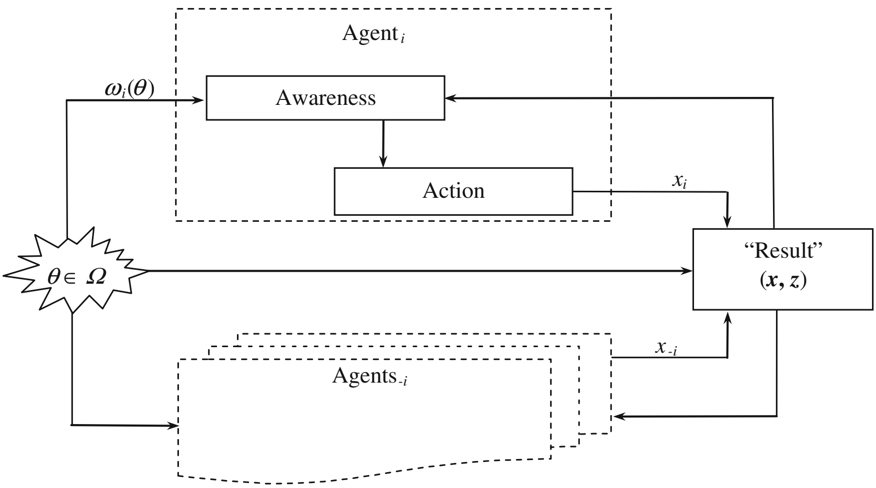


Fig. 1.4 The model of team adaptation: the general structure

Let us pass to the formal statement of the model. Consider a team $N = \{1, 2, \ldots, n\}$ composed of n agents. The external conditions of functioning (see the definition of adaptation above) of this team are described by the *state of nature* $\theta \in \Omega$, predetermining all essential characteristics of an external environment. Agent $i \in N$ has interval[4] information $\omega_i(\theta) \subseteq \Omega$ on the state of nature, and this information does not contradict the actual state of the things, i.e., $\forall \theta \in \Omega, \forall i \in N : \theta \in \omega_i(\theta)$. The total result $z = G(\theta, x)$ of the team depends on the action vector $x = (x_1, x_2, \ldots, x_n) \in X' \prod_{i \in N} X_i$ of all team members, where $x_i \in X_i$, and on the state of nature θ. We believe that each agent observes the action vector of all agents, the total result and the payoffs of all agents.

Suppose that the payoff of each agent depends on the state of nature θ and the total result z of the team: $f_i(z) = f_i(\theta, G(x, \theta)),\ i \in N$. Moreover, the set of agents N, their real-valued goal functions $\{f_i(\cdot)\}$ and feasible sets $\{X_i\}$, as well as the set Ω of the feasible states of nature, the function $G(\cdot)$ and the fact of observing the total result, all payoffs and the action vector by each team member form common knowledge.[5] If agents choose their actions simultaneously and independently, we have a game among them.

Denote by

$$E_N(\theta) = \{\{x_i\}_{i \in N} \in X' | \forall i \in N,\ \forall y_i \in X_i$$

$$f_i(\theta,\ G(\theta, x_1,\ \ldots,\ x_n)) \geq f_i(\theta,\ G(\theta, x_1,\ \ldots,\ x_{i-1},\ y_i, x_{i+1},\ \ldots,\ x_n))\} \tag{1.20}$$

the set of parametric Nash equilibria. Here the parameter is the state of nature–see the link between awareness and action in Fig. 1.4).

The set Ω_0 of the feasible states of nature is common knowledge among all agents. And so, by supposing that they eliminate the existing uncertainty via maximum guaranteed result evaluation, we obtain the following set of equilibria in their game:

$$E(\Omega_0) = \{\{x_i\}_{i \in N} \in X' | \forall i \in N,\ \forall y_i \in X_i$$

$$\left. \min_{\theta \in \Omega_0} f_i(\theta,\ G(\theta, x_1,\ \ldots,\ x_n)) \geq \min_{\theta \in \Omega_0} (\theta, G(\theta, x_1, \ldots, x_{i-1}, y_i, x_{i+1}, \ldots, x_n)) \right\} \tag{1.21}$$

[4] Traditionally, control theory studies models of adaptation mostly with the probabilistic uncertainties of an external environment. Applying the corresponding (and well-developed) mathematical tools to the problems of team adaptation seems to have good prospects.

[5] Possible extensions of the model are different cases of incomplete observations; e.g., an agent does not observe the action vectors of other agents, their payoffs, etc. (see the previous section).

Designate by $\pi(x) \subseteq \Omega$ the set of states of nature, under which the action vector observed by agents represents an equilibrium:

$$\pi(x) = \{\theta \in \Omega | \exists \Omega_0 : \theta \in \Omega_0, x \in E(\Omega_0)\}. \tag{1.22}$$

Let $g = (g_1, g_2, \ldots, g_n) \in \Re^n$ be the vector of the values of agents' goal functions observed by them.

Denote by

$$\delta(g, z) = \left\{\theta \in \Omega \middle| f_j(\theta, z) = g_j, j \in N\right\} \tag{1.23}$$

the set of states of nature, under which (in combination with the observed result z) the observed payoffs g of agents can be implemented. We analyze the awareness of agents in a greater detail. Agent i disposes of (at most) four "sources" of information on the state of nature:

(1) the a priori individual information $\omega_i(\theta) \subseteq \Omega$;
(2) the actions of other agents; by observing them and assuming the rational decision-making of opponents (see the link between awareness and action in Fig. 1.4), an agent may perform reflexion (believing that common knowledge takes place at the first level of the awareness structure[6] Novikov and Chkhartishvili 2014), i.e., assess the information $\pi(x)$ on the state of nature leading to exactly these rational choices of the opponents;
(3) the payoffs g of agents; using this information, agents make conclusions on the states of nature, under which the observed result leads to the observed payoffs–see the expression (1.23);
(4) the set $\rho \subseteq \Omega$ of states of nature, under which the observed vector of agents' actions leads to the observed result z:

$$\rho(x, z) = \{\theta \in \Omega | G(\theta, x) = z\}. \tag{1.24}$$

Due to the assumptions introduced earlier, information (2)–(4) is common knowledge among agents. By observing same parameters, different agents should identically (and predictably for the opponents) modify their beliefs about the state of nature In other words, the following information forms common knowledge:

$$I(x, z, g) = \pi(x) \cap \rho(x, z) \cap \delta(g, z) \subseteq \Omega.$$

[6] More complicated cases are also possible, where agents have nontrivial mutual awareness. Then the parametric Nash equilibrium (1.20) is replaced by the informational equilibrium in the game of agents.

The last assumption, in combination with the assumption that each agent believes in common knowledge at the first level of an awareness structure, rule out agents' reflexion with respect to the awareness of their opponents. Still, this issue may be considered in further investigations.

On the basis of the above information sources, agent i can evaluate the estimate $j_i \subseteq \Omega$ of the state of nature as the intersection of the common knowledge $I(x, z, g)$ and its individual information ω_i:

$$J_i(\omega_i, x, z, g) = \omega_i \cap I(x, z, g). \tag{1.25}$$

Let θ_0 be the actual state of nature; consider several models in the order of gradually growing complexity, namely, the single-agent model and the multi-agent model with the static and dynamic modes.[7]

The single-agent static model. Suppose that an agent makes a decision (chooses a certain action) one-time. Then, at the moment of decision-making, the agent knows only the set $\omega \subseteq \Omega$ representing the values of the states of nature. We believe that agent's decision-making in the conditions of interval uncertainty agrees with the principle of the maximum guaranteed result (MGR). This means that the agent chooses the action

$$x_{\mathrm{MGR}}(\omega) = \arg \max_{x \in X} \min_{\theta \in \omega} f(\theta, G(\theta, x)). \tag{1.26}$$

Recall that we focus on the static mode (one-time choice of an action by an agent) and other agents are missed. And so, the agent appears unable to use the information (1.25) on the observed result or its payoff.

Example 1.1
Set $n = 1, x \geq 0, \Omega = [1; 4], \omega = [2; 4]; \theta_0 = 3, z = x/\theta$,

$$f(\theta, z) = (\theta - \alpha z)z - z^2/2 \tag{1.27}$$

where $\alpha > 0$ is a (known) dimensional constant. Conceptually, it is possible to treat the agent as the manufacturer of some product with the demand depending on production volume. In this case, θ stands for the demand level (in terms of quantity and quality). The greater is the value of θ, the higher are the price $(\theta - \alpha z)$ and quality requirements; to reach a same "volume," the manufacturer needs applying greater efforts (represented by action x). On the other hand, the higher is the production volume, the lower is the price.

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[7] In the discrete model studied, the "static" mode corresponds to one-time choice of actions by agents, whereas the "dynamic" mode answers to a sequence of such choices.

According to the payoff function (1.27), the agent's payoff is defined as the difference between the income (the price multiplied by the production volume) and the costs described by a quadratic function.

Should the agent know the state of nature for sure, it will choose the action

$$x^*(\theta)\frac{\theta^2}{2\alpha+1}, \tag{1.28}$$

maximizing the goal function which depends on the state of nature and its action:

$$f_0(\theta,x) = (\theta - \alpha x/\theta)x/\theta - x^2/\left(2\theta^2\right) \tag{1.29}$$

As far as the goal function (1.27) increases monotonically in θ for any feasible actions of the agent, the expression (1.26) implies that

$$x_{\mathrm{MGR}}(\omega) = 4/(2\,\alpha + 1) \tag{1.30}$$

By observing (10) and the result $x_{\mathrm{MGR}}(\omega)/\theta_0$ or the payoff $f(\theta_0, x_{\mathrm{MGR}}(\omega)/\theta_0)$ (or even both these quantities), the agent can uniquely evaluate the actual state of nature θ_0.

Example 1.1 illustrates situations when one-time observation of corresponding information is sufficient for retrieving the actual state of nature by the agent. Interestingly, repeating the observations and employing auxiliary information on the choice of other agents (if available) becomes useless. However, sometimes one-time observation appears insufficient for the agent. We provide an example.

Example 1.2
Set $n = 1, x \geq 0, z = x, \theta = \left(\theta_p, \theta_c\right)\Omega = [1,4] \times [1,4], \omega = [2,4] \times [2,4], \theta_0 = (3,3)$,

$$f(\theta,\, x) = \left(\theta_p - \alpha x\right)x - x^2\theta_c/2, \tag{1.31}$$

where $\alpha \geq 0$ is a (known) dimensional constant. In contrast to Example 1.1, the state of nature represents a two-dimensional vector (the first component describes price parameters, while the second one stands for costs' parameters).

Should the agent know the state of nature for sure, it will choose the action

$$x^*(\theta) \;=\; \frac{\theta_p}{2\alpha + \theta_c}. \tag{1.32}$$

As far as the goal function (1.31) increases monotonically in θ_p and decreases monotonically in θ_c for any feasible actions of the agent, the expression (1.26) dictates that

$$x_{\text{MGR}}(\omega) = 1/(\alpha + 2). \tag{1.33}$$

In Example 1.2, the agent's action coincides with its result; hence, observation of its actual payoff is the only information source for the agent. Based on this observation, it draws the following conclusion regarding the set of feasible states of nature:

$$I = \{\theta \in \Omega | \theta_c = 2\,\theta_p(\alpha + 2) - 6\,\alpha - 9\}. \tag{1.34}$$

For instance, under $\alpha = 1$ it appears from (1.25) that

$$J = \{(\theta_p;\ \theta_c | \theta_c) = 6\,\theta_p - 15,\ \theta_p \in [17/6;\ 19/6]\}. \tag{1.35}$$

We emphasize that still the agent's information and the actual situation are consistent, i.e., $J \subseteq \omega$ and $\theta_0 \in j$, $\theta_0 \in I$.

The single-agent dynamic model. The "repeated" usage of information obtained during observation of actions becomes possible when the agent chooses actions many times. Assume that the agents choose their actions simultaneously at each step and the steps are "uniform."

Example 1.3
In the conditions of Example 1.2, set $\alpha = 1$ and imagine that the agent makes decisions sequentially several times. After the first "step," it possesses the information (1.35). According to the expression (1.26), the agent will choose the action $x_{\text{MGR}}(J)$ = 17/31 at the second "step." Observing its payoff as the result of this action, the agent may uniquely retrieve the actual state of nature $\theta_0 = (3, 3)$.

Thereby, in the present example, two observations (two "steps") are sufficient for retrieving the missed information by the agent.

We omit the case of multiple agents in the static mode, proceeding directly to the dynamic mode.

The multi-agent dynamic model. Denote by $x_i^t \in X_i$ the action of agent i at the moment t and by $x^{1,\ t}$ the set of action vectors of all agents during t periods. By the end of the period t, the information

$$I(x^t, z^t, g^t) \ = \ \pi(x^t) \cap \rho(x^t, z^t) \cap \delta(g^t, z^t) \subseteq \Omega$$

is the common knowledge of all agents.

Based on all information sources, agent i can evaluate the estimate $J_i^t \subseteq \Omega$ of the state of nature within t periods as the intersection of the common knowledge $I(x^t, z^t, g^t)$ and its individual information J_i^{t-1} corresponding to the previous period:

$$J_i^t \ = \ J_i^{t-1} \cap I(x^t, z^t, g^t). \tag{1.36}$$

In other words, its estimate of the state of nature is narrowed to the set

$$J_i^t\left(\omega_i, x^{1,t}, z^{1,t}, g^{1,t}\right) = \omega_i \cap \bigcap_{\tau=1}^{t} I(x^\tau, z^\tau, g^\tau). \quad (1.37)$$

Example 1.4

Consider the Cournot's oligopoly model (Mas-Collel et al. 1995; Myerson 1991) in uncertain conditions. Set $n = 2, x_i \geq 0, i = 1, 2, z = x_1 + x_2, \Omega = [1;5], \omega_1 = [1;4], \omega_2 = left[2;5]\theta_0 = 3,$

$$f_i(\theta, z) = (\theta - \alpha z)z - x_i^2 r/2, \quad (1.38)$$

where $\alpha > 0$, $r > 0$ are known dimensional constants. That is, agents differ only in their awareness about the state of nature.

Should agents know the state of nature for sure, they will choose the actions

$$x_i^*(\theta) = \frac{\theta}{4\alpha + r}, i = 1, 2. \quad (1.39)$$

Since the payoff functions (1.38) increase monotonically in θ for any feasible actions of agents, in the first period the agents choose the actions

$$x_1^1 = 1/(4\alpha + r),\ x_2^1 = 2/(4\alpha + r) \quad (1.40)$$

according to the expression (1.26).

As the result of such choice, agents retrieve the actual state of nature by observing the action vectors and payoffs several times.

Let us introduce the notion of "*adaptation time*" in a team. This is the time required for the unambiguous identification of the state of an invariable external environment by team members based on observed information. Adaptation time (the duration of a corresponding transient process) depends on the parameters observed by agents, the dimensionality of the vector describing the states of nature and the properties of point-set mappings (1.22)–(1.24). Adaptation time equals 1 (one period) in Examples 1.1 and 1.4 and 1.2 (two periods) in Example 1.3.

As a matter of fact, adaptation time decreases (more specifically, does not increase) if team members observe more parameters and increases (more specifically, does not decrease) in the case of higher dimensionality of the vector of states of nature and higher a priori uncertainty (wider sets $\{\omega_i\}$ describing the individual information of agents).

Example 1.5

Consider Example 1.4 and add agent 3 with the initial awareness $\omega_3 = [2.5; 3.5]$.

If each agent still observes the actions and payoffs of all agents, then all agents can retrieve the state of nature during one step, exactly as in Example 1.4. Adaptation time may increase if the awareness of agents "gets worse", i.e., the set of observed parameters is narrowed or only a few aggregate attributes remain observable (e.g., the sum of actions performed by all agents).

Therefore, suppose that the agent i observes its action x_i and payoff g_i, as well as the total action z of all agents[8] z. Moreover, the fact of such observations makes the common knowledge of all agents.Under known x_i, z and g_i, the equation

$$(\theta - \alpha z)z - x_i^2 r/2 = g_i$$

possesses a unique solution θ, i = 1, 2. In other words, increasing the number of agents would not raise adaptation time in the current example.

Example 1.6

Keeping in mind the conditions of Example 1.5, assume that each agent observes its own action and payoff only. Then observations lead to the following equation for agent i:

$$(\theta - \alpha(x_1 + x_2))(x_1 + x_2) - x_i^2\, r/2 = g_i, \tag{1.41}$$

with two unknown variables $x_{3\text{-}i}$ and θ, i = 1, 2.

Suppose that each agent considers the situation of common knowledge, i.e., the opponents are provided with the same level of awareness as the agent in question. Then an agent thinks that an opponent would choose a same action as it does. Recall that in the current example agents differ in their awareness about the state of nature. Substituting the actual payoff of the agent and

$$x_{3-i} = x_{\mathrm{MGR}_i}(\omega_i)$$

into (1.41), we obtain

$$\left(\theta - 2\,\alpha\, x_i^1\right)2\,x_i^1 - \left(x_i^1\right)^2 r/2 = \left(\theta_0 - \alpha\left(x_1^1 + x_2^1\right)\right)\left(x_1^1 + x_2^1\right) - \left(x_i^1\right)^2 r/2 \tag{1.42}$$

Thus, agent i can evaluate the lower estimate of the state of nature by the end of the first period:

$$\theta_i^1 = \left(\theta_0 - \alpha\left(x_1^1 + x_2^1\right)\right)\left(x_1^1 + x_2^1\right)/2\,x_i^1 + 2\,\alpha\, x_i^1. \tag{1.43}$$

Here i = 1, 2.

[8] In the case of two agents, each of them can evaluate the action of another based on the known total action and its own action. For three and more agents, such information becomes insufficient for retrieving unambiguously the actions of the opponents.

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Take the case of $\alpha = r = 1$. Subsequently,

$$x_1^1 = 0.2,\ x_2^1 = 0.4,\ \theta_1^1 = 4,\ \theta_2^1 = 2.6.$$

During the second period, agents substitute the corresponding estimates θ_1^1 and θ_2^1 into the expression (1.39). In other words, they choose the actions

$$x_1^2 = 0.8, x_2^2 = 0.52,$$

substitute them into the analog of formula (1.42), calculate the new estimates of the state of nature, and so on.

Generally, the estimates of the state of nature obtained by agents have the following dynamics (compare this result with (1.42)):

$$\theta_i^t = \left(\theta_0 - \alpha\left(x_1^t + x_2^t\right)\right)\left(x_1^t + x_2^t\right)/2\, x_i^t + 2\,\alpha\, x_i^t,\ i = 1,\ 2,\ t = 1, 2,\ \ldots. \quad (1.44)$$

Based on these estimates, agents choose the actions (see the expression (1.39))

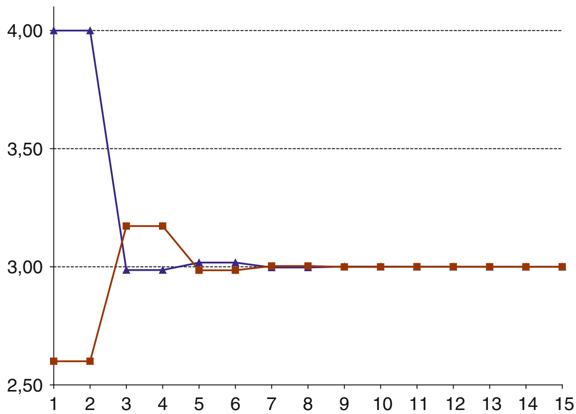
$$x_i^t\left(\theta_i^{t-1}\right) = \frac{\theta_i^{t-1}}{4\alpha + r},\ i = 1,\ 2,\ t = 1,\ 2,\ \ldots. \quad (1.45)$$

Consequently, team adaptation is described by the system of iterated functions (1.44) and (1.45), with initial conditions (1.40) defined under the a priori information of agents according to the principle of maximum guaranteed result.

Figures 1.5 and 1.6 demonstrate the dynamics of the estimated states of nature obtained by agents (the first level of adaptation) and the dynamics of agents' actions (the second level of adaptation).

Obviously, the processes describing variations in the estimates obtained by agents have rapid convergence (after 8–10 steps, the variations become negligible). Interestingly, these processes tend to the actual state of nature. Furthermore, even

Fig. 1.5 The dynamics of the estimated states of nature (*triangles*–agent 1, *square boxes*–agent 2)



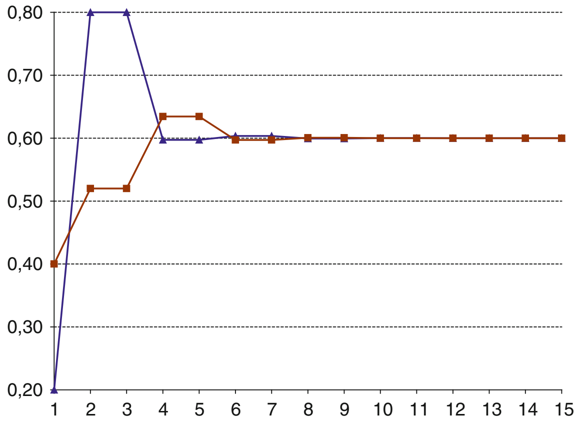


Fig. 1.6 The dynamics of agents' actions (*triangles*–agent 1, *square boxes*–agent 2)

having different a priori awareness, agents eventually choose identical actions (it seems natural, since agents have same goal functions). Strictly speaking, here adaptation time is infinite, though the period of reaching any preassigned nonempty neighborhood of the actual state of nature appears finite.

Adaptation corresponds to accommodation, getting accustomed to varying external conditions, etc. In this section, we have discussed adaptation models allowing description of such effects (see examples in Novikov 2008a). Adaptation makes sense if adaptation time does not exceed the characteristic time of external environment variation. On the other hand, external conditions may vary gradually and a team should adapt to such "slow" changes in the conditions of functioning.

Finally, note the following aspect. By the above assumption, each agent assigns same awareness to the opponents as it has. This assumption can be violated by considering more complicated structures of agents' awareness (Novikov and Chkhartishvili 2014) and believing that agents choose informational equilibrium actions. In addition, more complicated structures of agents' "observations" may take place. For instance, some agents observe only few parameters (e.g., the actions and payoffs for a certain set of agents), while the others observe other parameters (e.g., the actions and payoffs for another set of agents and information on the state of nature), etc. Perhaps, all such cases can be described similarly to the ones discussed above.

In this section, adaptation has been treated as accommodation to certain (basically, external) conditions and as getting accustomed to them; in fact, adaptation depends on information on these conditions[9] being available to agents at the moment of their decision-making. In contrast, modification of team parameters (the

[9] Of course, generally adaptation of a system presumes not only changing the awareness and behavior of its elements (the first and the second levels of adaptation), but also changing system parameters (the third level of adaptation), e.g., the types of agents, in response to varying external conditions. Moreover, active adaptation can be considered when the system directly influences on an external environment (the fourth level of adaptation).

third level of adaptation in Fig. 1.3) can be viewed as *learning*.[10] Therefore, our analysis switches to the models of team learning.

1.3 Team Learning

In this section, we consider the models of iterative learning implemented during professional activity, i.e., the problem of optimal collective learning (task allocation among team members (Novikov 2012; Novikov 1998).

While acting jointly, the members of a team or collective (*agents*) consciously or unconsciously gain experience in individual and collective activity. In other words, the process of their *learning* takes place. Here and in the sequel, we understand learning as "the process and result of gaining individual experience" (Hull 1943; Novikov 1998). This interpretation is a special case of the more general notion of learning as the process of acquiring knowledge, skill, and habits. Let us consider a series of models describing the learning effects of team members during their collective work. Starting from the general problem statement and quantitative description of learning process, we consider the model of individual learning process, and then the model of learning process for a collective of agents.

General problem statement and the model of learning process. In qualitative terms, the general problem of optimal learning can be formulated as follows. Each agent in a collective is characterized by some initial level of skill (e.g., labour productivity). With the course of working activity, the labour productivity of an agent grows owing to gaining experience, improving practical skills, etc. (*learning during working*, *learning-by-doing* takes place). However, the rate of this growth (the so-called *learning rate* formally defined below) is individual for each agent. We are interested in optimal allocation of work tasks among agents. Imagine an agent with a low level of initial professional skills; being strongly loaded by work from the very beginning, this agent can improve its skills rapidly and work with higher productivity later. On the other hand, is it reasonable to load agents with higher initial professional skills? The answers to these questions are not trivial. Moreover, we have to determine what is understood as the "optimal" allocation of work tasks among agents. Possible efficiency criteria are the total costs of agents, the time required for performing a given volume of work by a collective, the result achieved within a fixed period, and so on.

Let us proceed to formal analysis. We begin with the simplest model and gradually increase the complexity. Our discussion gets confined to the case of *iterative learning* (Novikov 1998) corresponding to routine activities. Iterative learning is multiple reiterations of actions, trials, attempts, etc., by a system for achieving a fixed goal in invariable external conditions. Iterative learning

[10] Learning and adaptation are close phenomena. However, learning may take place in invariable external conditions, whereas adaptation happens only when these conditions vary.

(IL) underlies formation of human habits, conditioned reflexes of animals, learning of many technical (materialized) and cybernetic (abstract logical) systems. This is the subject of research in pedagogical and engineering psychology, psychophysiology, pedagogics, control theory, and other sciences (see the survey Novikov 1998).

The invariability of external conditions and the goal allows describing IL quantitatively via *learning curves* representing the level of learning as functions of time and the number of iterations.

According to numerous experimental data, the most important general regularity of iterative learning consists in slowed-down asymptotic behaviour of learning curves. They are monotonic; the rate of change in learning level decreases in time; the curve itself asymptotically tends to some limit. In most cases, iterative learning curves can be approximated by exponential curves.

The following two aspects of learning seem relevant. The first aspect concerns the results of learning. While learning, a system has to achieve a required result with the quality of actions and admissible costs of time, energy, etc. The second aspect is associated with the process of learning and includes adaptation of a system learnt to some activity by working (e.g., exercises), etc. Accordingly, there exist the efficiency characteristics of iterative learning and adaptation (Novikov 1998). As a rule, adaptation characteristics relate to the physiological components of activity (fatiguability, etc.). This section considers just the characteristics of learning efficiency (adaptation characteristics have quite different dynamics).

Recall that iterative learning is often described by slowed-down asymptotic learning curves admitting approximation by the *exponential curves*

$$r(t) = r^{\infty} + \left(r^{0} - r^{\infty}\right)e^{-\gamma t},\ t \geq 0, \tag{1.46}$$

or the discrete sequence[11]

$$r^{k} = r^{\infty} + \left(r^{0} - r^{\infty}\right)e^{-\gamma t}, \quad t \geq 0, \tag{1.47}$$

Here t is the time moment of learning, k indicates the number of iterations (trials, attempts) from the starting moment of learning; $r(t)$ (r_k) means *agent's type* (the level of practical or professional skills) at the moment t (or iteration k); $r^0 > 0$ specifies *the initial professional skills* (the type value at the starting moment of learning, i.e., the initial moment of time); r^{∞} gives the "final" value, $r^{\infty} \geq r^0$; γ is a nonnegative constant defining the rate of change in the type (*the learning rate*).

Learning of a single agent. First, we consider *the model of learning* for a single agent. Denote by $y^k \geq 0$ *the volume of work* performed by the agent within period k. If the agent's type (skill level) $r^k \in [0; 1]$ is interpreted as the share of its

[11] Throughout this section, the superscript denotes the number of a time period, whereas the subscript designates the number of an agent. In the single-agent model, the subscript is omitted.

successful actions, then the agent achieves *the result* $z^k = r^k\, y^k$ by performing the volume of work y^k within period k.

Consequently, the agent's result (the total volume of works successfully performed by it within k periods) makes up

$$z^k = \sum_{l=1}^{k} r^l y^l. \tag{1.48}$$

On the other hand, the agent performs a greater volume of (successful and unsuccessful) works:

$$Y^k = \sum_{l=1}^{k} y^l. \tag{1.49}$$

This volume of works can be treated as the "*experience*" gained by the agent (Novikov 2008b), i.e., the "effective time" of the agent (the period consumed for learning process). By substituting (1.48) into the exponent (1.46), we have

$$r^k = 1 - \left(1 - r^0\right) \exp\left(-\gamma Y^{k-1}\right), k = 2,\ 3,$$

Let $y^{1,\tau} = (y^1, y^2, \ldots, y^\tau)$, $\tau = 1, 2, \ldots$ and assume that $y^0 = 0$. Combining (1.46)–(1.49) yields the following expressions for the volumes of works performed successfully and the types of the agent:

$$z^k = \sum_{l=1}^{k} y^l \left\{ 1 - (1 - r^0) \exp\left(-\gamma \sum_{m=1}^{l-1} y^m \right) \right\}, \tag{1.50}$$

$$r^k = 1 - \left(1 - r^0\right) \exp\left(-\gamma \sum_{l=1}^{k-1} y^l \right), k = 2, 3, \ldots \tag{1.51}$$

Under a fixed total volume of works, the agent's type is uniquely defined by formula (1.51) regardless of the distribution of works over time periods. Therefore, the problem of maximizing the agent's type with a fixed total volume of works makes no sense within the framework of this model.

The model incorporates three "macro-parameters," namely, the total volume of works Y, the number of periods T, and the result Z. The desired variable is the "*learning trajectory*" $y^{1,\,T}$.

Optimal learning problems lie in extremalization of one variable under fixed other variables.[12] Thus and so, the following problem statements appear reasonable:

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[12] In more general case, one would desire to extremize some functional (e.g., learning expenses, learning quality, etc.) taking into account some additional constraints, varying several variables simultaneously, etc. All these problems form the prospective subject of future research.

1. Fix the total volume of works Y to-be-performed by the agent and the result Z to-be-achieved. It is necessary to find a trajectory minimizing the time of achieving the result:

$$\begin{cases} T \to \min \\ Y^T \leq Y \\ Z^T \geq Z \end{cases}. \tag{1.52}$$

The problem (1.52) can be called the minimum time problem.

2. Fix the total volume of works Y to-be-performed by the agent and the learning time T. It is necessary to find a trajectory maximizing the result Z:

$$\begin{cases} Z^\tau \to \max \\ Y^\tau \leq Y \\ \tau \leq T \end{cases}. \tag{1.53}$$

The problem (1.53) can be called *the problem of optimal agent learning*. Interestingly, this problem is closest to pedagogical problems: under fixed time and the volume of teaching material, one has to distribute this material in time to maximize the "volume of learnt material" (the "quality of learning"). However, didactic aspects (the content of teaching material) seem insignificant due to the routine character of learning.

Since the expression (1.50) is monotonic in the sum of the volume of agent's works and the learning period, the problem (1.53) can be rewritten as

$$\sum_{l=1}^{T} y^l \exp\left(-\gamma \sum_{m=1}^{l-1} y^m\right) \to \min_{\left\{y^{1,T} | \sum_{\tau=1}^{T} y^\tau = Y\right\}}. \tag{1.54}$$

Formula (1.54) does not employ the initial skill r^0 of the agent. In other words, we have the following result.

Assertion 1 (Novikov 2012). The solution to the optimal learning problem is independent from the initial skill of the agent.

This fact is interesting for the methodology of learning. Really, only the differences between the individual learning rates of independent agents are essential from the viewpoint of the ultimate results.

3. Fix the learning time T and the result Z to-be-achieved by the agent. It is necessary to find a learning trajectory minimizing the total volume of works:

$$\begin{cases} Y^\tau \to \min \\ \tau \leq T \\ Z^T \geq Z \end{cases}. \tag{1.55}$$

Any of the problems (1.52)–(1.55) admits reduction to appropriate dynamic programming problems.

Learning of multiple agents. Let us generalize the derived results to the case of several agents working simultaneously. First, we study the situation when the results and type of each agent are independent from the results and types of other agents. And second, we switch to the problem of learning of dependent agents.

Consider *a team* which is a set $N = \{1, 2, \ldots, n\}$ of n agents. By analogy to the expressions (1.50) and (1.51), we obtain the following formulas for the volumes of works performed successfully and the types of agents, respectively:

$$\sum_{l=1}^{k} y_i^l \left\{ 1 - (1 - r_i^0) \exp\left(-\gamma_i \sum_{m=1}^{l-1} y_i^m \right) \right\}, \tag{1.56}$$

$$r_i^k = 1 - \left(1 - r_i^0\right) \exp\left(-\gamma_i \sum_{l=1}^{k-1} y_i^l \right), k = 2,\ 3,\ \ldots, i \in N. \tag{1.57}$$

Suppose that the result of the team makes the sum of the individual results of all team member:

$$z^k = \sum_{i=1}^{n} Z_i^k, k = 1,\ 2,\ \ldots \tag{1.58}$$

In this case, *the problem of optimal learning of a collective* (compare with (1.53)) is defined by

$$Z^T \to \max_{\left\{ y_i^{1,T} | \sum_{\tau=1}^{T} \sum_{i=1}^{N} y_i^\tau = Y \right\}}, \tag{1.59}$$

which is equivalent to

$$\sum_{i=1}^{n} \sum_{l=1}^{T} y_i^l \left\{ 1 - (1 - r_i^0) \exp\left(-\gamma_i \sum_{m=1}^{l-1} y_i^m \right) \right\} \to \max_{\left\{ y_i^{1,T} | \sum_{\tau=1}^{T} \sum_{i=1}^{N} y_i^\tau = Y \right\}}. \tag{1.60}$$

The problem (1.60) can be solved by the dynamic programming method. The optimal solution to the problem (1.60) generally depends on the individual rates of the agents' learning $\{\gamma_i\}$ and their initial skills $\left\{r_i^0\right\}$.

Assertion 2 (Novikov 2012). Let the learning rates of agents be identical. Then the optimal distribution of works consists in performing the whole volume of works by an agent with the maximum initial skill. If the initial skills of the agent coincide, then the optimal distribution of works is performing the whole volume of works by an agent with the maximum learning rate.

Thus, in the case when all agents have same learning rates, the solution to the optimal learning problem turns out "degenerate"; only one agent works and learns while the rest do nothing. On the other hand, such collectives would be hardly considered to full value. Unfortunately, such situations happen in real life.

Now, suppose that agents differ both in their initial skills and learning rates.

Nominally, the solution structure of the problem (1.60) when the whole volume of works is performed by the "best" agent (in the sense of the initial skill and learning rate) includes more variables under a single constraint. Substantially, the problem may have other constraints besides the one imposed on the total volume of works performed by team members. The most natural constraint applies to the maximum volume of works performed by each agent within one iteration (period of time).

Collective learning. Up to this point, our discussion of agents' learning-by-doing has been based on the following assumption. Each agent learns only owing to "its own experience." Nevertheless, collectives are remarkable for experience exchange; agents gain additional experience by observing the activity of other agents (their successes and difficulties). To take this effect into account, we describe the "experience" gained by an agent as the sum of its own actions and the weighted sum of actions of other agents. Subsequently, we have the following expressions for the volumes of works performed successfully and agents' types, respectively:

$$Z_i^k = \sum_{l=1}^{k} y_i^l \left\{ 1 - (1 - r_i^0) \exp\left(-\gamma_i \sum_{j=1}^{n} \alpha_{ij} \sum_{m=1}^{l-1} y_j^m \right) \right\}, \tag{1.61}$$

$$r_i^k = 1 - \left(1 - r_i^0\right) \exp\left(-\gamma_i \sum_{j=1}^{n} \alpha_{ij} \sum_{j=1}^{k-1} y_j^l \right), k = 2,\ 3,\ \ldots,\ i \in N \tag{1.62}$$

Here the constants $\{\alpha_{ij} \geq 0\}$ can be interpreted as *the efficiencies of experience transfer* from agent j to agent i ($i, j \in N$).

Then the optimal learning problem takes the form

$$\sum_{i=1}^{n} \sum_{l=1}^{T} y_i^l \left\{ 1 - (1 - r_i^0) \exp\left(-\gamma_i \sum_{j=1}^{n} \alpha_{ij} \sum_{m=1}^{l-1} y_i^m \right) \right\} \to \max_{\left\{ y_i^{1,T} \mid \sum_{\tau=1}^{T} \sum_{i=1}^{N} y_i^{\tau} = Y \right\}}. \tag{1.63}$$

Example 1.7

Consider the problem (1.63) in the case of two agents with $T = 11$, $r_1^0 = 0.1$, $r_2^0 = 0.3$, $\gamma_1 = \gamma_2 = 0.75$, $Y = 10$ and $\| \alpha_{ij} \| = \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix}$. Clearly, both agents have identical learning rates, but agent 2 has higher initial skill. Agent 1 learns by its own experience and the experience of agent 2 (even more efficiently than by its own experience). And agent 2 learns only by its own experience. The dynamics of the

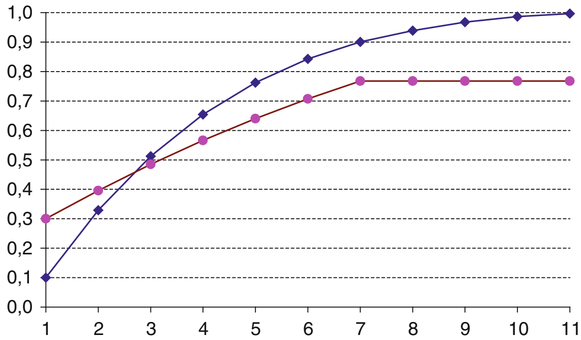

Fig. 1.7 The dynamics of agents' types

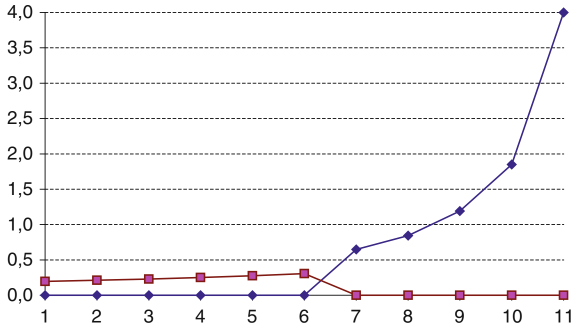

Fig. 1.8 The dynamics of the optimal volumes of works

agents' types is demonstrated by Fig. 1.7. The dynamics of the optimal volumes of works can be found in Fig. 1.8.

Within the starting six periods, agent 1 does not work but "observes" the actions of agent 2. However, the professional skill of agent 1 grows more rapidly than that of agent 2. Beginning with period 7, the optimal solution is performing the whole volume of works by agent 1 instead of agent 2.

This example elucidates how the lack of initial skill can be compensated owing to the efficient learning by other's experience. In another interpretation, agent 2 acts as a teacher, a tutor, an instructor possessing a higher initial skill and training agent 1. At some moment, the learner "outruns" the teacher and works independently.

Discussion. We have considered the models of learning-by-doing. Under the assumption that the volume of works already performed by an agent reflects the "experience" gained by it, we have stated and solved the optimal learning problem of allocating the volumes of works performed by agents in certain time intervals. The conducted analysis brings to the following conclusions:

- with a fixed total volume of works of one agent, the characteristics of the learning efficiency are independent from the volumes of works distributed over time periods;

- the solution to the problem of optimal iterative learning of one agent appears independent from its initial skill;
- the higher is agent's learning rate, the greater volume of works should be performed by it within last periods (and, respectively, the smaller volume of works should be assigned to the starting periods to improve its initial skill);
- the optimal learning strategy consists in increasing the volume of agent's works with the course of time; the higher is the learning rate, the more "convex" is the optimal learning trajectory;
- in the absence of constraints on the individual volumes of works, the whole volume of works in a team should be done by the "best" agent (in the sense of initial skill and learning rate);
- the lack of agent's initial skill can be compensated via efficient learning using its own experience and the experience of other agents.

In conclusion, we acknowledge the existence of learning curves with more complex structures (than exponential or logistic ones), the so-called sequential logistic curves corresponding to the development of various adjacent or more complex kinds of activity, generalized logistic curves, etc. Their detailed analysis goes beyond the scope of this paper. Although, if the learning laws of team members are known (even despite their complexity), then the problem of optimal distribution of works can be stated similarly. Yet, searching for the general (preferably, analytical) solution to this problem makes the subject of future research.

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Chapter 2
Incentive Mechanisms for Multi-agent Organizational Systems

D.A. Novikov

Abstract This work considers game-theoretic models of incentive mechanisms for multi-agent organizational systems. Three main principles of optimal incentive scheme design for interacting agents are derived, namely, the principle of compensation, the principle of decomposition and the principle of aggregation. Models of agents' self-coordination are explored in terms of side-payoff games. And finally, we study identification problems for agents' preferences.

An incentive means motivation of a subject to perform specific actions; in organizational systems, a *Principal* stimulates an *agent* by exerting an impact on its preferences (i.e., a goal function) (Novikov 2013a).

Interests' coordination between a Principal and agents is not a trivial problem. This fact was realized at the turn of the 1960–1970s, when theory of contracts appeared. Among the pioneering results, we mention the Azariadis-Baily-Gordon (ABG) model (Azariadis 1975; Baily 1974; Gordon 1974) which intended to explain the difference between efficient (predicted by labor economics) and observed wage levels–see the survey (Hart and Holmstrom 1987).

The parallel and intensive development of mechanisms theory in the 1970–1990s, namely:

- *contract theory* (CT) by Grossman and Hart (1983), Hart (1983), Mookherjee (1984), Myerson (1982), Salanie (2005) and others,
- *theory of active systems* (TAS) by Burkov (1977), Burkov et al. (1993, 2015), Burkov and Enaleev (1994), Novikov (1997) and others,

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- *theory of hierarchical games* (THG) by Germeier Yu (1986), Germeier (1971), Kononenko (1977), Kukushkin (1972) and others,[1]

yielded the fruitful and diversified theory of mathematical models of incentives in organizations (see the overview Burkov et al. 1993), as well as the monographs and textbooks (Bolton and Dewatripont 2005; Laffont and Martimort 2001; Novikov 2013a, c; Salanie 2005; Stole 1997).

This chapter describes in brief the state-of-the-art of the individual and collective incentive mechanisms for multi-agent organizational systems (OSs).

2.1 Individual Incentive Mechanisms

Let $N = \{1, 2, \ldots, n\}$ be a set of agents, $y_i \in A_i$ stand for an *action* of agent *i*, and $c_i\,(y)$ mean its *costs*. By assumption, costs functions are monotonic and nonnegative, $c_i\,(0) = 0$—see the details below. Moreover, denote by $\sigma_i\,(y)$ a reward given by a Principal to agent *i* ($i \in N$); accordingly, $y = (y_1, y_2, \ldots, y_n)$ represents an action profile of all agents, $y \in A' = \prod_{i \in N} A_i$. Suppose that the Principal gains an income $H(y)$ from agents' activity. Hence, the Principal's goal function acquires the form

$$\Phi(\sigma(\cdot), y) = H(y) - \sum_{i \in N} \sigma_i(y)\,, \tag{2.1}$$

where $\sigma(\cdot) = (\sigma_1(y), \ldots, \sigma_n(y))$ forms the vector of individual rewards and the goal function of agent *i* is

$$f_i(\sigma_i(\cdot), y) = \sigma_i(y) - c_i(y). \tag{2.2}$$

If agent's reward depends generally on the actions of all agents, the incentive scheme is called *collective*. Special cases include *individual rewards* ($\sigma_i = \sigma_i(y_i)$) and uniform rewards ($\sigma_i = \sigma_0(y_i)$).

An elementary extension of the basic single-agent model (Novikov 2013c) concerns a *multi-agent OS* with independent (noninteracting) agents. In this case, the incentive problem is decomposed into a set of corresponding single-agent problems.

Suppose that identical constraints are imposed on the incentive mechanism for all agents or a certain subset of agents. As a result, we derive the incentive problem in an *OS with weakly related agents* (discussed below). This problem represents a

[1] In short, these three scientific schools differ in the following. TC analyzes incentives under stochastic uncertainty when an agent is risk-averse (i.e., has a concave utility function). In TAS, agents are typically considered risk-neutral, but much attention belongs to incentives' compatibility and applications. And finally, THG focuses mostly on mathematical aspects and dynamic models.

set of parametric single-agent problems, and it is possible to search for optimal parameter values using standard constrained optimization techniques.

If agents are interrelated, viz., the costs or/and rewards of an agent depend on its actions and the actions of the rest agents, one obtains a “full-fledged” multi-agent incentive model. It will be studied in the present section.

The solution procedures of the multi- and single-agent problems have much in common. At the beginning, one has to apply the **principle of compensation**, i.e., to construct a *compensatory incentive scheme* (Novikov 2013c) implementing a certain action (an arbitrary feasible action under given constraints). In fact, this is Stage 1 known as *incentives' compatibility analysis*. Put forward the *hypothesis of benevolence*: if the agent is choice-indifferent, it chooses the action beneficial to the Principal. Then in single-agent OSs it suffices to verify that the maximum of the agent's goal function is attainable by an implementable action. On the other hand, in multi-agent systems one should demonstrate that the choice of a corresponding action makes up an *equilibrium strategy* in the game of agents. Imagine that there exist several equilibria; in this case, we have to verify the hypothesis of *rational choice* for the action in question. In most situations, it takes only to accept the *unanimity axiom* (according to the latter, agents do not choose equilibria dominated by other equilibria in the sense of Pareto). Sometimes, the Principal has to evaluate its *guaranteed result* on the set of equilibrium strategies of agents, and so on. Further, it is necessary to equate the incentive and the costs and solve a standard optimization problem: find an implementable action to-be-rewarded by the Principal. Actually, this is Stage 2 known as *incentive-compatible planning* (Burkov et al. 2015; Novikov 2013c). Let us describe the above approach in detail.

Incentives in OSs with weakly related agents. Let (a) agents' goal functions depend only on their individual actions (the so-called *separable costs*), (b) the incentive of each agent depend on its individual actions exclusively, and (c) some constraints be imposed on the total incentive of all agents. The formulated model is an *OS with weakly related agents*. As a matter of fact, this is an intermediate case between individual and collective incentive schemes.

Suppose that the individual rewards of agents are majorized by the quantities $\{C_i\}_{i \in N}$; in other words, $\forall\, y_i \in A_i$: $\sigma_i\,(y_i) \leq C_i$, $i \in N$. In addition, the *wage fund* (WF) has an upper bound R: $\sum_{i \in N} C_i \leq R$. Then the maximal *set of implementable actions* of agent i depends on the corresponding constraint R of the incentive mechanism: $P_i(C_i) = [0; y_i^+(C_i)]$, where

$$y_i^+(C_i) = \max \{y \in A_i | c_i(y) \leq C_i\}, i \in N.$$

Consequently, the optimal solution to the incentive problem in an OS with weakly related agents is defined as follows. One has to maximize the function

$$G(R) = \max_{\{y_i \in P_i(C_i)\}_{i \in N}} H(y_1, \ldots, y_n)$$

by an appropriate choice of the individual constraints $\{C_i\}_{i \in N}$ satisfying the *budget constraint* $\sum_{i \in N} C_i \leq R$. Apparently, this is a standard constrained optimization problem.

For a fixed WF, the agent's costs are not extracted from its income. At the same time, in the case of a variable WF, the optimal value R^* makes a solution to the following optimization problem:

$$R^* = \arg\max_{R \geq 0} [G(R) - R].$$

Incentives in OSs with strongly related agents. For agent i, designate by $y_{-i} = (y_1, y_2, \ldots, y_{i-1}, y_{i+1}, \ldots, y_n) \in A_{-i} = \prod_{j \neq i} A_j$ its opponents' action profile.

In the incentive model (2.1) and (2.2), the individual incentive and the individual costs of agent i to choose the action y_i generally depend on the actions of all agents.

Adopt the following sequence of moves in the OS. At the moment of their decision-making, the Principal and agents know the goal functions and feasible sets of all OS participants. Enjoying the right of the first move, the Principal chooses incentive functions and reports them to the agents. Next, under known incentive functions, agents simultaneously and independently choose their actions to maximize appropriate goal functions.

We make a series of assumptions on different parameters of the OS:

(1) for each agent, the set of feasible actions coincides with the set of nonnegative real values;
(2) the cost functions of agents are continuous and nonnegative; moreover, $\forall\, y_i \in A_i : c_i\,(y)$ does not decrease in y_i and $\forall\, y_{-i} \in A_{-i} : c_i\,(0, y_{-i}) = 0$ $(i \in N)$;
(3) the Principal's income function is continuous with respect to all arguments and attains the maximum for nonzero actions of agents.

In essence, Assumption 2 implies that (regardless of the actions of the rest agents) any agent can minimize its costs by choosing an appropriate (zero) action.

The costs and incentive of each agent generally depend on the actions of all agents. Hence, agents get involved in a *game*, where the payoff of each agent depends on the actions of all opponents. Suppose that $P(\sigma)$ is the *set of equilibrium strategies* of agents under the incentive scheme $\sigma(\cdot)$ (actually, this is the set of game solutions). For the time being, we do not specify the type of equilibrium, only presumming that agents choose their strategies simultaneously and independently. Thus, they do not interchange information and utility.

The guaranteed efficiency (or simply "*efficiency*") of an incentive scheme represents the minimum value (within the hypothesis of benevolence, the maximum value) of the Principal's goal function over the corresponding set of game solutions:

$$K(\sigma) = \min_{y \in P(\sigma)} \Phi(\sigma, y). \tag{2.3}$$

Under a given set M of feasible incentive schemes, the problem of *optimal incentive function/scheme design* lies in searching for a feasible incentive scheme σ^* which maximizes the efficiency:

$$\sigma^* = \arg\max_{\sigma \in M} K(\sigma). \tag{2.4}$$

In the special case of independent agents (i.e., the reward and costs of each agent get predetermined by its actions only), the *compensatory incentive scheme* (Novikov 2013c)

$$\sigma_{iK}(y_i) = \begin{cases} c_i(y_i^*) + \delta_i, & y_i = y_i^* \\ 0, & y_i \neq y_i^* \end{cases}, i \in N, \tag{2.5}$$

appears optimal (to be correct, δ-optimal, where $\delta = \sum_{i \in N} \delta_i$). In the formulas above, $\{\delta_i\}_{i \in N}$ designate arbitrarily small strictly positive constants (bonuses). Moreover, the optimal action y^*, being implementable by the incentive scheme (2.5) as a *dominant strategy equilibrium*[2] (DSE), solves the following problem of optimal incentive-compatible planning:

$$y^* = \arg\max_{y \in A'} \{H(y) - \sum_{i \in N} c_i(y_i)\}.$$

Suppose that the reward of each agent depends on the actions of all agents (this is exactly the case for collective incentives studied here) and the *costs are inseparable* (i.e., the costs of each agent generally depend on the actions of all agents, reflecting their interrelation). Then the sets of *Nash equilibria*[3] $E_N(\sigma) \subseteq A'$ and DSE $y_d \in A'$ acquire the form

$$E_N(\sigma) = \{y^N \in A \mid \forall i \in N \, \forall y_i \in A_i, \tag{2.6}$$

$$\sigma_i(y^N) - c_i(y^N) \geq \sigma_i(y_i, y_{-i}^N) - c_i(y_i, y_{-i}^N)\}.$$

By definition, $y_{i_d} \in A_i$ is a *dominant strategy* of agent i iff

$$\forall y_i \in A_i, \forall y_{-i} \in A_{-i}:$$

$$\sigma_i(y_{i_d}, y_{-i}) - c_i(y_{i_d}, y_{-i}) \geq \sigma_i(y_i, y_{-i}) - c_i(y_i, y_{-i}).$$

[2] Recall that a DSE is an action vector such that each agent benefits from choosing a corresponding component regardless of the actions chosen by the rest agents.

[3] A Nash equilibrium is an action vector such that each agent benefits from choosing a corresponding component provided that the rest agents choose equilibrium actions.

Imagine that a dominant strategy exists for each agent under a given incentive scheme. In this case, the incentive scheme is said to implement the corresponding action vector as a DSE.

Fix an arbitrary action vector $y^* \in A'$ of agents and consider the following incentive scheme:

$$\sigma_i(y^*, y) = \begin{cases} c_i(y_i^*, y_{-i}) + \delta_i, & y_i = y_i^* \\ 0, & y_i \neq y_i^* \end{cases}, \delta_i \geq 0, i \in N. \tag{2.7}$$

It was shown in Novikov and Tsvetkov (2001) that the vector y^* forms a DSE under the incentive scheme (2.7) applied by the Principal. Moreover, if $\delta_i > 0$, $i \in N$, then y^* makes up a unique DSE.

The *collective incentive scheme* (7) means that the Principal adopts the **principle of decomposition**. It suggests to agent i, "Choose the action y_i^*, and I compensate your costs regardless of the actions chosen by the rest agents. Yet, if you choose another action, the reward is zero." Using such strategy, the Principal decomposes the game of agents.

Assume that the incentive of each agent depends implicitly on its action only. By fixing the opponents' action profile for each agent, pass from (2.7) to *an individual incentive* scheme. Notably, fix an arbitrary action vector $y^* \in A'$ of agents and define the incentive scheme

$$\sigma_i(y^*, y_i) = \begin{cases} c_i(y_i^*, y_{-i}) + \delta_i, & y_i = y_i^* \\ 0, & y_i \neq y_i^* \end{cases}, \quad \delta_i \geq 0, i \in N. \tag{2.8}$$

In this case, we have the following interpretation. The Principal suggests to agent i, "Choose the action y_i^*, and I compensate your costs as if the rest agents would have chosen the corresponding actions y_{-i}^*. Yet, if you choose another action, the reward is zero." Adhering to such strategy, the Principal also decomposes the game of agents, i.e., implements the vector y^* as a Nash equilibrium of the game.

Interestingly, the incentive scheme (2.8) depends only on the action of agent i, while y_{-i}^* enters this function as a parameter. Moreover, in contrast to the incentive scheme (2.7), the incentive scheme (2.8) provides each agent merely with indirect information about the action vector desired by the Principal. For the incentive scheme (2.8) to implement the vector y^* as a DSE, additional assumptions should be introduced regarding the cost functions of agents, see Novikov and Tsvetkov (2001). This is not the case for the incentive scheme (2.7).

It seems quite appropriate here to discuss the role of $\{\delta_i\}_{i \in N}$ in the expressions (2.5), (2.7) and (2.8). If one needs implementing a certain action as a Nash equilibrium, these constants can be chosen zero. Imagine that the equilibrium must be unique (in particular, agents are required not to choose zero actions; otherwise, in evaluation of the guaranteed result (2.3) the Principal would be compelled to expect zero actions of agents). In this case, agents should be paid excess an arbitrarily small (strictly positive) quantity for choosing the action expected by the Principal.

Furthermore, the parameters $\{\delta_i\}_{i \in N}$ in formulas (2.5), (2.7) and (2.8) appear relevant in the sense of stability of the compensatory incentive scheme with respect to the model parameters. For instance, suppose that we know the cost function of agent i up to some constant $\Delta_i \leq \delta_i / 2$. Consequently, the compensatory incentive scheme (2.7) still implements the action y^*, see Novikov and Tsvetkov (2001).

The vector of optimal implementable actions y^*, figuring in the expression (2.7) or (2.8) as a parameter, results from the following *problem of optimal incentive-compatible planning*:

$$y^* = \arg\{\max_{t \in A'}\{H(t) - v(t)\}, \tag{2.9}$$

where $v(t) = \sum_{i \in N} c_i(t)$, and the efficiency of the incentive scheme (2.7), (2.9) constitutes

$$K^* = H(y^*) - \sum_{i \in N} c_i(y^*) - \delta.$$

It was demonstrated in Novikov and Tsvetkov (2001) that the incentive scheme (2.7), (2.9) appears *optimal*, i.e., possesses the maximum efficiency among all incentive schemes in multi-agent OSs.

An interested reader can find some examples of designing optimal collective incentive schemes for multi-agent OSs in the book (Novikov 2013c).

We have finished the discussion of incentive mechanisms for individual results of agents' activity. To proceed, let us describe some collective incentive mechanisms.

2.2 Collective Incentive Mechanisms

The majority of well-known incentive models consider two types of OSs. The first type is when a Principal observes the result of activity for all agents, being uniquely defined by their actions. The second type includes OSs with *uncertainties*, where the observed result of agents' activity depends not only on their actions, but also on uncertain and/or random factors (e.g., see the survey and models in Novikov 2013a, c).

The present section provides the statement and solution to the collective incentive problem in a multi-agent deterministic OS, where a Principal possesses only some aggregated information about the results of agents' activity.

In an n-agent OS, let the *result of agents' activity* $z \in A_0 = Q(A')$ be a certain function of their actions: $z = Q(y)$. In this case, $Q(\cdot)$ is termed the *aggregation function*. The preferences of OS participants, i.e., the Principal and agents, are expressed by their goal functions. In particular, the Principal's goal function makes up the difference between its income $H(z)$ and the total incentive $\upsilon(z)$ paid to agents:

$\upsilon(z) = \sum_{i \in N} \sigma_i(z)$. Here σ_i (z) stands for the incentive of agent i, $\sigma(z) = (\sigma_1(z), \sigma_2(z), \ldots, \sigma_n(z))$, i.e.,

$$\Phi(\sigma(\cdot), z) = H(z) - \sum_{i \in N} \sigma_i(z). \tag{2.10}$$

The goal function of agent i represents the difference between the reward given by the Principal and the costs c_i (y):

$$f_i(\sigma_i(\cdot), y) = \sigma_i(z) - c_i(y), i \in N. \tag{2.11}$$

We adopt the following sequence of moves in the OS. At the moment of decision-making, the Principal and agents know the goal functions and feasible sets of each other, as well as the aggregation function. The Principal's strategy is assigning incentive functions, while agents choose their actions. Enjoying the right of the first move, the Principal chooses incentive schemes and report them to agents. Under known incentive functions, agents subsequently choose their actions by maximizing the corresponding goal functions.

Imagine that the Principal observes the individual actions of agents (equivalently, the Principal can uniquely recover the actions using the observed result of activity). Then the Principal may employ an incentive scheme being directly dependent on the agents' actions: $\forall\, i \in N$: $\tilde{\sigma}_i(y) = \sigma_i\,(Q(y))$. We refer to the previous section for the detailed treatment of such incentive problems. Therefore, our analysis focuses on a situation when the Principal observes merely the result of activity in the OS (which predetermines the Principal's income). It is unaware of the individual actions of agents and cannot restore this information. In other words, *aggregation of information* takes place–the Principal possesses incomplete information on the agents' action vector $y \in A'$. It knows just some aggregated rate $z \in A_0$ (a parameter characterizing the results of agents' joint actions).

In the sequel, we believe that the OS parameters meet the assumptions from the previous section. Moreover, suppose that the aggregation function is a one-valued continuous function.

By analogy to the aforesaid, the efficiency of incentive is comprehended as the minimum value (or the maximum value–under the hypothesis of benevolence) of the Principal's goal function on the solution set of the game:

$$K(\sigma(\cdot)) = \min_{y \in P(\sigma(\cdot))} \Phi(\sigma(\cdot), \mathrm{Q}(y)). \tag{2.12}$$

The problem of optimal incentive function design lies in searching for a feasible incentive scheme σ^* maximizing the efficiency:

$$\sigma^* = \arg\max_{\sigma(\cdot)} k(\sigma(\cdot)). \tag{2.13}$$

The decomposition of the agents' game in the previous section bases on the Principal's ability to motivate agents for choosing a specific (observable!) action. Under unobservable actions of agents, direct application of the decomposition principle seems impossible. Thus, solution of the incentive problems (where agents' rewards depend on the observed aggregated result of activity) should follow another technique.

This technique is rather transparent. Find a set of actions yielding a given result of activity. Then separate a subset with the minimul total costs of agents (accordingly, with the minimum costs of the Principal to stimulate the agents under optimal compensatory incentive functions). Next, construct an incentive scheme implementing this subset of actions. Finally, choose the result of activity with the most beneficial outcome for the Principal.

Now, let us give a formal description to the solution of the incentive problem in an OS with aggregation of information about agents' activity.

Define the set of agents' action vectors leading to a given result z of activity:

$$Y(z) = \{y \in A' | Q(y) = z\} \subseteq A', z \in A_0.$$

Recall that, under observable actions of agents, the minimum costs of the Principal to implement the action vector $y \in A'$ equal the total costs of agents $\sum_{i \in N} c_i(y)$. Similarly, we evaluate the minimum total costs of agents to achieve the result of activity $z \in A_0$: $\tilde{\vartheta}(z) = \min_{y \in Y(z)} \sum_{i \in N} c_i(y)$, and the corresponding action set $Y^*(z) = Arg \min_{y \in Y(z)} \sum_{i \in N} c_i(y)$, which attains the minimum.

Fix an arbitrary result of activity $x \in A_0$ and an arbitrary vector $y^*(x) \in Y^*(x) \subseteq Y(x)$. We make a technical assumption as follows: $\forall\ x \in A_0$, $\forall\ y' \in Y(x)$, $\forall\ i \in N$, $\forall\ y_i \in Proj_i\ Y(x)$: the function $c_j\ (y_i, y'_{-i})$ does not decrease in y_i, $j \in N$. It was demonstrated in Novikov and Tsvetkov (2001) that:

(1) under the incentive scheme

$$\sigma^*_{ix}(z) = \begin{cases} c_i(y^*(x)) + \delta_i, & z = x \\ 0, & z \neq x \end{cases}, i \in N, \qquad (2.14)$$

the agents' action vector $y^*(x)$ is implementable as a unique equilibrium with the minimum costs of the Principal to stimulate agents (these costs constitute $\tilde{\vartheta}(x) + \delta$, $\delta = \sum_{i \in N} \delta_i$);

(2) the incentive scheme (2.14) enjoys δ-optimality.

Hence, Step 1 of solving the incentive problem (2.13) is to find the minimum incentive scheme (2.14) which (a) incurs the Principal's costs $\tilde{\vartheta}(x)$ to stimulate the agents and (b) implements the agents' action vector leading to the given result of activity $x \in A_0$. And Step 2 lies in evaluating the most beneficial (for the Principal) result of activity $x^* \in A_0$ via resolving the problem of optimal incentive-compatible planning:

$$x^* = \arg\max_{x \in A_0} [H(x) - \tilde{\vartheta}(x)]. \tag{2.15}$$

And so, the expressions (2.14) and (2.15) provide the solution to the problem of optimal incentive scheme design in the case of agents' joint activity.

Next, we explore how the Principal's ignorance (infeasibility of observations) of agents' actions affects the efficiency of incentives. By a natural assumption, the Principal's income function depends on the result of activity in the OS. Consider two possible cases, namely,

1. the actions of agents are observable, and the Principal motivates agents based on their actions and the result of collective activity;
2. the actions of agents are unobservable, and the incentives depend on the observed result of collective activity (exclusively).

The idea is to compare the efficiency of incentives in these cases.

Under observable actions of agents, the Principal's costs $\vartheta_1(y)$ to implement the agents' action vector $y \in A'$ constitute $\vartheta_1(y) = \sum_{i \in N} c_i(y)$, and the efficiency of incentives is $K_1 = \max_{y \in A'} \{H(Q(y)) - \vartheta_1(y)\}$ (see the previous section).

The actions of agents being unobserved, the minimum costs of the Principal $\vartheta_2(z)$ to implement the result of activity $z \in A_0$ are defined by (see (2.14) and (2.15)): $\vartheta_2(z) = \min_{y \in Y(z)} \sum_{i \in N} c_i(y)$. Accordingly, the efficiency of incentives makes up $K_2 = \max_{z \in A_0} \{H(z) - \vartheta_2(z)\}$.

The paper (Novikov and Tsvetkov 2001) argued that $K_1 = K_2$. The described phenomenon can be called the **principle of aggregation** or *the perfect aggregation theorem* for incentive models. Besides comparative efficiency estimation, the phenomenon has an extremely important methodological sense. It turns out that, under a collective incentive scheme, the Principal ensures the same level of efficiency as in the case of a corresponding individual incentive scheme!

In other words, aggregation of information by no means decreases the operational efficiency of an organizational system. This sounds somewhat paradoxically, since existing uncertainties and aggregation generally reduce the efficiency of managerial decisions. The model considered includes *perfect aggregation*. In practice, the practical interpretation is that the Principal does not care what actions are selected by the agents: they must lead to the desired result of activity under the minimum total costs. *The informational load* on the Principal goes down, yet the efficiency of incentives remains the same.

Therefore, the performed analysis yields the following conclusions. If the Principal's income depends only on the aggregated indicators of agents' activity, their usage is reasonable for agents' motivation. Even if the individual actions of agents are observed by the Principal, an incentive scheme based on these actions does not increase the efficiency of control (but definitely raises the informational load on the Principal).

Thus, the compensation principle (Novikov 2013a, c) is generalized to models with data aggregation in the following way. The minimum costs of the Principal to implement a given result of activity in an OS are defined as the minimum total costs of agents compensated by the Principal (provided that the former choose an action vector leading to this result of activity). This idea is also used in the models of team building and functioning below.

2.3 Incentives in Agents' Self-coordination

Above we have considered hierarchical two-level systems, where the upper level corresponds to a Principal and the lower level is occupied by controlled agents. Now, consider an organizational system composed of n agents located on a single hierarchical level. Our intention lies in analyzing the capabilities of their coordinated interaction within the game-theoretic model.

In the general case, the issue regarding the choice of agents with independent decision-making based on their individual interests remains open. If there exists a dominant strategy equilibrium (DSE), then researchers often believe that agents choose exactly dominant strategies (Novikov 2013c). A DSE being absent, a common approach is to consider a Nash equilibrium as the state of a system. Imagine that several Nash equilibria take place and some of them appear undominated by other equilibria in the Pareto sense. In such conditions, agents are assumed to choose undominated equilibria.

Concerning their practical interpretations, the concepts of dominant strategy equilibria and Nash equilibria reflect the individual rationality of agents' behavior. In the former case, there exists an optimal action independent from an opponents' action profile, whereas in the latter case a unilateral deviation of any agent becomes nonbeneficial to it if all other agents follow the equilibrium actions (Myerson 1991; Novikov 2013c).

Unfortunately, in many situations individual rationality contradicts collective rationality (formally described by the Pareto axiom, i.e., a hypothesis that the state of a system must be efficient). This conflict consists in the following. On the one hand, the set of individually rational actions (e.g., a DSE or Nash equilibrium) can be dominated by another set of actions (where all agents obtain not smaller payoffs and some agents gain strictly more). On the other hand, there may be several collectively rational (Pareto efficient) actions, and they can be unstable against the unilateral deviations of agents (there exists an agent who increases its payoff via an appropriate variation of the action). Furthermore, in cooperative games such behavior can be demonstrated by coalitions (groups of agents) and the solution of a game must enjoy stability against these deviations. Thus, the correlation of individual and collective rationality forms a key problem in game theory (see examples and references in Fudenberg and Tirole 1995; Germeier Yu 1986; Myerson 1991).

It seems intuitively clear that, if there is a best behavioral line for all agents (in comparison with individual rationality), one should design a penalty mechanism for those agents deviating from this line. Such "penalization" can be performed by agents or a meta-player (a Principal). Note that a penalty mechanism turns out "external" to agents and is often dictated, e.g., by a Principal, or represents the subject of their negotiation (an extension of the game Germeier Yu 1986). Let us clarify this statement.

Suppose that several plays of a game are organized successively. By varying their actions, agents can penalize an agent in the current or future periods for its deviation in the preceding period. Such strategies are constructed in theory of repetitive games (Fudenberg and Tirole 1995). The things seem more complicated in the static mode (a single-play game), as the threat of future penalization by partners becomes pointless.

However, the threat of penalization acquires a definite sense in the static mode if there is a third (external) subject with powers of authority, e.g., a Principal. By applying control actions, viz., stimulating agents, imposing penalties, etc., the Principal can make nonbeneficial their unilateral deviation from a collective optimum. In other words, the Principal guarantees the Nash stability of a Pareto optimal strategy. This is the first thing the Principal suggests to agents. The second effect from the Principal consists in reduced data processing by agents. Really, consider, e.g., Nash equilibrium "evaluation"; each agent must know the goal functions and admissible sets of all agents so that, again, each agent can independently solve the system of inequalities defining a Nash equilibrium. Now, assume that we incorporate the Principal into the system. Being aware of all relevant information on each agent (the mutual awareness of agents becomes unnecessary), the Principal easily calculates all equilibria, designs an incentive-compatible system of the so-called "side payments" (see the description of the incentive problem above) and provide the corresponding information to agents. The stated control problem can be solved by an agent (the initiator of interests' coordination), or agents simply choose their representative. An alternative is when agents invite a third party for interests' coordination (an analyst, a consulting company, etc.).

Consider the case without the explicit presence of a Principal and describe the corresponding problem of horizontal interests' coordination.

Fix a vector $x \in A'$ and study the following system of side payments:

$$\sigma_{ij}(x, y_j) = \begin{cases} s_{ij}(x), & y_j = x_j \\ 0, & y_j \neq x_j \end{cases}, i, j \in N. \tag{2.16}$$

Here $\sigma_{ij}(\cdot) \geq 0$ denotes the payment of agent i to agent j ($i, j \in N$). Naturally, $\forall\, x \in A'$: $s_{ii}(x) = 0$, i.e., an agent pays itself nothing, $i \in N$. Hence, the system of payments (2.16) is defined by $(n^2 - n)$ numbers.

Now, express the condition that x forms a Nash equilibrium in the agents' game:

$$\sum_{k \in N} s_{ki}(x) \geq \max_{y_i \in A_i} f_i(y_i, x_{-i}) - f_i(x), i \in N. \tag{2.17}$$

In this formula, we believe that any agent pays other agents regardless of its own action.

Note that our analysis ignores an important issue as follows. How can one force agents to pay each other under the assumption that an appropriate compulsion mechanism does exist? (otherwise, a certain agent may disagree to pay other agents after receipt of their payments). A possible compulsion mechanism is to introduce a Principal in the system–a higher-level representative in the hierarchy with the power of imposing penalties on agents refusing to fulfill their obligations. Such behavior (opportunistic behavior) is explored in contract theory (Hart and Holmstrom 1987; Laffont and Martimort 2001; Salanie 2005).

Suppose that there exists a vector $u = (u_1, u_2, \ldots, u_n)$ restricting agents' payoffs–the so-called *reserved utility*. The quantity u_i specifies the guaranteed payoff of agent i from participation in an organizational system, $i \in N$. Reserved utility can be evaluated from a Nash equilibrium in the absence of interests' coordination: $u_i = f_i(y^N)$, or as the guaranteed payoff $u_i = \max_{y_i \in A_i} \min_{y_{-i} \in A_{-i}} f_i(y_i, y_{-i})$, or by another method.

Then the individual rationality condition of agent i (the condition of its participation in the interests' coordination procedure) can be formulated as

$$f_i(x) + \sum_{k \in N} s_{ki}(x) - \sum_{j \in N} s_{ij}(x) \geq u_i, i \in N. \tag{2.18}$$

Therefore, agent's payoff in a new equilibrium must be not smaller than its reserved utility after the payments of all agents.

And finally, sum up inequalities (2.18) over all agents (in this case, "internal" payments get compensated) to arrive at the following result. **By side payments, one can pass to a system state, where the total payoff of all participants is not less than in the initial state**.

The set of incentive-compatible plans in this model comprises plans such that there exists a system of side payments (2.16) meeting the conditions (2.17) and (2.18):

$$S = \{x \in A' \mid \exists s_{ij}(x), i, j \in N : (2.17), (2.18)\}. \tag{2.19}$$

Consider an example. *Linear* organizational systems are the ones, where the goal function of each agent linearly depends on the strategies of all agents:

$$H_i(y) = a_{i0} + \sum_{j \in N} \alpha_{ij} y_j. \tag{2.20}$$

The quantities $\{\alpha_{ij}\}$ and $\{\alpha_{i0}\}$ are known constants and, without loss of generality, let A_i = [0; 1], $i \in N$. In linear systems, each agent has the dominant strategy y_i^D = Sign(α_{ii}), where Sign(z) = $\begin{cases} 1, & z \geq 0 \\ 0, & z < 0 \end{cases}$.

Denote $\beta_j = \sum_{i \in N} \alpha_{ij}$, $\beta_0 = \sum_{i \in N} \alpha_{i0}$. Then the total payoff of all agents makes up

$$\sum(y) = \beta_0 + \sum_{j \in N} \beta_j y_j. \tag{2.21}$$

The following action of agent i is Pareto optimal and maximizes the expression (2.21):

$$y_i^P = \mathrm{Sign}(\beta_i), i \in N. \tag{2.22}$$

If $\forall$ $i \in N$: Sign(α_{ii}) = Sign(β_i), then the DSE enjoys Pareto efficiency. If $\exists$ $i \in N$: Sign(α_{ii}) $\neq$ Sign(β_i), then interests' coordination is required for agents.

We endeavor to establish conditions when the *plan* y^P becomes incentive-compatible, i.e., there exists a corresponding system of agents' mutual payments satisfying inequalities (2.17) and (2.18). For simplicity, set n = 2:

$$f_1(y) = y_1 - 2y_2, f_2(y) = -3y_1 + y_2.$$

The dominant strategy of each agent is choosing the unit action: y^D = (1; 1). And the agents' payoffs constitute $f_1(y^D)$ = −1, $f_2(y^D)$ = −2.

The maximum sum of the goal functions is achieved under the action vector y^P = (0; 0) which leads to the agents' payoffs $f_1(y^P)$ = $f_2(y^P)$ = 0.

Zero actions are beneficial to both agents (such choice dominates the DSE in the Pareto sense). However, this is not a Nash equilibrium, as any agent easily increases its own payoff by a nonzero action (simultaneously decreasing the opponents' payoff).

As reserved utility, choose the agent's payoff in the DSE: $u_i = f_i(y^D)$, i = 1, 2.

Then the system of inequalities (2.17) acquires the form

$$s_{12}\left(y^P\right) \geq 1, s_{21}\left(y^P\right) \geq 1;$$

and the system of inequalities 2.18) gets reduced to

$$s_{12}\left(y^P\right) - s_{21}\left(y^P\right) \geq -2, s_{21}\left(y^P\right) - s_{12}\left(y^P\right) \geq -1.$$

The sum of the mutual payments of agents is minimized under

$$s_{12}(y^P) = 1, s_{21}(y^P) = 1.$$

Interestingly, each agent pays the opponent exactly the amount received from it: in fact, payments are pointless, the only important thing is the agreement about the conditions of such payments!

On the one hand, the difference $\Sigma(y^P) - \Sigma(y^D) = 3$ can be treated as the effect owing to interests' coordination. On the other hand, this quantity estimates the maximum beneficial payments of agents to an external arbitrator (e.g., a Principal) so that it establishes and guarantees observance of game rules.

Consequently, **the necessity and feasibility of efficient interests' coordination among interacting agents explain hierarchies' occurrence in organizational systems.**

2.4 Problems of Agents' Preferences Identification

Motivation represents a key function of organizational control and consists in stimulating controlled subjects to choose actions desired by a Principal. Competent selection of an incentive scheme calls for predicting possible responses of subordinates to certain variations in the forms and amounts of wages. Accordingly, it is desired to know its preferences regarding these factors. Description of controlled subjects (*agents*) within motivation problems and incentive problems (Armstrong 2000; Novikov 2013c) lies, first, in defining their preferences regarding the forms and amounts of wages, viz., possible responses (variations in *labor supply*) to variations in an incentive scheme (Novikov 2010).

Rather complete (theoretical and experimental) investigations of labor demand and supply have been conducted mostly in countries with advanced market economy. According to the modern circumstances in Russia, the experience and data of domestic research seem insufficient, whereas unadapted usage of foreign experience appears unreasonable. On the other hand, the experimental studies of labor supply performed by foreign researchers *par excellance* proceed from analysis of actual data on incomes and working time acquired via polling (e.g., Panel Study of Income Dynamics). The average curve of labor supply is constructed using actual earned incomes gained by respondents and their actual working time. Applying such approach to Russian economy would yield a paradoxical result: labor supply (measured as the actual working time) is almost independent from wages (see the discussion in Myerson 1982). Furthermore, if we are interested in the motivational role of financial incentives (the influence on an agent depending on other primary characteristics such as sex, age, education level, etc.), then averaged indices may appreciably distort "the real picture." Notably, panel or other "averaged" statistical data make it impossible to explore the *individual strategies of labor supply* comprehended as the relationship between the desired working time of an individual and a wage system and its parameters (wage rates, etc.).

Taking into account the above grounds, the book (Novikov 2010) focused on individual questioning: a respondent models its behavior in different conditions and fills an electronic questionnaire. This approach seems advantageous, as it allows drawing the labor supply curve averaged over actual data (including comparison with the results of other types of questioning) and examining[4] the relationship between individual preferences and the forms and amounts of wage. That is, the approach enables analyzing the relationship between the individual strategies of labor supply and the individual characteristics of respondents.

Suppose that the strategy of an agent as the labor supply side is the choice of working time under a given wage and working conditions. For simplicity, we believe that the only alternative to working time is leisure time.[5] Hence, labor supply appears equivalent to leisure demand (Ashenfelter and Layard 1986; Mas-Colell et al. 1995). In addition, assume that the maximum admissible working time in a day makes up $T = 16$ h (at least, 8 h must be allocated to sleeping, eating, etc.), i.e., *working time* $\tau \in [0; 16]$. If t designates *free time* (leisure activities), then $\tau + t = T$. Again, for the sake of simplified exposition, we hypothesize that the total income is proportional to working time (if there is no clear provision for the opposite). This means that labor market admits only proportional incentive schemes (time wages) with fixed wage rates independent from the total working time and other sources of income are absent. All results can be generalized to the case of arbitrary wage systems, see (Novikov 2013c) for details.

Under the stated assumptions, the alternative costs of 1-h leisure equal the wage rate (and vice versa)–the extra earnings owing to working within this period of time. Let us analyze agent's behavior on labor market, i.e., its preferences in the "labor-leisure" dilemma. Here labor supply is characterized by agent's desired working time.

According to labor economics, individual labor supply is defined by the income effect and the substitution effect (Ashenfelter and Layard 1986; Mas-Colell et al. 1995).

The income effect gets manifested in the following. For a fixed *wage rate* α (wage per unit time), the desired working time goes down as the total income grows. Imagine that an agent aims at maintaining a certain level of the total income. Then the income effect reduces the desired working time in case of increasing the wage rate. And conversely, for maintaining a fixed level of the total income, an agent has to raise working time under a reduced wage rate.

[4] No doubt, it may happen that the answers of respondents mismatch the reality: in real-life conditions, respondents can choose other actions than they report during questioning. A separate issue concerns the truthfulness of their answers. Being active, respondents can demonstrate strategic behavior and manipulate information. For instance, if agents know that managerial decisions affecting their interests will be made based on their answers, they can report untrue information to guarantee most beneficial decisions. Analysis of deliberate and purposeful manipulation of procedures makes the subject of separate (perhaps, extremely promising) research, but goes beyond the scope of this work.

[5] This simplifying assumption eliminates from further consideration the problems of agent's decision-making on hiring, firing, job hopping and hunting, etc. Moreover, in most real situations an employee is unable to choose working time independently or selects it from a short range.

The substitution effect leads to the following. Wage rate growth increases the desired working time τ, i.e., the alternative costs of 1-h leisure go up and an agent prefers working more time.

Thus, under the income effect, an agent responds to wage rate growth by reducing labor supply; domination of the substitution effect brings to labor supply increase.

Suppose that the preferences of a given agent on the set of admissible incomes and working time (or leisure time) are described by its *utility function* $u(q, t)$. Here q denotes the total (e.g., daily, monthly, etc.) *income*, and $t \in [0; T]$ specifies leisure time.

Further exposition focuses on the case of a fixed wage rate. If unearned incomes are absent, working time τ yields the wage $q(\alpha) = \alpha\ \tau(\alpha)$ to the agent.

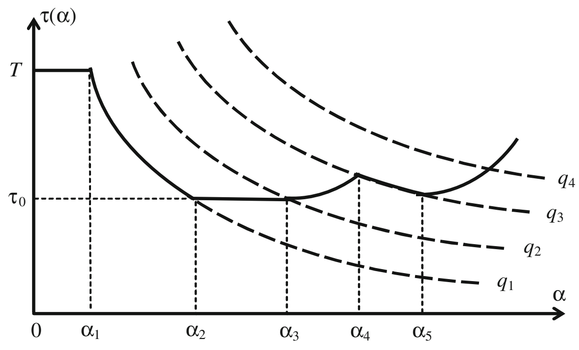
Assume that agent's preferences are defined as follows. First, the agent has the right to choose any daily working time under a fixed time wage. Second, we know the relationship between the desired working time τ and the wage rate α. Which decision rule is adopted by the agent in such choice conditions? Agent's decision-making principle (reflected by the function τ(α)) will be called its *strategy*.

The list of possible strategies includes income maximization, free time maximization, ensuring daily working time above a certain threshold, and so on (Novikov 2010). Consider the following hypothetical example illustrated by Fig. 2.1.

On the plane (α, τ(α)), draw the isoquant curves corresponding to the total income $q_1 \le q_2 \le q_3 \le q_4$. These values can be interpreted as the subjective norms of total income. For instance, the minimum income value q_1 means the living wage, q_2 is the average income of a social group this agent belongs to, q_3 gives the total income desired by the agent at the current moment under existing external conditions, q_4 indicates the total desired income unachievable under existing external conditions (as it corresponds to a higher level of welfare), and so on.

In Fig. 2.1, individual strategies are marked by heavy line. Let us analyze the characteristic segments of wage rate values. Within the segment $[0; \alpha_1]$, all available time is dedicated to working, but this yields a smaller income than q_1. The free time maximization strategy dominates on the segment $[\alpha_1; \alpha_2]$ under a constant

Fig. 2.1 A combination of individual strategies



income q_1 (the income effect takes place). The segment [α_2; α_3] is remarkable for additional "activation" of the strategy "working not less than τ_0 h daily." Having reached the income level q_2, the agent strives for increasing the total income to the new "norm" q_3 following wage rate growth. In other words, the curve goes up on the segment [α_3; α_4] (the substitution effect), and within the segment [α_4; α_5] the agent is quite satisfied with its new total income (the curve moves along the isoquant curve q_3). As wage rate exceeds α_5, the agent observes the feasibility of achieving a higher level of welfare (the curve again demonstrates growth, which answers the substitution effect). Interestingly, the curve in Fig. 2.1 meets *the income monotonicity condition* (Novikov 2010): as wage rate raises, the agent prefers working time such that its total income is not decreasing.

The book (Novikov 2010) described the results of verification experiments for the hypothesis on the existence of the following agents' typology. According to the hypothesis, the types of labor supply agents depend on their response to wage rate variations. The experiment yielded 5541 correctly filled questionnaires. The author acquired information corresponding to the following indicators:

- *primary social indicators*: sex, age, family status, family structure (the number of co-residing dependents–children and pensioners), education level, current learning (type of educational institution), position at the principal place of business;
- *primary economic indicators*: the actual total income of a person at the principal place of business, the actual daily mean working time at the principal place of business, the actual average per capita income of a family (taking into account all working members), the minimum monthly wage for which a respondent is willing to work daily for a given time (from 1 to 16 h), the desired daily working time under a given wage rate within a defined range.

Different individual labor supply strategies lead to certain relationships between the desired working time τ and the wage rate α. Experimental data testify to an important feature: by analyzing the real curves $\tau(\alpha)$ and performing expertise (!), one can identify five qualitatively different types of agents (the corresponding actual data illustrating this thesis are provided below):

- *type 1* the desired working time is independent or almost independent from the wage rate starting from some threshold α^0 (an agent disagrees to work under smaller wage rates), see Fig. 2.2;
- *type 2* the desired working time increases monotonically with the wage rate exceeding the "minimum" threshold α^0, see Fig. 2.3;
- *type 3* the desired working time monotonically decreases with the wage rate exceeding the "minimum" threshold α^0, see Fig. 2.4;
- *type 4* the desired working time increases with the wage rate exceeding the "minimum" threshold α^0, and decreases for $\alpha \geq \alpha_{max}$, see Fig. 2.5;
- *type 5* the desired working time has nontrivial behavior with wage rate variation (e.g., possesses a minimum or even several minima, etc.), see Fig. 2.6.

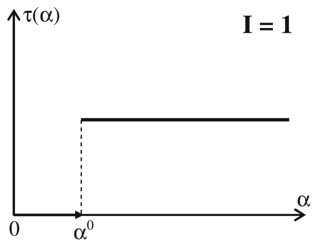


Fig. 2.2 Type 1 of agents

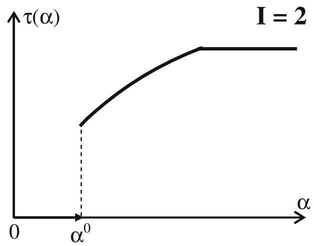


Fig. 2.3 Type 2 of agents

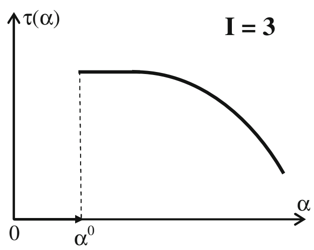


Fig. 2.4 Type 3 of agents

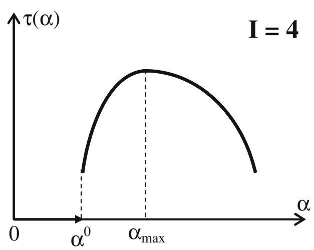


Fig. 2.5 Type 4 of agents

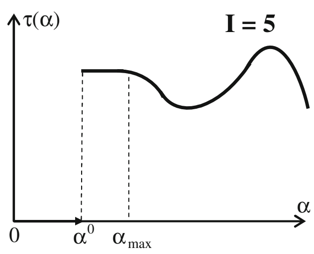
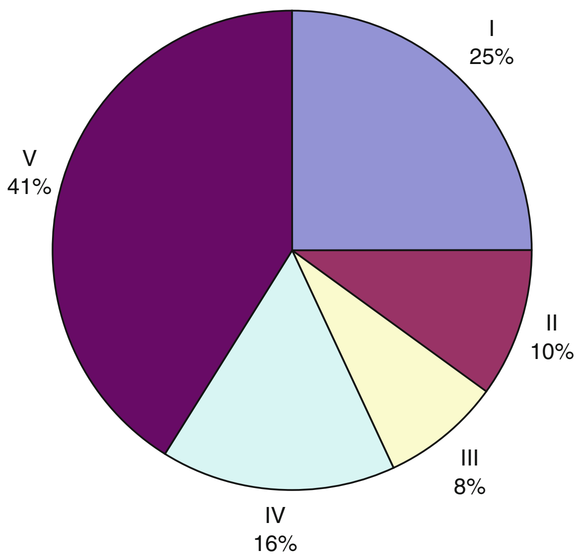


Fig. 2.6 Type 5 of agents

Fig. 2.7 The distribution of respondents by their types (I)



The results of this expert classification fully agree with the results of automatic classification of labor supply curves obtained in Novikov (2010).

The corresponding indicator *I* which reflects agent's type (predetermines its individual labor supply strategy) and takes values {1; 2; 3; 4; 5} is called **the type of individual labor supply strategies** or simply *agent's type*.

The suggested typology of agents was tested (Novikov 2010) using the results of a similar questioning of more than 400 respondents in 1999. Almost the same sample size was selected for the study performed in 2003. Recall that in 2009 the sample size exceeded 5000 respondents. The time-invariable distribution of respondents by their types is demonstrated in Fig. 2.7.

Therefore, **the existence of five different "type" values allows claiming the presence of five general types of agents, which are defined by common classes of their individual labor supply strategies**. The experimentally established five types of agents can be described from the viewpoint of individual labor supply strategies introduced in Novikov (2010) based on a series of hypotheses. Moreover, the book (Novikov 2010) posed and solved the problem of finding statistically significant relationships between the primary characteristics of agents and the types of their individual labor supply strategies.

It is possible to explain the existence of the five types of individual labor supply strategies in different ways. By proceeding from agent's decision-making criteria (income maximization and free time maximization), we obtain that type 1 corresponds to the following situation. An agent works a common fixed time without income/free time maximization. Next, type 2 is when income maximization dominates free time maximization, type 3 describes the opposite case. If an agent makes decisions based on both criteria equally, we observe type 4 or type 5. Choosing other grounds for agent's decision-making or accepting some typology of its personal qualities, one can suggest other interpretations for the types of individual behavior strategies.

In conclusion, we discuss how the results of such experiments may serve for identification of the above game-theoretic incentive models.

The knowledge of the relationship $\tau(\alpha)$ allows constructing the functions $\alpha(\tau)$, $q(\alpha) = \alpha\ \tau(\alpha)$ and $q(\tau) = \tau\ \alpha(\tau)$. Imagine that the agent's action is the choice of the working time $y = \tau$ (in this case, the incentive $\sigma(\tau)$ and the Principal's income $H(\tau)$ both depend only on its working time). Then it is necessary to evaluate the optimal working time from the Principal's viewpoint: $\tau^* = \arg \max_{\tau \in [0;T]} \{H(\tau) - q(\tau)\}$. If agent's working time has a more complicated dependence on its action, e.g., $y = G(\tau)$ (but the Principal and an operations' researcher know it), then the minimum stimulation costs of implementing the action y make up $\upsilon(y) = \min_{\tau \in \{\tau \geq 0 \mid G(\tau) = y\}} q(\tau)$. The optimal implementable action y^* is the action maximizing the Principal's goal function, i.e., the difference between the Principal's income function $H(y)$ and the minimum stimulation costs: $y^* = \arg \max_{y \in A} \{H(y) - \upsilon(y)\}$.

Recall that the game-theoretic framework characterizes agent's preferences (see above) by its goal function $f(\cdot)$, i.e., the difference between its incentive and costs: $f(y, \sigma) = \sigma(y) - c(y)$, where $y \in A$ denotes agent's action. In macroeconomic models, agent's preferences are specified by a utility function $u(q, t)$ defined on the "income × free time" set or by the relationships $\tau(\alpha)$ (the desired working time τ as a function of the wage rate α) or $\alpha(\tau)$ (the minimum wage rate as a function of the working time).

We have emphasized that the variables of the utility function and the goal function possess a simple interconnection: $y \leftrightarrow \tau$, $\tau = T - t$, $\sigma \leftrightarrow q$, $A \leftrightarrow [0; T]$. Under the proportional incentive scheme, we have $q(\tau) = \alpha\ \tau$ (in the general case, $q(\tau) = \sigma(\tau)$).

Establishing interconnections between different models implies exploring the following problem. Information on the individual preferences is specified in one of the four ways (see Novikov 2010 and references therein):

I. We know the utility function $u(q, t)$;
II. We know the minimum time wage rate $\alpha(\tau)$ for which an agent agrees to work τ h;
III. We know the relationship $\tau(\alpha)$ between the desired daily working time τ and the time wage rate α;
IV. We know the goal function $f(\tau, \sigma)$.

For each of the four descriptions (under a given relationship), is it possible to "restore" other relationships and how should this be done? As a matter of fact, solution of this problem was introduced in Novikov (2010).

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Chapter 3
Optimal Organizational Structures for Change Management in Production

Mikhail Goubko

Abstract We consider a problem of a rational organizational structure for change management support being an important aspect of the strategic management process in a firm. We combine recent theoretical findings with experience in strategic consulting to suggest mathematical models of an organizational structure for change management based on a formal representation of a strategy of the firm and of available labor resources. The model of managers' interactions employs an idea of linear duplication of efforts. The problem of an optimal organizational structure is reduced to an extremely complex mixed optimization problem. Then we attack a problem of an optimal organizational form (functional vs. divisional vs. matrix) for a special case of identical and "symmetric" projects of strategic development. We find span of control to be constant across the levels of an optimal functional, divisional, and matrix hierarchy, and directly compare costs of optimal organizational forms. A matrix organizational structure appears to be optimal when the number of projects and managerial functions is large enough, while matrix and divisional organizations are robust with respect to the project count increase.

3.1 Introduction

In modern world manufacturing companies are involved in a process of continuous change. If a company does not change, it loses the global competition and perishes in short time.

Importance of *change management* processes is universally recognized by top managers both in manufacturing and in service industries. Contemporary consulting practices help companies to reveal their strengths and develop competitive positions.

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These practices have been in great favor in the end of 2000s in the course of a global economy crisis. Companies, which conceived the *crisis as a* "*window of opportunities*", managed to concentrate their efforts on aggressive forced development and capture the sensitive market share. Critical activities of the strategic development process included company re-structuring, and also innovations in manufacturing and management (Balashov et al. 2009).

The cycle "planning-organization-incentives-controlling" demonstrates a typical sequence of managerial activities in business administration (Burkov et al. 2013). Typically recommendations of strategic management consultants concern the planning stage, e.g., company's strategy statement, its decompositions into strategic goals, brainstorming and idea reduction support, strategic development project planning, and construction of metrics to evaluate the progress of implementation of the strategic development plan.

These metrics then used in incentive schemes for employees involved in projects of strategic development, those aligning the employees' interests with company's strategic goals (Novikov 2013). They also form the basis of the controlling procedures and reports employed at the final stage of the management cycle.

At the same time, the "*organization*" *stage* of the strategic management process is much less developed in popular business reengineering techniques. Many authors underline the role of special personnel training for change management support, importance of the process of building a team, which will guide and drive the process of strategic development, and, finally, the demand for specialized organizational structures to support strategic management in a company. In practice, formation of an organizational structure of strategic management support typically involves transition from a linear (functional) organizational structure to modern project-oriented structures (the matrix or the divisional structure) (Balashov et al. 2009).

Although many *formal models of company's optimal structure* were studied in the theory of the firm (see the survey in Goubko 2008), there is still lack of applied routines for rational organizational structure formation support. The theory must supply this routine with a formal model of the project-oriented organizational structure and with efficient structure optimization techniques. Therefore, development of such models and techniques is a great challenge for the contemporary management science and operations research.

Below in this chapter we introduce the mathematical model of an organizational structure for strategic management, set formally the problem of *structure optimization*, and discuss the complications of modeling and optimization processes.

In general, the problem of an optimal structure reduces to the complex problem of *discrete optimization*. Even finding the approximate solution can be very time-consuming. We find a closed-form solution for the optimal structure problem in the special case of identical symmetric projects of strategic development, which can be thought of as a first-order approximation to the general framework, and discuss the policy recommendations derived from the expressions for the shape of the optimal organizational structure.

3.2 Model

3.2.1 *Projects and Activities*

A relevant mathematical model of an organizational structure for strategic management must capture major factors influencing structure formation. The model presented below, on the one hand, is inspired by the model of responsibility delegation in multi-level hierarchies suggested in Mishin (2007b, 2011) and, on the other hand, condenses the experience of management consulting projects, where numerous development-oriented organizational structures were constructed (Balashov et al. 2009).

Let us define the source data our model is based upon.

The notion of a *strategic project* lies in the heart of the development process in a company. A strategic project is a project of enterprise performance improvement, which is chosen in the course of strategy decomposition process to maximize performance gain under the limited resources. The duration of a strategic project varies from several months (for high-priority management performance-boosting projects) up to several years (manufacturing retooling, vertical and horizontal integration). Let $L = \{1, \ldots, l\}$ be the set of projects enumerated in some order.

Execution of any project requires managerial efforts. For every project $i \in L$ define the list P_i of *managerial activity types* demanded by the administration process of this project. Then the intensity (measured in labor hours) is estimated for each activity type. Managerial activity type can be thought of as a consolidated *competence* (as understood by human relations staff) required for the successful project management.

Examples of such competences elicited from duty instructions of a workshop chief include "design of the production planning process"; "enforcement of production plan execution"; "planning, maintaining, and controlling speed-up activities", "labor and raw material rates calculation", etc.

In the other words, managerial activity types from the list P_i represent some taxonomy of any activity a manager spends his or her working time on when administering the ith project. Along with "external" activities, which drive directly the project outcome, P_i typically includes special "internal" activities, generated with processes inside a management hierarchy (reporting to a superior, controlling subordinated managers, meetings, etc.). Different lists may share some activity types (which is a typical situation for internal activity types).

Let us join these lists, remove the duplicates and obtain the consolidated *set of managerial activities* $P = \bigcup_{i \in L} P_i = \{1, \ldots, p\}$. Some of these activities are project-specific, while the others are required by all projects.

From the analysis of detailed business plans for all projects we derive a p-dimensional vector $x = (x^j)_{j=1,\ldots,p}$ of demand for each managerial activity $j = 1, \ldots, p$. The jth component x^j of the vector x (the upper index here and elsewhere stands for the activity number) is the total workload (e.g., in working days per year) of the jth managerial activity, which is needed for the success of all

l projects. Demand for internal activities is equal to zero (the internal demand arises later, after the management hierarchy is formed, since the value of demand for internal activities depends, in general, upon the organizational structure). Below, when explaining the mechanism of *duplication*, we introduce the step-by-step process of designing the demand for internal activities.

It is clear that, in general, the workload of a task depends on the skills of an employee this task is assigned to. Nevertheless, when planning an organizational structure, we adopt "standardized" workloads, which later will be adjusted to account for skills of a responsible employee.

The demand for managerial activities is considered to be constant in time, since an organizational hierarchy is supposed to be designed once, in the very beginning of the strategy implementation period (a typical period is 3 years, or up to 1 year when fast changes are considered), and is never changed until the end of the planned period. At the end of the period the strategy is revised, the project portfolio is corrected, both project plans and demands are tuned, and the hierarchy is rebuilt. We postpone several words on the organization restructuring to the fourth section of the chapter.

The vector of the managerial activity demand is the first important piece of source data of the considered model of an organizational structure for change management. The vector of demand provides a quantitative alignment of the model to the official strategy of development in a considered company. It is difference in demand vectors makes different companies and, hence, different organizational structures.

3.2.2 Employees and Hierarchies

All organizations consist of employees, and an efficient management team is a necessary condition for successive change. It is competences of employees, which determine their responsibilities, their interaction and, finally, the shape of a rational management hierarchy in a company. Therefore, characterizing the management team and skills of its members is a necessary element of the model of a management hierarchy.

Let $W = \{1, \ldots, n\}$ be the set of n employees, which, in principle, can be assigned to one or another position in a hierarchy of change management. Endow each employee $w \in W$ with a *managerial skills profile*—a p-dimensional vector $r_w = (r_w^i)_{i=1,\ldots,p}$. Its component r_w^i is an efficiency coefficient of the ith managerial activity executed by the employee w. If $r_w^i = 1$, then the employee w has moderate skill (experience, performance) in the ith type of managerial activity. This is the performance supposed by a business plan, and it is on this performance we based an estimate x_i of demand for the managerial activity.

Below it will be convenient to think that the higher value of r_w^i corresponds to the lower skill level for the ith managerial activity. The value of r_w^i is the ratio of time the employee w needs to execute tasks connected with the ith activity to the execution time by the employee with moderate skills.[1]

The managerial skills profile also includes the performance ratios for internal managerial activities arising in multi-level management hierarchies. The examples of internal skills include the personal autonomy of decision-making, ability to mutual adjustment (see Minzberg 1983), which makes possible horizontal bonds both inside a department and between departments in an organizational structure.

Below we will also use an alternative notation for the skills profile in the form of $p \times p$ matrix $R_w = \mathrm{diag}(r_w)$ where diagonal cells store the components of managerial skills, while the other cells being zero.

A yet another important parameter is the *cost* c_w of the employee w, which is employee's fixed wage excluding position-dependent bonuses.

Therefore, the vector of demand for managerial activities binds the model to company's strategic goals, while the set W of employees along with their skills profiles binds the model to available resources for management hierarchy construction. Together these factors determine a unique organizational structure for change management in a company.

To determine an organizational structure we need to fix:

1. The set $M = \{1, \ldots, q\}$ of (arbitrary indexed) *managerial positions* in a strategic management hierarchy. The examples are "chief financial officer", "project manager", "process engineer", "researcher", etc.
2. *Responsibility areas*—a collection *of* p-dimensional vectors $y_m = (y_m^i)_{i=1,\ldots,p}$, each describing the authority delegated to the position $m \in M$. The component y_m^i of this vector corresponds to the volume of the ith managerial activity a position m is in charge of. In particular, the vector y_m determines whether the position m is a *functional* position (covers many projects and one or two activity types, such as finance or technology management), a *project-oriented* position (covers many activities inside a single project), or a *mixed* position (several activities and several projects of strategic development).
3. *The relation* $E \subseteq M \times M$, which determines subordination of positions in a management hierarchy: $(m, m) \in E$ if and only if the manager m reports to (is subordinated to) the manager m'. We also keep the same notation $E = (e_{mm'})$ for the square $q \times q$ matrix whose element $e_{mm'}$ is equal to unity when the position m is subordinated to the position m' and zero otherwise. In general, a manager may have several superiors in case of *common agency* (*multiple subordination*).
4. An injective function $\pi : M \to W$ defining *assignment* of employees to positions (so that $\pi(m)$ is an employee assigned to the position $m \in M$ in an organizational structure.)

[1]Besides the volume, the *quality* is an important characteristic of the executed task, but below we suppose the task to be performed only with constant quality. Quality difference can be accounted for by assigning different managerial activities to the same sort of tasks, when executed with different quality.

The formally defined organizational structure (i.e., a list $H = \langle M, (y_m)_{m \in M}, E, \pi(\cdot) \rangle$) below is referred to as a *hierarchy*.

3.2.3 Duplication and Manager Costs

A complex management hierarchy inevitably results in some costs being the result of efforts spent to align and coordinate managers' decisions in an organization. These *coordination costs* can be accounted in the model using the notion of efforts' *duplication*, when decisions and actions of a manager induce the response from the other managers (typically, his or her subordinates or superiors) in a hierarchy.

To define formally effort duplication we employ the *linear duplication model* suggested in Mishin (2011). The level of effort duplication in this model is determined by virtue of *duplication coefficients* d_{mm}^{ji}. It is supposed that if some volume y_m^i of the ith managerial activity is delegated to a position $m \in M$ in some hierarchy H, then for a manager assigned to this position to execute the task y_m^i, he or she has to execute also the volume $d_{mm}^{ji} y_m^i$ of the jth type of activity. Moreover, every unit of efforts of the ith type gives rise to some additional workload $d_{m'm}^{ji}$ of the jth activity type for another position $m' \in M$ in a hierarchy.

For instance, any work done by a manager gives rise to some control actions by his or her superior. When reporting to the superior, the time is spent both by a manager and by a superior.

For a fixed position $m \in M$, duplication coefficients $d_{m'm}^{ji}$ depend on where this position is located inside a hierarchy H, but in our notation we omit this dependency for short.

For each pair m, $m' \in M$ define the square $p \times p$ *duplication matrix* $D_{m'm} = (d_{m'm}^{ji})$. All interactions between the position $m \in M$ and the rest of a hierarchy are determined by the collection of matrices $D_{m'm}$, $m' \in M$, where the matrix D_{mm} determines duplication of managerial efforts for the position m, i.e., the volume of auxiliary tasks of different types, which have to be accomplished to execute successively a unit of the ith task.

Hence, the vector z_m of *workload* for a position m adds up from external managerial activities delegated to this position, and from *duplicated* efforts induced by activities performed by all managers (including m) at their positions in a hierarchy: $z_m = \sum_{m' \in M} D_{mm'} y_{m'}$. Diagonal elements of a duplication matrix can differ from unity due to inevitable performance degradation depending upon the place of the position inside a hierarchy and on the shape of a hierarchy as a whole (for example, due to the *loss of control* (Williamson 1967).

If an employee $w \in W$ is assigned to some position $m \in M$, his or her vector of workload z_{wm} is defined as a product of the vector of workload z_m of the position m to the matrix R_w of the employee's skills profile. Therefore,

$$z_{wm} = R_w z_m = R_w \sum\nolimits_{m' \in M} D_{mm'} y_{m'}.$$

The workload for all activity types is measured in hours per year, therefore, the total workload t_w^m of an employee w assigned to a position m is calculated as a sum of his or her workload vector components: $t_{wm} = \sum\nolimits_{i \in P} (z_{wm})^i = \mathbf{1}^T z_{wm}$, where $\mathbf{1}$ is a p-dimensional column with all components being equal to unity.

A hierarchy is called *feasible*, when the following conditions hold.

1. The total responsibility delegated to hierarchy positions covers the demand for every managerial activity, i.e., the vector $y = \sum\nolimits_{m \in M} y_m$ of total delegated responsibility is component-wise greater than or equal the vector x of demand for managerial activities.
2. *The total workload* t_w^m of the employee $w = \pi(m)$ assigned to any position m does not exceed a limit, which is sometimes called *productivity norm* (for instance, productivity norm can limit the total workload of any employee to 250 working days per year).

An feasible hierarchy assures achievement of company's strategic goals with available labor resources. For a fixed set L of l projects, a corresponding vector x of demand for managerial activities, and a management team W with given skill profiles R_w, $w \in W$, define $\Omega(x, W)$—a set of feasible hierarchies.

3.2.4 Hierarchy Optimization Problem

We reduce the problem of formation of an organizational structure for change management to the following mixed optimization problem: for the given source data (a set L of projects, a vector x of demand for managerial activities, management team W with skills profiles R_w, $w \in W$) find an feasible hierarchy H^* of minimal cost (total cost of employees assigned to positions in a hierarchy), i.e., find

$$H^* \in \operatorname{Arg} \min_{H \in \Omega(x,W)} \sum_{m \in M} c_{\pi(m)}.$$

To build a feasible hierarchy we need to choose the number q of positions (and, consequently, the set of positions M), fill the subordination relation E (i.e., determine mutual subordination of positions), assign a manager $\pi(m)$ to each position $m \in M$, and, finally, calculate such a responsibility distribution $(y_m)_{m \in M}$ that the demand is satisfied and productivity norm is exceeded by neither of the managers (with account to duplication and employee's skills profile).

Note that without duplication matrices the problem in hand reduces to the standard assignment problem. Content of duplication matrices reflects internal laws and mechanisms of hierarchical structure functioning, and construction and identification of duplication matrices appears to be the main task in the considered model of organizational structure formation.

A general routine for duplication matrices design and tuning is a subject of a long-term research program. Below we study in detail a comparatively simple case of *identical symmetric* projects (those inducing identical demands for managerial activities). We use this special case to illustrate the roadmap of problem setting and then derive a closed-form solution, which allows us to make some general conclusions on an optimal hierarchy shape and features.

3.3 Identical Symmetric Projects

3.3.1 Matrix of Projects and Functions

In the previous section we reduced the problem of a rational organizational structure to the problem of an optimal hierarchical organization under linear duplication of managerial efforts. This problem was suggested and studied in Mishin (2011). In particular, it is shown in Mishin (2007b, 2011) that, in general, the problem of an optimal hierarchical organization is extremely difficult (from the computational point of view). Nowadays efficient algorithms for optimal and near-optimal hierarchies are suggested only for the special cases of the general optimization framework.

Several such special cases were considered in Mishin (2007a, 2011) In particular, in Mishin (2007a) the author considers the problem of building a management hierarchy over a collection of symmetric projects, all including the same sequence of tasks. It is assumed that the links between tasks (*project links*) require some administration for successful project implementation. It is also supposed that every task needs some coordination among projects (*functional links* exist between corresponding tasks of adjacent projects). When managers of a hierarchy under construction are limited to work either within one project or within one task (function) of several projects, it is shown in Mishin (2007a) that one of three classical organizational forms (functional, divisional, or matrix) is optimal under all combinations of parameters of the model (functional and project links intensity, skills of managers, etc.) and the optimal organizational form is found.

Yet, the model of Mishin (2007a) does not support the notion of responsibility delegation, since delegated authority is completely determined by the position of a manager in a hierarchy. Below we extend the ideas of Mishin (2007a) and include them into the theoretical framework of a linear duplication model developed in Mishin (2011). On the other hand, since innovation projects share the similar lifecycle, the case of identical projects can be seen as a first-order approach to the general model of a hierarchy of strategic management.

Consider a set $L = \{1, \ldots, l\}$ of projects, which are supposed to be identical from the point of view of management (every project demands the same set of

$F = \{1, \ldots., f\}$ of *managerial functions*). Examples of managerial functions are manufacturing planning and enforcement of plans, personnel training and team building.

Successful implementation of each function within every project requires two sorts of managerial activity: the demand for the *project-oriented activity* is equal to a, while the demand for the *function-oriented activity* is equal to b. Typical examples of a project-oriented activities are starting a task and controlling task execution time. Examples of function-oriented tasks include personnel training, site preparation, and quality assessment.

The case of *identical symmetric projects* relies on a basic assumption that demands for project-oriented and for functional activities are equal across all functions and projects. The ratio $s = a/b$ of the demand for the project activity to the demand for the functional activity becomes the most important parameter of the considered model. It determines the comparative complexity (from the managerial point of view) of intra-project interactions (how complex are interactions of participants within a project) as compared to inter-project interactions (how closely related projects of strategic development are).

Therefore, the set of managerial activities includes two distinct activity types for every function within each project, which gives $2 \cdot l \cdot f$ components to the vector of demand for managerial activity, one half of them being equal to a, and one half being equal to b. Figure 3.1 illustrates components of the demand vector.

Every circle in the figure corresponds to a certain management function within a certain project. Demands for project-oriented and for function-oriented managerial work are shown inside every circle. A row of circles forms a project, while a column of circles groups certain function across projects. We lay the obtained "matrix" of circles "horizontally" in the figure to underline that it is over this matrix an organizational structure is built.

Then we equip these $2 \cdot l \cdot f$ managerial activities with two internal activities. The $(2 \cdot l \cdot f + 1)$th activity corresponds to transferring information about all functions up and down the hierarchy, the $(2 \cdot l \cdot f + 2)$th activity corresponds to transferring project-oriented information. We talk about these activities in more detail later, when introducing a duplication matrix. Therefore, the vector x of demand for managerial activities has $p = 2 \cdot l \cdot f + 2$ components in our model.

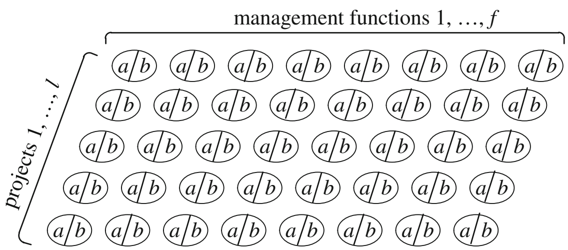


Fig. 3.1 Demand for managerial activities in identical symmetric projects

Now define the management team. In reality, it is hard to find a "universal master" (at least, at reasonable wage), and the organization design process has to account for typical limitations of labor resources. Experience of an ordinary applicant is limited to one or several functions of management, or to a single subject area (the project, in terms of the considered model). Only the most experienced employees can work as managers at higher levels of a hierarchy, coordinating project portfolios or many management functions across all projects.

3.3.2 Standard Organizational Forms

Therefore, the assumptions presented below reflect the idea of *specialization* of managerial work. It is assumed that infinite number of potential managers of the following four types is available.

1. The skills profile of *functional managers* allows them to control a single function across several projects, i.e., their skill coefficients are equal to unity for all functional activities within a single function across all projects. Therefore, we have *f* subtypes of functional managers, each specializing on a single managerial function.
2. Skills of *project-oriented managers* allow them to perform all function-oriented activities within a single project (i.e., coefficients of skills profile are equal to unity for project-oriented activities within a single project). Therefore, there are *l* sub-types of project managers.

   Both project-oriented and functional managers are also supposed to be good at communication (information transfer), i.e., skill coefficients for internal managerial activities are equal to unity.[2] The rest skill coefficients of project-oriented and functional managers are equal to infinity (or any sufficiently large number).
3. A *strategic functional manager* is allowed to perform **any** functionally-oriented activity. Yet, distinct to ordinary functional manager, they can transfer only the functionally-oriented information, but not the project-oriented one.
4. A *strategic project manager*, in turn, performs **any** project-oriented activity and transfers only project-oriented information.

Assume, for simplicity, that a manager of any type has the same cost, which, without loss of generality, can be set equal to unity. Also assume equal spans of control of all managers, which, in turn, without loss of generality can be set to unity.

[2]An obvious extension of the considered model assumes different skills coefficients for internal activities. For instance, project-oriented communication can be more efficient for project managers, while functional-oriented communication is "cheaper" for functional managers.

Definition 3.1 Mishin (2011). A *symmetric hierarchy* is a sequence of *levels* indexed upward from 1 to some natural number h with $q_i > 0$ managers on the level $i = 1, \ldots, h$. Managers on one level of a hierarchy share the same delegated authority vectors, they have identical skills profiles and duplication matrices. The latter depend only on the number of managers on the hierarchical level.

Note that a symmetric hierarchy may have *several* top-managers located at the highest level of a hierarchy, which are supposed to use mutual adjustment (see Minzberg 1983) for intra-level coordination.

The following definitions are in line with the notions of classical organizational forms, as defined in Mishin (2007a), but we adjusted them to the considered model.

Definition 3.2 A *department* is a symmetric hierarchy consisting of functional managers, to which the total volume of all functional activities within one managerial function is delegated.

Definition 3.3 A *division* is a symmetric hierarchy consisting of project managers, to which the total volume of all project-oriented activities within one project is delegated.

Definition 3.4 A *hierarchy for department coordination* is a symmetric hierarchy built over several departments and consisting of strategic project managers, to which the total volume is delegated of all project-oriented activities within the functions of these departments.

Definition 3.5 A *hierarchy for division coordination* is a symmetric hierarchy built over several divisions and consisting of strategic functional managers, to which the total volume is delegated of all functional activities within the projects of these divisions.

Definition 3.6 A *functional hierarchy* is a hierarchy consisting of f departments (one department per managerial function) and a hierarchy coordinating all departments (see Fig. 3.2a).

Definition 3.7 A *divisional hierarchy* is a hierarchy consisting of l divisions (one division per project) and a hierarchy coordinating all divisions (see Fig. 3.2b).

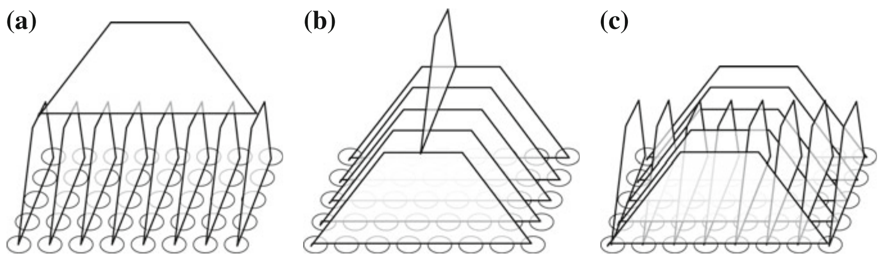


Fig. 3.2 An example of functional (**a**), divisional (**b**), and matrix (**c**) hierarchies for five projects and eight managerial functions

Therefore, functional activities are performed at lower levels of a functional hierarchy, where each department coordinates a certain managerial function across projects, while at higher levels all functions are coordinated regardless of the project. Conversely, in a divisional hierarchy lower levels accomplish project-specific tasks, while on the higher levels inter-project coordination is performed of all functional activities.

In terms of "hierarchies of knowledge" (see Garicano 2000), all project-specific problems are solved on the lower levels of a divisional hierarchy, while solution of functional problems is postponed to the higher levels; in functional hierarchies functional problems are solved first (on the lower levels of a hierarchy) and project-specific problems wait for the higher authority.

Definition 3.8 A *matrix* hierarchy consists of f departments and l divisions. Since they completely fulfill the demand for all managerial activities, no strategic managers are required in a matrix hierarchy (see Fig. 3.2c).

Figure 3.2 illustrates the classical organizational forms. Symmetric hierarchies are depicted with trapezoids.

Although skills profiles of managers of different types considerably limit the set of feasible hierarchies, it is not reduced to the three classical from presented above, since an enormous number of complex interlaces of managers of different types are possible. It is proved in Mishin (2007a) for a similar model that only one of three classical organizational forms can be optimal for all combinations of parameters.

Whereas the formal proof of a similar result for the considered model is tricky, below we solve a simpler problem of comparing these three organizational forms and determining the conditions when one of them is preferable to the two others.

Even this problem is far from trivial, since there is a variety of functional hierarchies with different number of levels in departments or in a coordinating hierarchy, different number of managers on each level, or different responsibility distribution among them (the same is true for functional and matrix hierarchies). We need to compare the best structures of each type to make conclusion about the preferred structure in every particular situation, and, therefore, the problem reduces to calculating the cost of the best functional, divisional, and matrix hierarchy for each combination of parameters of the model and then choosing the cheapest organizational form.

3.3.3 Direct Supervision and Mutual Adjustment

To complete the model description, we need to define duplication matrices for each of three organizational forms.

Following the approach suggested in Mishin (2011) (which, in turn, relies on the organization theory by Minzberg (1983), there are two basic instruments of managers' interaction in organizations: *direct supervision* (which corresponds to vertical interaction between managers in an organizational hierarchy) and *mutual* *adjustment* (which corresponds to horizontal bonds between managers at one hierarchical level).

Direct supervision is employed intensively in *formal bureaucratic* style of management, when a manager on middle and higher levels of a hierarchy makes decisions of the basis of his or her subordinates' reports and implements these decisions by virtue of a *chain of command* (a sequence of subordinates) Direct supervision generates information flows through the chain of command: an ascending flow of reports from subordinates to their superiors, and a descending flow of instructions from superiors back to their subordinates.

These information transfers add up to the internal workload of managers in a chain of command and duplicate the external activities delegated to these managers. To be more precise, if some volume y of a function-oriented activity is delegated to a manager, then any other manager in his or her chain of command has additional workload $\kappa \cdot y$ connected with the transfer of functional information. A coefficient κ is equal to the ratio of information transfer workload to the workload of performing this managerial activity; assume the same duplication arises in case of project-oriented work.[3]

Mutual adjustment is intended for coordination of managerial decisions with the other managers at his or her hierarchical level. In the same manner to direct supervision, mutual adjustment gives rise to duplication of managerial work, since the time of coordination is added to manager's workload. The more managers at the hierarchical level, the more time is spent for coordination.

The simplest model of mutual adjustment (see Mishin 2011) in a symmetric hierarchy assumes the power relation q^{α} between the number q of managers at the hierarchical level and the workload of any manager at this hierarchical level when compared to the situation of a single manager at the level (when a manager is alone, he or she spends no time for coordination, and no duplications arises). The parameter $\alpha \in (0, 1)$ here is a complexity coefficient of mutual adjustment. Together with the parameter κ they completely determine the management technology adopted by the company.

Therefore, all elements of a duplication matrix of any manager are multiplied by q^{α}. For a functional manager the number q is equal to the number of managers at his or her hierarchical level of a department (see the lower line of trapezoids in Fig. 3.2a or a similar line in Fig. 3.2c), while for a project manager q is equal to the number of managers at his or her level of a division (see the lower line of trapezoids in Fig. 3.2b or a similar line in Fig. 3.2c). For a strategic manager q is equal to the number of managers at his or her level in a corresponding coordinating hierarchy (the upper trapezoids in Fig. 3.2a, b).

[3] We will not consider here a natural extension of the model, which assumes different duplication coefficients for functional and project-oriented information; any difference between them is assumed negligible.

3.3.4 Costs of Standard Organizational Forms

The considered model appears to be a special case of the model of authority delegation and duplication in symmetric hierarchies suggested in Mishin (2011). It is shown in Mishin (2011) that since all managers sharing the same level in a symmetric hierarchy are identical, we can considerably simplify the problem by replacing duplication matrices of single managers with duplication matrices of hierarchy levels.

Below we describe this transition in detail and, by the way, additionally simplify the problem by reducing the number of components in a demand vector.

Only functional activities within one function and across all projects in a company can be delegated to managers in a department. The total demand for these activities is $b \cdot l$. Since all functional managers share the same skill coefficients for all these activities, we can merge such activities into one "consolidated" activity. Denote with $y_i^{\mathrm{F}} \in [0, +\infty)$ the total volume of functional activities delegated to the ith level in a department. Any department must cover completely the demand in functional activities of one managerial function, so, if there are h_{F} hierarchical levels in a department, then $\sum_{i=1}^{h_{\mathrm{F}}} y_i^{\mathrm{F}} = b \cdot l$.

The total workload of managers at the ith level in a department adds up from the authority y_i^{F} delegated to this level, the workload $\kappa \sum_{j=i+1}^{h_{\mathrm{F}}} y_j^{\mathrm{F}}$ of function-oriented information transfers to higher levels in a chain of command (according to the idea of direct supervision, this information concerns the volume $\sum_{j=i+1}^{h_{\mathrm{F}}} y_j^{\mathrm{F}}$ of activities delegated to the superiors of the ith level), and the workload $\kappa \cdot a \cdot l$ of transferring project-oriented information delegated to the managers of a coordinating hierarchy built over the department in a functional hierarchy. The whole sum is multiplied by the coefficient $(q_i^{\mathrm{F}})^{\alpha}$ of mutual adjustment, where q_i^{F} is the number of managers at the ith level in the department. Finally, we write the total workload of the ith level of a department as

$$z_i^{\mathrm{F}} := \left(y_i^{\mathrm{F}} + \kappa \sum\nolimits_{j=i+1}^{h_{\mathrm{F}}} y_j^{\mathrm{F}} + \kappa \cdot a \cdot l\right)(q_i^{\mathrm{F}})^{\alpha}. \tag{3.1}$$

The summands of the first bracket in (3.1) are depicted in Fig. 3.3. The trapezoid in the left side of the figure represents a department. A bar in the center of the figure

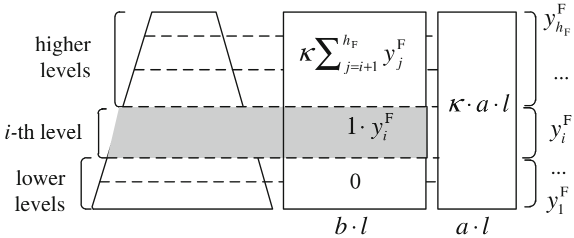


Fig. 3.3 Calculation of the workload of the ith hierarchical level in a department

corresponds to the volume $b \cdot l$ of functional activities corresponding to this department. All this volume has to be delegated to managers in the department. Horizontal dashed lines divide the whole bar into the boxes with box height being proportional to the volume of activities delegated to a level in a department (for instance, the box filled with gray corresponds to the volume y_i^{F} of managerial activity delegated to the ith level). The second summand in (3.1) is the total volume of managerial activities delegated to the higher levels of the department, multiplied by κ (see Fig. 3.3). This workload corresponds to information transfers induced by direct supervision. The authority delegated to the lower levels of a department does not affect the workload of the ith level, since this activity is assumed to be performed at the lower levels and needs no supervision from the ith level. The bar on the right side represents the volume $a \cdot l$ of project-oriented activities generated by the function of the considered department. All this volume (multiplied by κ) is added to the first bracket in (3.1) increasing the workload of the ith level.

In the same manner we calculate the total workload of the ith level in a division:

$$z_i^{\mathrm{P}} := (y_i^{\mathrm{P}} + \kappa \sum\nolimits_{j=i+1}^{h_{\mathrm{P}}} y_j^{\mathrm{P}} + \kappa \cdot b \cdot f)(q_i^{\mathrm{P}})^{\alpha}, \tag{3.2}$$

where h_{P} is the number of levels in a division, q_i^{P} is the number of managers at the ith hierarchical level, and y_i^{P}—is the volume of managerial activities delegated to the ith level. Also the equality $\sum\nolimits_{i=1}^{h_{\mathrm{P}}} y_i^{\mathrm{P}} = a \cdot f$ holds.

Strategic project managers in a functional hierarchy are delegated the project-oriented activity across all projects. As above, we join project-oriented activities for all f functions and l projects into one activity, and distribute the whole volume $a \cdot f \cdot l$ of this activity to the levels of a coordinating hierarchy in such a way that $\sum\nolimits_{i=1}^{h_{\mathrm{SF}}} y_i^{\mathrm{SF}} = a \cdot f \cdot l$, where y_i^{SF} is the volume of activity delegated to the ith level of a strategic hierarchy. The workload of the ith level adds up from the workload of performing the delegated activity y_i^{SF} and the workload $\kappa \sum\nolimits_{j=i+1}^{h_{\mathrm{SF}}} y_j^{\mathrm{SF}}$ of transferring information to the higher levels of a coordinating hierarchy (as supposed by the idea of direct supervision), both multiplied by the coefficient $(q_i^{\mathrm{SF}})^{\alpha}$ of mutual adjustment. Therefore, the total workload of the ith level in a hierarchy for department coordination is equal to

$$z_i^{\mathrm{SF}} := \left(y_i^{\mathrm{SF}} + \kappa \sum_{j=i+1}^{h_{\mathrm{SF}}} y_j^{\mathrm{SF}} \right) (q_i^{\mathrm{SF}})^{\alpha}. \tag{3.3}$$

By analogy, the total workload of managers at the ith level of a hierarchy for division coordination (in divisional structure) is equal to

$$z_i^{\mathrm{SP}} = \left(y_i^{\mathrm{SP}} + \kappa \sum_{j=i+1}^{h_{\mathrm{SP}}} y_j^{\mathrm{SP}} \right) (q_i^{\mathrm{SP}})^{\alpha}, \tag{3.4}$$

where h_{SP} is the level count in the coordinating hierarchy, q_i^{SP} is manager count at the ith level, and y_i^{SP} is the authority (managerial activity) delegated to the managers at the ith level. As before, $\sum_{i=1}^{h_{\mathrm{SP}}} y_i^{\mathrm{SP}} = b \cdot f \cdot l$.

The cost C_{F} of a functional hierarchy builds up from the costs of f departments and the cost of a coordinating hierarchy. Since the unit cost of a single manager is assumed, we have

$$C_{\mathrm{F}} = f \cdot \sum_{i=1}^{h_{\mathrm{F}}} q_i^{\mathrm{F}} + \sum_{i=1}^{h_{\mathrm{SF}}} q_i^{SF}. \tag{3.5}$$

By analogy, the cost C_{P} of a divisional hierarchy adds up from the costs of l divisions and the cost of a coordinating hierarchy:

$$C_{\mathrm{P}} = l \cdot \sum_{i=1}^{h_{\mathrm{P}}} q_i^{\mathrm{P}} + \sum_{i=1}^{h_{\mathrm{SP}}} q_i^{\mathrm{SP}}. \tag{3.6}$$

Finally, the cost C_{M} of a matrix hierarchy adds up from the costs of l divisions and of f departments:

$$C_{\mathrm{M}} = f \cdot \sum_{i=1}^{h_{\mathrm{F}}} q_i^{\mathrm{F}} + l \cdot \sum_{i=1}^{h_{\mathrm{P}}} q_i^{\mathrm{P}}. \tag{3.7}$$

An additional requirement is that the workload of any manager in a hierarchy should not exceed the productivity norm, which is supposed to be equal to unity.

3.4 Optimal Organizational Form

3.4.1 Results

To solve the problem of the optimal organizational form we, firstly, calculate the optimal shape for each organizational form, i.e., determine the number of levels, the number of managers at each level, and authority delegation to minimize the hierarchy cost: C_{F}, C_{P}, or C_{M} under productivity and demand cover constraints. From formulas (3.1)–(3.7) we see that we can independently find the optimal structure of a division, of a department, of a department- or division-coordinating hierarchy.

Each of these partial problems can be reduced to the, so called, "*model of a scalar managerial activity in a symmetric hierarchy under a uniform cost function*" suggested and studied in Mishin (2011). Our model appears to be a special case for the levels' duplication matrix D designed to account for mutual adjustment and for direct supervision:

$$D = diag(q_1^{\alpha}, \ldots, q_h^{\alpha}) \cdot \begin{pmatrix} \rho & \varphi & \ldots & \varphi \\ \psi & \rho & \varphi & \varphi \\ \ldots & \psi & \ldots & \ldots \\ \psi & \ldots & \psi & \rho \end{pmatrix},$$

where α is the complexity coefficient of mutual adjustment, ρ—is the duplication coefficient of delegated activity, φ—is the duplication coefficient of activity delegated to superior levels, and ψ is the duplication coefficient of activity delegated to subordinate levels. The ijth cell of the matrix D defines the coefficient of duplication by the ith level of the activity delegated to the jth level.

Consider a functional hierarchy. Recall that $s := a/b$. Since $\sum_{i=1}^{h_F} y_i^F = b \cdot l$, we rewrite the expression (3.1) as

$$z_i^F = \left[(1+\kappa)y_i^F + \kappa(1+s)\sum_{j=i+1}^{h_F} y_j^F + \kappa s \sum_{j=1}^{i-1} y_j^F\right](q_i^F)^{\alpha}.$$

Then the vector $z^F = (z_i^F)_{i=1,\ldots,h_F}$ of levels' workloads can be written in the form $z^F = D_{MA} \cdot D_{DS} \cdot y$, where $D_{MA} = diag((q_1^F)^{\alpha}, \ldots, (q_{h_F}^F)^{\alpha})$ is the duplication matrix of mutual adjustment, and D_{DS} is the duplication matrix of direct supervision, which takes the form

$$D_{DS} = \begin{pmatrix} \rho_F & \varphi_F & \ldots & \varphi_F \\ \psi_F & \rho_F & \varphi_F & \varphi_F \\ \ldots & \psi_F & \ldots & \ldots \\ \psi_F & \ldots & \psi_F & \rho_F \end{pmatrix},$$

where

$$\rho_F = 1 + ks,\ \varphi_F = k(1+s),\ \psi_F = ks \tag{3.8}$$

are, accordingly, duplication coefficients of level's own activity, of activity delegated to superior levels, and of activity delegated to subordinate levels.

Similarly, for a division we write

$$\rho_P = 1 + k/s,\ \varphi_P = k(1+1/s), \psi_P = k/s, \tag{3.9}$$

For both division- and department-coordinating hierarchies we have

$$\rho_C = 1,\ \varphi_C = k,\ \psi_C = 0. \tag{3.10}$$

The duplication matrix D_{MA} of mutual adjustment is the same for all these hierarchies, and only the number of levels varies.

In Mishin (2011) a closed-form solution of the optimal hierarchy problem is found under continuous approximation, when fractional number of levels and fractional number of managers at the level are allowed. An optimal hierarchy appears to be *uniform*, i.e., *span of control r* (the ratio of number of managers at two sequential levels, or, which is the same, the number of immediate subordinates of a manager) does not vary from level to level. Moreover, it is shown that characteristics of an optimal hierarchy are as follows.

Span of control (which is the same at all levels) is written as:

$$r = \left(\frac{\rho - \psi}{\rho - \varphi}\right)^{1/\alpha}. \tag{3.11}$$

Number of levels is defined by the formula:

$$h = \frac{\ln(\varphi/\psi)}{(1-\alpha)\ln r}. \tag{3.12}$$

Note that under continuous approximation $h \to +\infty$ when $\varphi = 0$ or $\psi = 0$. Nevertheless, this is not critical, since the total manager count

$$q = \left[x\frac{\rho - \psi}{\varphi - \psi}(\varphi - \psi r^{-\alpha h})\right]^{\frac{1}{1-\alpha}}\left(\frac{1 - r^{-h}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}} \tag{3.13}$$

in a hierarchy remains finite under all combinations of parameters.

The variable x here is the total volume of managerial activity delegated to managers in a hierarchy: $x_F = b \cdot l$ for a department, $x_P = a \cdot f$ for a division, $x_{SF} = a \cdot f \cdot l$ for a department-coordinating hierarchy, $x_{SP} = b \cdot f \cdot l$ for a division-coordinating hierarchy.

3.4.2 Discussion

Traditionally, span of control is one of the most important parameters of a management hierarchy, being a subject of experimental and theoretical studies (Keren and Levhari 1979; Hirst et al. 2013 and many others). It is clear from (3.8)–(3.10) and (3.11) that the optimal span of control is the same in a department, a division, and in a coordinating hierarchy: $r = r_F = r_P = r_{SF} = r_{SP} = (1 - \kappa)^{-1/\alpha}$. This means that in the considered model the optimal span of control is determined by the information processing technology rather than by the hierarchy shape, and, I particular, by the level of a manager's position in a hierarchy.

The span of control increases when κ increases. This coefficient measures how costly are information transfers due to direct supervision. The span decreases with the increase of α. This parameter measures how costly mutual adjustment is (see Fig. 3.4). This is predictable behavior, since the greater span of control is, the less

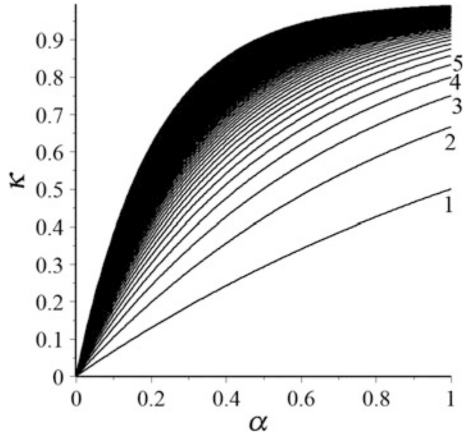


Fig. 3.4 Span of control r versus duplication coefficients: continuous approximation (bounds of optimality of span of control r = 1, 2, … are shown)

the number of levels in a hierarchy is (under fixed total headcount), and the more important is mutual adjustment between them when compared to direct supervision.

From Fig. 3.4 we see that the part of parameter combinations is not relevant (e.g., values of α close to zero under κ close to one), since they results in very large values of optimal span of control. We will return to this observation later. Under the other parameters' combinations it follows from Fig. 3.4 that the optimal span of control is less than one. This is a result of a continuous approximation we adopted for simplicity. The span of control equal to one results in the optimal hierarchy having the form of the "chain of control" with the sole manager at each level. The value of the span of control less than one corresponds to the "reversed" hierarchy, which widens upwards.

The number of levels in an optimal department is equal to $h_{\mathrm{F}} = \frac{\ln(1+1/s)}{(1-\alpha)\ln r}$, and is equal to $h_{\mathrm{P}} = \frac{\ln(1+s)}{(1-\alpha)\ln r}$ in an optimal division. In contrast to the span of control, both h_{F} and h_{P} increase with α and decrease with κ (see Fig. 3.5). A department becomes

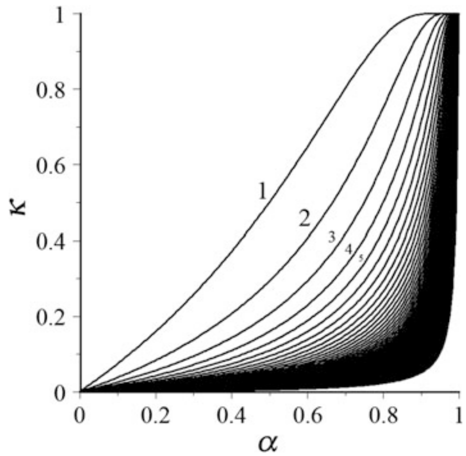


Fig. 3.5 Number of levels h (under s = 1) versus duplication coefficients: continuous approximation (bounds of optimality of h = 1, 2, … are shown)

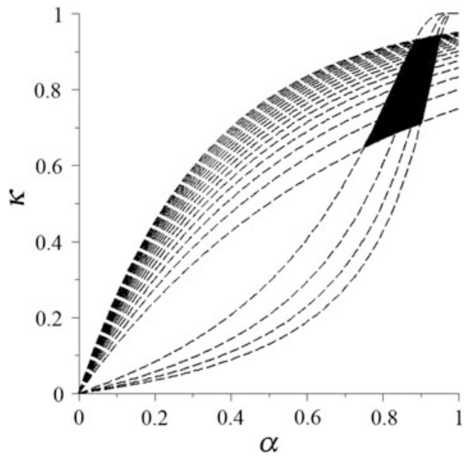


Fig. 3.6 Area of realistic combinations of duplication coefficients κ and α

taller when the volume of functional activity increases as compared to project-oriented one, while a division becomes flatter. Therefore, departments and divisions are complements in all three organizational forms.

Joining Figs. 3.4 and 3.5 we obtain an area of values of parameters κ and α (marked with black in Fig. 3.6) which results in realistic span of control (in the range from 4 to 20) and the number of levels (in the range from 2 to 5). This is the area of model parameters, where it makes sense to solve the problem of an optimal organizational structure. On the plane of model parameters this area forms a trapezoid, in which α takes values from 0.8 to 0.95, while κ varying from 0.6 to 0.9.

When duplication coefficient κ varies from 0.6 to 0.9, duplication of managerial activity due to direct supervision is substantial (for smaller κ the extremely tall and narrow hierarchy is beneficial). This observation to some extent justifies high salaries of top managers and substantial headcount of corporate bureaucracy. An alternative way to obtain a realistic span of control under small duplication κ is to introduce some amount of fixed wage paid to a manager irrespective of his or her workload. Fixed wage penalizes adding new managers, thus increasing the optimal span of control. Presence of fixed wage is connected with low labor mobility and can be understood as a bonus paid to managers for the organization-specific skills.

The number of managers in an optimal department is calculated as

$$q_{\mathrm{F}} = \left[b \cdot l(1 + (1 - r^{-\alpha h_{\mathrm{F}}})s)\right]^{\frac{1}{1-\alpha}} \left(\frac{1 - r^{-h_{\mathrm{F}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}}, \tag{3.14}$$

while the number of managers in an optimal division is calculated as

$$q_{\mathrm{P}} = \left[a \cdot f\left(1 + \frac{1 - r^{-\alpha h_{\mathrm{P}}}}{s}\right)\right]^{\frac{1}{1-\alpha}} \left(\frac{1 - r^{-h_{\mathrm{P}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}}. \tag{3.15}$$

Please note that the optimal number of levels does not depend on the total volume x of managerial activity, and is completely determined with duplication coefficients and the relative weight s of project-oriented activities. As we see from expressions (3.14) and (3.15), the increase of x just results in the increase of managers' count at each level.

Under a continuous approximation the infinite number of levels is optimal for strategic hierarchies. Nevertheless, this is not critical, since the total manager count

$$q_{\mathrm{SF}} = (a \cdot f \cdot l)^{\frac{1}{1-\alpha}}\left(1 - r^{-1}\right)^{\frac{\alpha}{1-\alpha}}, \quad q_{\mathrm{SP}} = (b \cdot f \cdot l)^{\frac{1}{1-\alpha}}\left(1 - r^{-1}\right)^{\frac{\alpha}{1-\alpha}} \tag{3.16}$$

is finite anyway.

Substituting (3.14)–(3.16) to expressions (3.5)–(3.7) we obtain the final closed-form expressions for the cost of a functional, divisional, and matrix organizational forms:

$$C_{\mathrm{F}} = f[bl(1 + (1 - r^{-\alpha h_{\mathrm{F}}})s)]^{\frac{1}{1-\alpha}}\left(\frac{1 - r^{-h_{\mathrm{F}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}} + (afl)^{\frac{1}{1-\alpha}}\left(1 - r^{-1}\right)^{\frac{\alpha}{1-\alpha}}, \tag{3.17}$$

$$C_{\mathrm{P}} = l\left[af\left(1 + \frac{1 - r^{-\alpha h_{\mathrm{P}}}}{s}\right)\right]^{\frac{1}{1-\alpha}}\left(\frac{1 - r^{-h_{\mathrm{P}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}} + (bfl)^{\frac{1}{1-\alpha}}\left(1 - r^{-1}\right)^{\frac{\alpha}{1-\alpha}}, \tag{3.18}$$

$$\begin{aligned} C_{\mathrm{M}} = {} & f[bl(1 + (1 - r^{-\alpha h_{\mathrm{F}}})s)]^{\frac{1}{1-\alpha}}\left(\frac{1 - r^{-h_{\mathrm{F}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}} \\ & + l\left[af\left(1 + \frac{1 - r^{-\alpha h_{\mathrm{P}}}}{s}\right)\right]^{\frac{1}{1-\alpha}}\left(\frac{1 - r^{-h_{\mathrm{P}}}}{1 - r^{-1}}\right)^{-\frac{\alpha}{1-\alpha}}. \end{aligned} \tag{3.19}$$

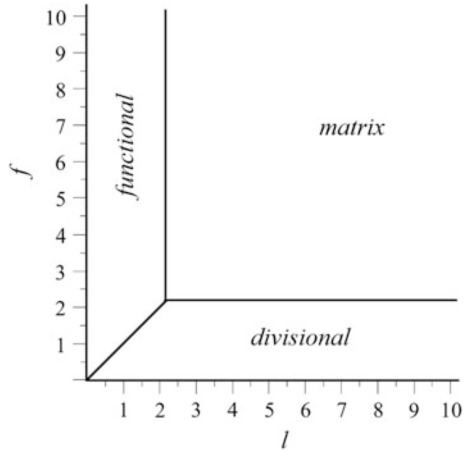
Now we can calculate the cost of all organizational forms and choose the best form for each combination of model parameters: project count l, function count f, the volume of project-oriented work a, the volume of functional-oriented work b, duplication coefficients of direct supervision κ and of mutual adjustment α.

Freeze the values of duplication coefficients $\kappa = 0.8$ and $\alpha = 0.9$ (laying in the very center of the area filled black in Fig. 3.6). They give the span of control $r \approx 6$ and the number of levels in a department $h \approx 4$ (under $s = 1$). In Fig. 3.7 we see the optimality areas of classical organizations forms against the project count and epy function count under $s = a/b = 1$.

From Fig. 3.7 we see that if the project count in an organization is small, the functional organization is optimal. When the managerial function count is small, the divisional structure becomes optimal. When the project count or the function count exceeds some limit (it is equal to approximately two in the figure), the matrix structure appears optimal.

Compare the costs C_{F}, C_{P}, and C_{M} pairwise to obtain expressions for the bounds of optimality of different organizations forms. Thus, $C_{\mathrm{F}} \geq C_{\mathrm{M}}$ when

Picture 3.7 Optimality areas of classical organizational forms



$$l \geq \frac{(1 + (1 - r^{-\alpha h_P})/s)^{1/\alpha}}{1 - r^{-h_P}} = \frac{\left(1 + 1/s - (1+s)^{-\frac{\alpha}{1-\alpha}}/s\right)^{1/\alpha}}{1 - (1+s)^{-\frac{1}{1-\alpha}}}. \tag{3.20}$$

This expression makes the coordinate of the vertical boundary in Fig. 3.7. $C_P \geq C_M$ when

$$f \geq \frac{\left[(1 + (1 - r^{-\alpha h_F})s)\right]^{1/\alpha}}{1 - r^{-h_F}} = \frac{\left(1 + s - s(1+1/s)^{-\frac{\alpha}{1-\alpha}}\right)^{1/\alpha}}{1 - (1+1/s)^{-\frac{1}{1-\alpha}}}. \tag{3.21}$$

This expression makes the coordinate of the horizontal boundary in Fig. 3.7.

From expressions (3.20) and (3.21) we see that the optimality area of a matrix structure does not depend on the duplication coefficient κ due to direct supervision, and depends only on the coefficient α of mutual adjustment and relative volume s of project-oriented activity.

The boundary equation of divisional and functional structures is easily written only for the case of $a = b = 1$, when it reduces to the straight line $l = f$ (we see this inclined line in Fig. 3.7).

When the volume increases of functional activity as compared to the volume of project-oriented one (and, therefore, s decreases), the optimality area of a functional structure expands, while the area of a divisional structure contracts. So, in Fig. 3.8 we see that under $s = 1/5$ the matrix structure becomes optimal for project count l exceeding 7.25 (instead of 2 under $s = 1$), but for f exceeding 1.3 (instead of 2).

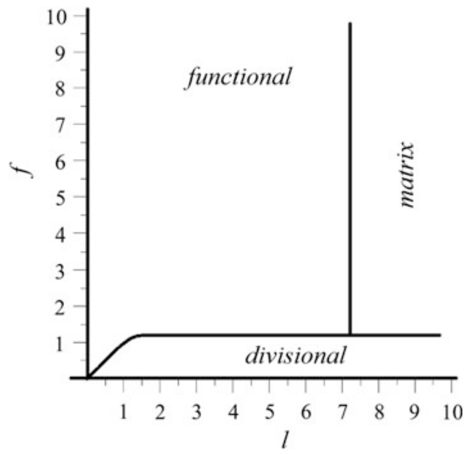


Fig. 3.8 Optimality areas for $s = 1/5$ (project-oriented work prevails over the functional work)

Therefore, the less the weight of project-oriented activity, the less often a divisional structure appears optimal, which seems reasonable.

We have a symmetric situation for $s > 1$: the optimality area of a divisional structure expands, while the area of a functional structure contracts at the cost of deformation of the optimality area of a matrix structure.

Also it is clear that the optimality area of a matrix structure expands with the increase of the duplication coefficient α of mutual adjustment; for instance, under $s = 1/5$ and $\alpha = 0.5$ the matrix structure becomes optimal for $l \geq 11$, but under $\alpha = 0.9$ it is optimal for $l \geq 7$ (see the vertical line in Fig. 3.8).

The above results tend us to the following basic conclusion. When the project count and the managerial function count are sufficiently large, the matrix hierarchy appears to be a preferable form of an organizational structure for strategic management support. When the managerial activity is ill-structured and cannot be divided into sufficiently large number of functions (managerial competences), a divisional hierarchy becomes preferable. When the number of projects is small, a functional hierarchy is the best choice. The critical project count and function count are calculated with expressions (3.20) and (3.21) and typically do not exceed a dozen (not a hundred or a thousand).

A yet another conclusion we make about the stability of an organizational form with respect to changes in environment. If under fixed f (the managerial function count) and some l (the number of projects of strategic management) a divisional or a matrix organizational form is preferred, then this form remains preferable with the increase of the project count l (so as we move right through the plane in Figs. 3.7 and 3.8). Moreover, the management hierarchy is adjusted at relatively small cost, when the number of projects changes, as relatively small number of managerial positions needs to be added, removed, or re-subordinated.

If the functional form was optimal, it loses its optimality when the project count increases, and keeping efficiency of organizational hierarchy requires a (much costlier!) restructuring to the divisional or the matrix form.

3.5 Conclusion

Therefore, in this chapter we challenged an optimal organizational structure problem with a model of authority delegation in multi-level hierarchies Mishin (2011) being a main mathematical tool. A model was suggested of an organizational structure for change management, a part of strategic management infrastructure in a company.

This general framework models a wide range of factors affecting the shape of an organizational hierarchy: staff experience and skills, unique features of strategic projects, costs of managers' coordination, etc. In particular, for a special case of identical symmetric projects we managed to comprehensively answer the question of comparative performance of three classical organizational forms (functional, divisional, and matrix), and to justify the major conclusions of the setting suggested in Mishin (2007a) remain valid for a more complicated framework, the one including optimal delegation of authority between hierarchical levels.

At the same time, we did not measure performance of these classical organizational forms against the other feasible organizational structures. Such comparison requires detailed analysis of duplication matrices and skill profiles of managers of all four types considered above. It seems a reasonable conjecture (proved formally in Mishin (2011) for a similar model) that one of these classical forms is an optimal feasible structure for all combinations of parameter values. By banning transition of functional information by strategic project managers (and, vice versa, transition of project-oriented information by functional managers) we bound them to occupy only the top levels of any feasible hierarchy (in fact, this is a natural position for a strategic manager). But it is still an open question whether this limitation is enough to prevent "interlacing" in the construction of the hierarchy (i.e., creating a divisional structure for several projects and a matrix hierarchy for the others).

A yet another challenge to the theory is a realistic generalization of duplication due to mutual adjustment to the case of an asymmetric hierarchy. The problem is that there is no natural definition of a hierarchical level in this case, which is the basic notion for our version of mutual adjustment. Such a generalization would be an important step towards managerial applications of a general theory of organizational structure optimization.

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Chapter 4
Knowledge-Based Models of Nonlinear Systems Based on Inductive Learning

Nataliya N. Bakhtadze and Vladimir A. Lototsky

Abstract This chapter discusses intelligent design techniques for predictive identification models of nonlinear dynamic plants. The techniques are based on inductive learning, i.e., on knowledge retrieval from process data. An identification method named *associative search* is presented. It is based on data mining techniques and enables the use of all available process data development in the identification model design. Process situations resembling the current one in the sense of close process variable values are being selected from the process history; such situations are called *associations*. Process data clustering improves the computing speed and saves computational resources.

Keywords System identification · Virtual model · Associative search · Knowledgebase

4.1 Mathematical Models and Algorithms for Automatic On-line Estimation of the Actual State of Nonlinear System

The design of control systems with identifier is a problem of significant practical value. The control plant identification is fulfilled by an identifier which realizes both the function of parametric disturbance generation for control plant and controller parameters adjustment. In control systems with the identifier an adjustable model is used not only for controller design but for solving auxiliary problems (e.g., prediction of slow parametric failures) thus demonstrating the universality of systems with identifier as against the direct control approach.

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The framework of identification-based control approach was formulated in 1950–1960s on the basis of Bayesian estimation (Bellman and Kalaba 1960). The first industrial ASI (adaptive system with identifier) with an identifier in a feedback loop used for compensator adjustment was implemented at a tube-rolling mill control (Bunich and Lototsky 2002). Strict theoretical results in the adaptive control of dynamic plants were obtained in the beginning of the 1980s. The identifier typically employed LMS technique and its modifications (Goodwin 1981). The progress was later achieved in control optimization with respect to control cost function for the plants with both parametric and non-parametric uncertainties (Juditsky and Nazin 2001).

The theoretical results were exemplified in software products such as MATLAB System Identification Toolbox, based on widely used algorithms (Ljung 1999).

The use of stochastic approximation algorithms (both gradient and pseudo-gradient ones) for minimizing the empirical functional makes it possible to adjust the model in real time. For example, with quadratic cost function one gets recursive generalized LMS technique, while more slow increasing cost functions result in different estimation algorithms, robust w.r.t. innovation distribution (Poznyak and Kaddour 1997).

The predictive model technique can be effectively implemented for Gaussian ARMA disturbances. For non-Gaussian disturbances, the optimal available control strategy is generally formed by nonlinear feedback loop (Chen 1984) posing obviously more challenges.

In present-day decision-making support and advanced process control (APC) systems predictive identification models are implemented as special software applications named *inferential models* or *soft sensors*. APC technology is mainly based by multivariable model-based predictive control (MPC) techniques and enables direct control of product qualities modeled by soft sensors. Typically, simple regression models are the most popular for soft sensors in APC applications. These models are steady-state, while all process dynamics is included in dynamic predictive models with some input signals supplied by soft sensors. Neither soft sensor nor predictive models are absolutely precise because both types are based on process history and step-test data collected under specific conditions while actual APC operating conditions may differ for various reasons. In an interrelated multi-variable plant operating in real time may become unstable within several time steps under strong disturbances if it is governed by an imprecise predictive model. The challenge is surmounted by using *robust MPC algorithms*, where the term “robust” means “able to handle model mismatch”.

In modern *decision-making support systems* the identification is done with the objective to investigate the process properties that result in optimal control decision-making by human operator. The predictive model technique belongs to the so-called *substitution methods*: the unknown parameter is determined implicitly as a unique point minimizing the cost functional, which is substituted by an empirical one obtained by estimate calculation.

The development of effective predictive model design techniques allowing for all available a priori information about both the control plant and the operating environment looks relevant even though such information may not always be formalizable.

In this chapter, the identification technique based on *virtual model* design is presented. The term "virtual" is to be understood as "ad hoc". This technique named "*associative search*" suggests predictive model design for dynamic plant at each time step using historical data sets ("associations") obtained at the learning stage rather than process approximation in time. Such approach is close to Ljung's idea (Ljung 2008) to use additional a priori information about the control plant in a learning process. Fuzzy logic technique is used to develop the algorithms. Thus, the proposed plant identification techniques simulate human operator behavior based on process knowledge formalization.

4.2 Virtual Model-Base Development Nonlinear Predictive Algorithm

In this subsection we discuss a predictive model design technique based on the imitation of decision-maker's associative thinking.

Identification algorithms employed in modern control systems often use expert knowledge from both human experts and knowledgebase. In the second case, the operator can either accept and implement the recommended control action or control manually based on the displayed process forecast.

Two knowledge types are distinguished: declarative and procedural (Larichev 2001). The first type includes the description of various facts, events, and observations, while skills and experience refer to the second type. Experts differ from novices by their structure and way of thinking and, in particular, the searching strategy (Patel and Ramoni 1997). If a person is not experienced, he/she would use the so-called 'backward reasoning'. He/she reviews different possible answers and makes a decision in favor of a specific answer based on the information received from the process at the current time step. On the contrary, an expert does not need to analyze current information in the process of decision-making, rather he/she uses the so-called 'forward reasoning' method which implies that the decision-making strategy is created subconsciously and this strategy is nonverbal. Therefore, in terms of the method of computational view of thought (Hunt 1989) the effectiveness of system will to a great extent be determined by expert's qualification and by the available a priori information.

Within the framework of this method, the cognitive psychology determines knowledge as a certain set of actually existing elements-symbols stored in human memory, processed during thinking and determining the behavior. The symbols, in turn, could be determined by their structure and the nature of neuron links (Simon 1997).

Knowledge processing in an intelligent system consists in the recovery (associative search) of knowledge by its fragment (Gavrilov 2002). The knowledge can be defined as an associative link between images. The associative search process can take place either as a process of image recovery using partially specified symptom (or knowledge fragment recovery by incomplete information; this process is usually emulated in various associative memory models) or as searching others images (linked associatively with the input image) related with other time steps. Those images have sense of a cause or an effect of an input image.

Gavrilov (2002) offered a model, which describes the associative thinking process as a sequential process of remembering based on associations—pairs of images defined by a set of symptoms. Such model can be considered as an intermediate level between neuron network models and logical models used in classical artificial intelligence systems. In this paper, we discuss an approach to developing on-line support of trader's decision-making based on the dynamic simulation of associative search and the identification technique based of virtual models.

An identification algorithm for complex nonlinear dynamic objects such as continuous and batch processes was presented by Chadeev (2004). The identification algorithm with continuous real-time self-tuning is based on virtual models design.

At every time step, a new virtual model is created. To build a model for a specific time step, a temporary "ad hoc" database of historic and current process data is generated. After calculating the output forecast based on object's current state, the database is deleted without saving.

The linear dynamical prediction model looks as follows:

$$y_t = a_0 + \sum_{i=1}^{r} a_i y_{t-i} + \sum_{j=1}^{s} \sum_{p=1}^{P} b_{jk} x_{t-j,p}, \tag{4.1}$$

where y_t is the object's output forecast at the tth step, x_t is the input vector, r is the output memory depth, s is the input memory depth, P is the input vector length.

The original dynamic algorithm consists in the design of an approximating hyper surface of input vector space and the related one-dimensional outputs at every time step (see Fig. 4.1). To build a virtual model for a specific time step, the points close in a manner to the current input vector are selected. The output value at the next step is further calculated using least mean squares (LMS).

4.3 Associative Search Technique for Virtual Model Design

We use a method based on the associative thinking model.

High-speed approximating hyper surface design algorithms enabling the usage of fuzzy models for various process applications were offered by Bakhtadze et al. (2007, 2008).

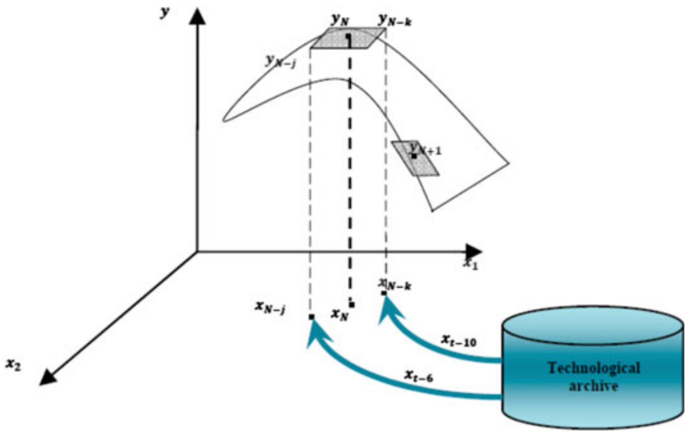

Fig. 4.1 Approximating hyper surface design

The following quantity

$$d_{t,t-j} = \sum_{p=1}^{P} \left| x_{tp} - x_{t-j,p} \right|, j = 1, \ldots, s$$

was introduced as distance (metric in $\Re^P$) between points of P-dimensional input space, where, generally, $s < t$, and x_{tp} are the components of the input vector at the current time step t.

Assume that for the current input vector $\boldsymbol{x}_t$:

$$\sum_{p=1}^{P} \left| x_{tp} \right| = d_t.$$

To build an approximating hyper surface for $\boldsymbol{x}_t$, we select such vectors $\boldsymbol{x}_{t-j}$, $j = 1, \ldots, s$ from the input data archive that for a given D_t the following condition will hold:

$$d_{t,t-j} \leq d_t + \sum_{p=1}^{P} \left| x_{t-j,p} \right| \leq d_t + D_t, j = 1, \ldots, s \tag{4.2}$$

The 2-D case is illustrated below (Fig. 4.2).

The preliminary value of D_j is determined on the basis of process knowledge. If the selected domain does not contain enough inputs for applying LMS, i.e., the corresponding SLAE has no solution, then the chosen points selection criterion can be slackened by increasing the threshold D_t.

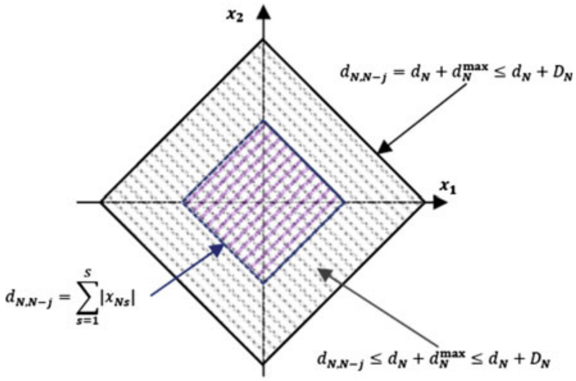

Fig. 4.2 Approximating hyper surface building

To increase the speed of the virtual models-based algorithm, an approach is applied based on employing a model of analyst's or trader's associative thinking for predicting.

For modeling the associative search procedure imitating the intuitive prediction of process status by a trader, we assume that the sets of process variable values, which are the components of an input vector, as well as the system outputs at previous time steps altogether create a set of symptoms, making an image of the object output at the next step.

The associative search process consists in the recovery of all symptoms describing the specific object based on its images. Denote the image initiating the associative search by R_0 and the corresponding resulting image of the associative search by R. A pair of images (R_0,R) will be further called association A or $A(R_0,R)$. The set of all associations on the set of images forms the memory of the knowledgebase of the intelligent system.

At the system learning phase, an archive of images is created. In our case, a set of n input vectors selected form the process history according to the algorithm described in Sect. 4.1 will be considered as an image. At the prediction stage, the input vector x_t will be considered as an initial image R_0^{a} of the associative search, while approximating hypersurface formed by the input vectors from the process history built with the help of the algorithm from Sect. 4.1 will be the final image R^{a} of the associative search. This means that to build a virtual model, one should select the existing hypersurfaces stored in the archive at the learning phase rather than individual vectors close to x_t. The selected hypersurface is an image of the current input vector which is used for output prediction. The algorithm implements the process of image R^{a} recovery based on R_0^{a}, i.e., the associative search process, and can be described by a predicate $\Xi = \{\Xi_i(R_{0i}^{\mathrm{a}},R_i^{\mathrm{a}},T^{\mathrm{a}})\}$, where $R_{0i}^{\mathrm{a}} \subseteq R_0$, $R_i^{\mathrm{a}} \subseteq R$, and T^{a} is the duration of the associative search.

For the algorithm described in this section, this predicate is a function asserting the truth or the falsity of input vector's membership of the specific domain in the inputs space. Therefore, the associative search process is reduced to the selection of a certain set of input vectors satisfying the condition (4.4) from the process archive. If the process history contains no image satisfying (4.4), then either the threshold D_t should be increased, or for a certain image of our input vector, some symptom should be replaced with a more relevant one. Formally, this means that the "worst" (i.e., located farther away from the current input then the rest ones w.r.t. the chosen criterion) vector from the process history will be deleted and replaced with a more relevant one, and so on.

Therefore, the analyst's decision-making process about to buy or to sell at any time step t could be constructed as associative search (process of remembering) of images (similar situations). The coordinates of approximating hypersurfaces used at previous steps are kept in archive.

4.4 Associative Search Procedures in Short Term Forecasting

In short-term price prediction, not only the current situation but also price dynamics is very important. The conventional regression models are not precise enough to handle this problem.

We apply the associative search procedure with more complicated requirements to approximating hypersurface selection. We select from the archive such hypersurface (corresponding to some $\boldsymbol{x}_{t-j}, j = 1, \ldots, s$), that (i) it contains input vector at the current time step t, and (ii) the hypersurface corresponding to $\boldsymbol{x}_{N-j-1}$, $j = 1, \ldots, s$ contains the input vector at the previous time step t − 1. Formally, this means that the predicate becomes more complex:

$$\Xi(R_0^a, R^a, T^a) = \left\{ \sum_{p=1}^{P} \left| x_{t-j,p} \right| \le D_t - \sum_{p=1}^{P} \left| x_{tp} \right|; \sum_{p=1}^{P} \left| x_{t-j-1,p} \right| \le D_{t-1} - \sum_{p=1}^{P} \left| x_{tp} \right| \right\}. \tag{4.3}$$

There is principal opportunity to find more precise rules in the process of price changing by increasing the memory, say, to l steps (l < t).

$$\Xi(R_0^a, R^a, T^a) = \left\{ \sum_{p=1}^{P} \left| x_{t-j,p} \right| \le D_t - \sum_{p=1}^{P} \left| x_{tp} \right|; \right. \\ \left. \sum_{p=1}^{P} \left| x_{t-j-1,p} \right| \le D_{t-1} - \sum_{p=1}^{P} \left| x_{tp} \right|; \ldots, \sum_{p=1}^{P} \left| x_{t-l,p} \right| \le D_{t-l} - \sum_{p=1}^{P} \left| x_{tp} \right| \right\} \tag{4.4}$$

4.5 Model Development by Means of Associative Search Technique Using Wavelet Analysis

There are a variety of processes, which cannot be controlled using linear predictive models. Associative search technique offers a constructive solution for nonlinear processes. However, such processes may feature irregularities at certain instants. In engineering systems, such irregularities often demonstrate oscillating nature. The variability of feed properties due to feed supplier changes in process industries is a typical example. Another example is seasonal and daily load oscillations in power networks that directly affect the optimization of power transmission control modes. The ups and downs of stock market caused by various economic reasons are also well known. Therefore, the design of predictive models by means of associative search technique for such type of time-varying processes looks relevant.

Over the past 20 years, the *wavelet transform* technique has been widely applied for time-varying process analysis (Daubechies and Lagarias 1991). Further we consider an approach to wavelet analysis application in identification tasks, in particular, in model development by means of associative search. Such approach looks promising under transient conditions both for time-varying input signal and unmodeled dynamics of the control object.

4.5.1 Associative Search in Case of Time-Varying Input Vector

In most of industrial applications, in particular, in control systems with an identifier, the input signal is a vector. Let each component of the input vector meet Gauss-Markov conditions, in particular, the independence of sequence members. Also, suppose that at any time instant, vector's components are mutually independent.

At the same time, we suppose that each component of the input vector is, generally, a time-varying sequence, but its singularities apparent at various instants are similar in a certain sense or identical. For example, stock market analysis techniques enables the detection of such "regularities" in market dynamics. In engineering systems, some repeatability (not necessarily periodical) of input signal's properties may be detected by applying statistical analysis to historical process data. Some processes, such as load dynamics in power networks, feature evident cyclicity (Bakhtadze et al. 2011, 2012).

In order to apply associative search algorithm for predicting the dynamics of such processes, we will, as usual, need to select from process history the vectors close to the current one in the sense of the selected criterion (associative impulse).

Case 1 a SISO system. As soon as the input sequence is time-varying, it makes sense to examine discrete wavelet expansions of input signals. In the general case, such expansion can be represented by the following expression:

$$f(t) = \sum_{k=-\infty}^{\infty} c_{jk}\varphi_{jk}(t) + \sum_{j=0}^{\infty}\sum_{k=-\infty}^{\infty} d_{jk}\psi_{jk}(t), \tag{4.5}$$

where j is the depth of multiresolution expansion, which specifies the detailing depth, c_{jk} are scale factors, d_{jk} are detail coefficients.

Let $\psi(t)$ be Haar wavelets: $\psi(t) = \begin{cases} 1, & 0 \le t < 0.5, \\ -1 & 0.5 \le t \le 1, \\ 0 & t < 0, t \ge 1, \end{cases}$

$$\varphi_{jk} = 2^{j/2}\varphi(2^j t - k),\ \psi_{jk} = 2^{j/2}\psi(2^j t - k).$$

For the chosen detailing level L and the current one-dimensional input $x(t)$ we obtain the following multiresolution expansion:

$$x(t) = \sum_{k=1}^{N/2^L} c_k\varphi_{L,k}(t) + \sum_{j=1}^{L}\sum_{k=1}^{N/2^j} d_{jk}\psi_{j,k}(t), N \ge 2^L$$

The coefficients are calculated by means of Mallat algorithm (Mallat 1999).

In the associative search procedure, we will choose from the archive such inputs $x(t^*)$ whose wavelet expansion with the same depth L

$$x(t^*) = \sum_{k=1}^{N/2^L} c^*{}_k\varphi_{L,k}(t) + \sum_{j=1}^{L}\sum_{k=1}^{N/2^j} d^*{}_{jk}\psi_{j,k}(t^*)$$

meets the following 2 conditions:

(1)
$$\left|\sum_{k=1}^{N/2^L} c_k^*\varphi_{Lk}(t^*)\right| + \left|\sum_{k=1}^{N/2^L} c_k\varphi_{Lk}(t)\right| \le c_L, \tag{4.6}$$

where c_L is a positive number, $c_L \underset{L\to\infty}{\to} 0$.

(2) for all coefficients $d_{jk}, k = 1, \ldots N/2^j$ there exists such constant $\tilde{c}_{jk}$ that:

$$\left|d_{kj}^*\right| \le \frac{\tilde{c}_{jk} - \left|\psi_{kj}(t)\right|\left|d_{kj}\right|}{\left|\psi_{kj}(t^*)\right|} \tag{4.7}$$

Now, by the triangle inequality, we get

$$\left|\sum_{k=1}^{N/2^j} d^*_{jk}\psi_{jk}(t^*) - \sum_{k=1}^{N/2^j} d_{jk}\psi_{jk}(t)\right| \leq \left|\sum_{k=1}^{N/2^j} d_{jk}\psi_{jk}(t^*)\right| + \left|\sum_{k=1}^{N/2^j} d_{jk}\psi_{jk}(t)\right| \leq \tilde{c}_j,$$

$$\tilde{c}_j = N/2^{j-1} \cdot \max_{k=1,..,N/2^j} \tilde{c}_{jk}.$$

Combining (4.6) and (4.7) we obtain

$$|x(t^*) - x(t)| \leq |x(t^*)| + |x(t)| = \left|\sum_{k=1}^{N/2^L} c^*_k\varphi_k(t^*) + \sum_{j=1}^{L}\sum_{k=1}^{N/2^j} d^*_{jk}\psi_{jk}(t^*)\right| + \left|\sum_{k=1}^{N/2L} c_k\varphi_k(t) + \sum_{j=1}^{L}\sum_{k=1}^{N/2^j} d_{jk}\psi_{jk}(t)\right| \leq$$
$$\left|\sum_{k=1}^{N/2^L} c^*_k\varphi_k(t^*)\right| + \left|\sum_{k=1}^{N/2^L} c_k\varphi_k(t)\right| + \sum_{j=1}^{L}\left|\sum_{k=1}^{N/2^j} d_{jk}\psi_{jk}(t)\right| + \sum_{j=1}^{L}\left|\sum_{k=1}^{N/2^j} d^*_{jk}\psi_{jk}(t^*)\right| \leq c_L + L\tilde{c}_j = C = const > 0.$$

Thus, the associative impulse, i.e., the criterion of input variables selection from the archive, is expressed by the combination of the conditions (4.6) and (4.7).

Multi-dimensional input case.

Consider the case where the conditions of Gauss-Markov theorem are met. The predicted output value in the associative search procedure is obtained by the LSM. In view of the independence of input vector's components, the associative search criterion should be built as the existence condition of such constants $\tilde{c}^s_{ij}$, where $s = \overline{1, S}$ is the input vector's length, that the following inequalities

(2a) $\left|d^{s*}_{kj}\right| \leq \dfrac{\tilde{c}^s_{jk} - \left|\psi^s_{kj}(t)\right|\left|d^s_{kj}\right|}{\left|\psi^s_{kj}(t^*)\right|}$ hold true simultaneously for all $s = \overline{1, S}$. P known outputs meeting virtual linear model equations $y(t^*) = \sum_{s=1}^{S}\hat{h}^s x^s(t^*)$ correspond to the P vectors $x(t^*)$ selected from the history. The predicted value $y(t)$ is calculated by the LSM.

4.5.2 The Case of Object's Unmodeled Internal Dynamics

At each step in the associative search procedure, we build a new linear model $y(t) = \sum_{s=1}^{S}\hat{h}^s(t)x^s(t)$ of the nonlinear plant. In the unsteady-state case, the coefficients of the transfer function, generally, depend on t.

Suppose, at the first stage of the associative search procedure, P input vectors $x(t^*)$ meeting the conditions (1) and (2a) are selected. The resulting virtual models look as follows:

$$y(t^*) = \sum_{s=1}^{S} \hat{h}^s(t^*) x^s(t^*).$$

In view of the wavelet expansion of the input signals, we have

$$\begin{aligned} y(t^*) &= \sum_{s=1}^{S} \hat{h}^s(t^*) \left[\sum_{k=1}^{N/2^L} c_k^{s*} \varphi_{Lk}^s(t^*) + \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) \right] \\ &= \sum_{s=1}^{S} \hat{h}^s(t^*) \sum_{k=1}^{N/2^L} c_{kj}^{s*} \varphi_{jk}^s(t^*) + \sum_{s=1}^{S} \hat{h}^s(t^*) \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} d_{jk}^{s*} \psi_{jk}^s(t^*). \end{aligned}$$

It should be noted that $\hat{h}^s(t)$ and $\hat{h}^s(t^*)$ are, generally, different. Consider 2 special cases where this difference can be formalized.

1. Additive shift

$$\hat{h}^s(t^*) = \hat{h}^s(t) + a^s(t^*)\,, \text{ where } |a^s(t^*)| \le C_a^{add} = const > 0 \quad \forall s = \overline{1,S}.$$

For simplicity, we confine ourselves by the case where the degree of the detailing of Multiresolution Analysis is rather high. That results in the nulling of the scale factors $c_{jk}^s, s = \overline{1,S}$. In this case, we have

$$\begin{aligned} \sum_{s=1}^{S} \left(\hat{h}^s(t) + a^s(t^*)\right) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) &= \sum_{s=1}^{S} \hat{h}^s(t) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) \\ &+ \sum_{s=1}^{S} a^s(t^*) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*). \end{aligned}$$

In particular, at

$$\begin{aligned} |a^s(t^*)| = C_a^{add} = const \text{ we have } y(t^*) - SC_a^{add} \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) = \\ = \sum_{s=1}^{S} \hat{h}^s(t) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*). \end{aligned}$$

Denote

$$\tilde{y}(t^*) = y(t^*) - SC_a^{add} \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) == \sum_{s=1}^{S} \hat{h}^s(t) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*). \quad (4.8)$$

P known outputs meeting virtual linear model Eq. (4.8) correspond to the P vectors $x(t^*)$ selected from the history. The predicted value $y(t)$ is calculated by the LSM. It should be noted that all equations now include the coefficients $\hat{h}^s(t)$ as unknown quantities.

2. Multiplicative shift

Now let $\hat{h}^s(t^*) = \hat{h}^s(t) \cdot a^s(t^*)$, where $|a^s(t^*)| \le C_a^{mult} = const > 0\ \forall s = \overline{1, S}$. Then the following equalities hold true:

$$y(t^*) = \sum_{s=1}^{S} \hat{h}^s(t^*) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*) = \sum_{s=1}^{S} \hat{h}^s(t) a^s(t^*) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{jk}^{s*} \psi_{jk}^s(t^*)$$
$$= \sum_{s=1}^{S} \hat{h}^s(t) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} a^s(t^*) d_{jk}^{s*} \psi_{jk}^s(t^*).$$

In particular, at $|a^s(t^*)| = C_a^{mult}$

$$y(t^*) = \sum_{s=1}^{S} \hat{h}^s(t) \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} C_a^{mult} d_{jk}^{s*} \psi_{jk}^s(t^*) \tag{4.9}$$

Equations (4.15) and (4.16) are used in the prediction algorithm directly together with the equation for $y(t)$. All equations now include the coefficients $\hat{h}^s(t)$ as unknown quantities.

4.6 Associative Model's Stability Conditions Derived by Means of Multiresolution Spectrum Analysis

Let a predictive associative model of a time-varying nonlinear object is described by Eq. (4.1).

For the specified detailing level L, we obtain the following multiresolution decomposition of the current input vector $x(t)$ (Daubechies and Lagarias 1991):

$$x(t) = \sum_{k=1}^{N/2^L} c_t^x(t) \phi_{L,k}(t) + \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{j,k}^x(t) \psi_{j,k}(t),\ N \ge 2^L \tag{4.10}$$

$$y(t) = \sum_{k=1}^{N/2^L} c_k^y(t) \phi_{L,k}(t) + \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d_{j,k}^y(t) \psi_{j,k}(t),\ N \ge 2^L, \tag{4.11}$$

where: L is the depth of the multiresolution decomposition ($k < t$); $\phi_{L,k}(t)$ are scaling functions; $\psi_{j,k}(t)$ are wavelet functions generated form mother wavelets by stretching/compressing and shifting,

$$\psi_{jk}(t) = 2^{j/2}\psi_{mother}(2^j t - k),$$

(Haar wavelets are further considered as mother ones); j is the analysis detailing level; c_{jk} and $d_{j,k}$ are scaling and detailing coefficients respectively. These coefficients are calculated by Mallat algorithm (Mallat 1999).

In view of the definition of discrete system's transfer function, Eq. (4.1) is equivalent to:

$$P(z) \cdot y(t) = W(z) \cdot x(t),$$

where $P(z)$ and $W(z)$ are transfer matrices whose elements are polynomials of degrees m and r respectively ($L < t{-}m$), z is a one step backward shift operator.

Let $W(z)$ be a diagonal matrix whose elements are polynomials with coefficients $b_{0s}, \ldots, b_{rs}$, $s = 1, \ldots, S$.

Then

$$[a_0 - a_1 z - a_2 z^2 - \cdots - a_m z^m] y(t) = \sum_{s=1}^{S} [b_0 + b_{1s} z + b_{2s} z^2 + \cdots + b_{rs} z^r] x_s(t). \tag{4.12}$$

Instead of the signals $x(t)$ and $y(t)$ we substitute multiresolution decompositions of input and output signals in this equation. As far as the first sums in (4.10) and (4.11) vanish and can be omitted at sufficiently large detailing level, (4.10) and (4.11) imply

$P(z)[\sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d^y_{j,k}(t)\psi_{j,k}(t)] = W(z)[\sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d^x_{j,k}(t)\psi_{j,k}(t)]$ or, in view of (4.12):

$$\begin{aligned} a_0 \sum_{j=1}^{L} \sum_{k=1}^{N/2^L} d^y_{j,k}(t)\psi_{jk}(t) = & \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} \{a_1 \cdot d^y_{j,k}(t-1) + \sum_{s=1}^{S} b_{1s} d^{x_s}_{j,k}(t-1)\}\psi_{j,k}(t-1) + \cdots \\ & + \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} \{a_m d^y_{j,k}(t-m) + \sum_{s=1}^{S} b_{ms} d^{x_s}_{j,k}(t-m)\}\psi_{j,k}(t-m) \\ & + \sum_{s=1}^{S} b_{m+1,s} \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d^x_{j,k}(t-m-1)\psi_{j,k}(t-m-1) + \cdots + \sum_{s=1}^{S} b_{rs} \sum_{j=1}^{L} \sum_{k=1}^{N/2^j} d^x_{j,k}(t-r)\psi_{j,k}(t-r) \end{aligned} \tag{4.13}$$

where x_s denotes the belonging of the corresponding coefficients to the sth component of the input vector.

The dynamic object described by Eq. (4.13) will be stable if the following objects (corresponding to the following expressions for each summand with respect to k $(k = 1, \ldots, N/2^j)$ and $j, (j = 1, \ldots, L)$ in the left and right sides of Eq. (4.13):

$$\begin{aligned} a_0 d_{jk}^y(t)\psi_{jk}(t) = {} & \{a_1 \cdot d_{j,k}^y(t-1) + \sum_{s=1}^{S} b_{1s} d_{j,k}^{x_s}(t-1)\}\psi_{j,k}(t-1) + \cdots \\ & + \{a_m d_{j,k}^y(t-m) + \sum_{s=1}^{S} b_{ms} d_{j,k}^{x_s}(t-m)\}\psi_{j,k}(t-m) + \cdots \\ & + \sum_{s=1}^{S} b_{m+1,s} d_{j,k}^{x_s}(t-m-1)\psi_{j,k}(t-m-1) + \cdots + \sum_{s=1}^{S} b_{rs} d_{j,k}^{x_s}(t-r)\psi_{j,k}(t-r) \end{aligned} \tag{4.14}$$

are stable altogether.

In other terms, as far as $a_0 d_k^y(t) \neq 0$, we have:

$$\begin{aligned} \psi_{jk}(t) = {} & \{[a_1 \cdot d_{j,k}^y(t-1) + \sum_{s=1}^{S} b_{1s} d_{j,k}^{x_s}(t-1)]/a_0 d_k^y(t)\} \cdot \psi_{j,k}(t-1) + \cdots \\ & + \{[a_m d_{j,k}^y(t-m) + \sum_{s=1}^{S} b_{ms} d_{j,k}^{x_s}(t-m)]/a_0 d_k^y(t)\}\psi_{j,k}(t-m) + \cdots \\ & + [\sum_{s=1}^{S} b_{m+1,s} d_{j,k}^{x_s}(t-m-1)/a_0 d_k^y(t)]\psi_{j,k}(t-m-1) + \\ & + \cdots + [\sum_{s=1}^{S} b_{rs} d_{j,k}^{x_s}(t-r)/a_0 d_k^y(t)]\psi_{j,k}(t-r)\,. \end{aligned} \tag{4.15}$$

To make it simple, we temporarily omit the indices k and j in (10) and denote:

$$\tilde{\mathbf{x}}(t) = \begin{bmatrix} [\tilde{x}_1(t)] \\ \ldots \\ [\tilde{x}_r(t-r+1)] \end{bmatrix}, \; \tilde{\mathbf{x}}(t) \in \mathbf{R}^r;$$

where

$$\begin{aligned} \tilde{x}_1(t) &= \psi(t); \\ \tilde{x}_2(t) &= \psi(t-1); \\ & \ldots \end{aligned} \tag{4.16}$$

$\tilde{x}_r(t) = \psi(t - r + 1)$, then:

$$\tilde{\mathbf{x}}(t) = \begin{bmatrix} [\psi(t)] \\ \dots \\ [\psi(t-r+1)] \end{bmatrix}; \tilde{\mathbf{x}}(t-1) = \begin{bmatrix} [\psi(t-1)] \\ \dots \\ [\psi(t-r)] \end{bmatrix}.$$

Further, we denote:

$$\begin{aligned} c_1 &= \left\{ a_1 d^y(t-1) + \sum_{s=1}^{S} b_{1s} d^{x_s}(t-1) \right\} / a_0 d^y(t); \dots \\ c_m &= \left\{ a_m d^y(t-m) + \sum_{s=1}^{S} b_{ms} d^{x_s}(t-m) \right\} / a_0 d^y(t); \\ c_{m+1} &= \sum_{s=1}^{S} b_{m+1,s} d^{x_s}(t-m-1) / a_0 d^y(t); \dots c_m = \\ &= \sum_{s=1}^{S} b_{rs} d^{x_s}(t-r) / a_0 d^y(t) \end{aligned} \tag{4.17}$$

and rewrite (4.17) as:

$$\begin{aligned} &\psi(t) - \frac{c_1}{2}\psi(t-1) - \dots - \frac{c_{r-1}}{2}\psi(t-r+1) = \frac{c_1}{2}\psi(t-1) + \dots + \frac{c_{r-1}}{2}\psi(t-r+1) + \dots \\ &\quad + c_m \cdot \psi(t-m) + c_{m+1}\psi(t-m-1) + c_r \cdot \psi(t-r)\,. \end{aligned} \tag{4.18}$$

Simultaneous fulfillment of the equalities

$$\begin{aligned} \psi(t) = \frac{c_1}{2}\psi(t-1); -\frac{c_1}{2}\psi(t-1) &= \frac{c_2}{2}\psi(t-2); \\ -\frac{c_{m-1}}{2}\psi(t-m+1) &= \frac{c_m}{2}\psi(t-m); \dots \\ -\frac{c_{r-1}}{2}\psi(t-m+1) &= \frac{c_r}{2} \cdot \psi(t-r) \end{aligned}$$

is a sufficient condition for the fulfillment of Eq. (4.18).

With the above notification we have

$$\begin{bmatrix} 1 & & 0 & 0 \\ 0 & -\frac{c_1}{2} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{c_{r-1}}{2} \end{bmatrix} \tilde{\mathbf{x}}(t) = \begin{bmatrix} \frac{c_1}{2} & & 0 & 0 \\ 0 & \dots & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{c_r}{2} \end{bmatrix} \cdot \tilde{\mathbf{x}}(t-1). \tag{4.19}$$

Let the matrix in the left side of (4.13) be invertible. Then:

$$\begin{aligned}\tilde{\mathbf{x}}(t) &= \begin{bmatrix} 1 & & 0 & 0 \\ 0 & -\frac{c_1}{2} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{c_{r-1}}{2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \frac{c_1}{2} & & 0 & 0 \\ 0 & \frac{c_2}{2} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & \frac{c_r}{2} \end{bmatrix} \cdot \tilde{\mathbf{x}}(t-1) = \\ &= \begin{bmatrix} 1 & & 0 & 0 \\ 0 & -\frac{2}{c_1} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{2}{c_{r-1}} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \frac{c_1}{2} & & 0 & 0 \\ 0 & \frac{c_2}{2} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & \frac{c_r}{2} \end{bmatrix} \cdot \tilde{\mathbf{x}}(t-1) = \\ &= \begin{bmatrix} \frac{c_1}{2} & & 0 & 0 \\ 0 & -\frac{c_2}{c_1} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{c_r}{c_{r-1}} \end{bmatrix} \cdot \tilde{\mathbf{x}}(t-1)\end{aligned} \tag{4.20}$$

We denote $\hat{\mathbf{x}}(t) = \tilde{\mathbf{x}}(t) \cdot d^y(t)$. By multiplying both sides of Eq. (4.20) by $d^y(t)$ and then multiplying and dividing its right side by $d^y(t-1)$ we obtain:

$$\hat{\mathbf{x}}(t) = \begin{bmatrix} \frac{c_1}{2} \cdot \frac{d^y(t)}{d^y(t-1)} & & 0 & 0 \\ 0 & -\frac{c_2}{c_1} \cdot \frac{d^y(t)}{d^y(t-1)} & & \dots \\ \dots & & \dots & 0 \\ 0 & & & -\frac{c_r}{c_{r-1}} \cdot \frac{d^y(t)}{d^y(t-1)} \end{bmatrix} \cdot \hat{\mathbf{x}}(t-1). \tag{4.21}$$

Equation (4.21) can be interpreted as a system's state-space representation. The system's stability is determined by the properties of the characteristic polynomial of the respective diagonal matrix.

Thus, a sufficient stability condition for the object (4.15) (and, hence, (4.13) for any $k = 1, \dots, N/2^j$) is ensured by the fulfillment of all inequalities

$$\left| \frac{c_1}{2} \frac{d^y(t)}{d^y(t-1)} \right| < 1 \text{ or } |c_1| \cdot |d^y(t)| < 2 \cdot |d^y(t-1)|;$$

$$\left| \frac{c_1}{2} \frac{d^y(t)}{d^y(t-1)} \right| < 1 \quad \text{or} \quad |c_1| \cdot \left| d^y(t) \right| < 2 \cdot \left| d^y(t-1) \right|;$$

$$\left| \frac{-c_2}{c_1}(t) \frac{d^y(t)}{d^y(t-1)} \right| < 1, \dots, \text{или} \quad |c_2| \left| d^y(t) \right| < |c_1| \left| d^y(t-1) \right|, \tag{4.22}$$

$$\dots \left| \frac{-c_r}{c_{r-1}} \frac{d^y(t)}{d^y(t-1)} \right| < 1, \dots, \text{или} \quad |c_r| \left| d^y(t) \right| < |c_{r-1}| \left| d^y(t-1) \right|,$$

or

$$\left|a_1 d^y(t-1)+\sum_{s=1}^{S} b_{1s} d^{x_s}(t-1)\right| / \left|a_0 d^y(t)\right| \cdot \left|d^y(t)\right| < 2\left|d^y(t-1)\right|;$$

$$\left|a_m d^y(t-m)+\sum_{s=1}^{S} b_{ms} d^{x_s}(t-m)\right| / \left|a_0 d^y(t)\right| \cdot \left|d^y(t)\right| <$$

$$\left|a_{m-1} d^y(t-m+1)+\sum_{s=1}^{S} b_{m-1s} d^{x_s}(t-m+1)\right| / \left|a_0 d^y(t)\right| \cdot \left|d^y(t-1)\right|;$$

$$\left|\sum_{s=1}^{S} b_{m+1,s} d^{x_s}(t-m-1)/a_0 d^y(t)\right| \left|d^y(t)\right| < \left|\sum_{s=1}^{S} b_{m,s} d^{x_s}(t-m)/a_0 d^y(t)\right| \left|d^y(t-1)\right|;$$

$$\ldots \left|\sum_{s=1}^{S} b_{rs} d^{x_s}(t-r)/a_0 d^y(t)\right| \left|d^y(t)\right| < \left|\sum_{s=1}^{S} b_{r-1,s} d^{x_s}(t-r+1)/a_0 d^y(t)\right| \left|d^y(t-1)\right|.$$

Therefore, the sufficient stability conditions for the object (4.22) for all coefficients of multiresolution wavelet decomposition of its input and output at a specified time step t look as follows:

$$\left|a_1 d^y(t-1)+\sum_{s=1}^{S} b_{1s} d^{x_s}(t-1)\right| < 2\left|a_0 d^y(t-1)\right|;$$

$$\left|a_2 d^y(t-2)+\sum_{s=1}^{S} b_{2s} d^{x_s}(t-2)\right| \left|d^y(t)\right| < \left|a_1 d^y(t-1)+\sum_{s=1}^{S} b_{1s} d^{x_s}(t-1)\right| \left|d^y(t-1)\right|;$$

$$\ldots$$

$$\left|a_m d^y(t-m)+\sum_{s=1}^{S} b_{ms} d^{x_s}(t-m)\right| \left|d^y(t)\right| < \left|a_{m-1} d^y(t-m+1)+\sum_{s=1}^{S} b_{m-1s} d^{x_s}(t-m+1)\right| \left|d^y(t-1)\right|;$$

$$\left|\sum_{s=1}^{S} b_{m+1,s} d^{x_s}(t-m-1)\right| \left|d^y(t)\right| < \left|\sum_{s=1}^{S} b_{m,s} d^{x_s}(t-m)\right| \left|d^y(t-1)\right|;$$

$$\ldots$$

$$\left|\sum_{s=1}^{S} b_{rs} d^{x_s}(t-r)\right| \left|d^y(t)\right| < \left|\sum_{s=1}^{S} b_{r-1,s} d^{x_s}(t-r+1)\right| \left|d^y(t-1)\right|.$$

4.7 Stability Conditions for an Associative Model of a Multimodal Object

A system approach to the study of the operation of large manufacturing and power plants can be effectively interpreted in terms of multimodal objects.

A feature of multimodal objects is the possibility of predicting their future operation based on the knowledge generated at the learning stage. These knowledge formalize the dynamics of process variables specific to a certain operating mode. The “belonging” to the operating mode is determined when a predictive model is built using clusterization.

Examples of multimodal objects are: product lifecycle (manufacturing and logistical aspects), the operation of a power generation system or its subsystems in normal, pre-emergency, emergency and post-emergency modes, oil pumping through a piping system with changing topology, etc.

The key attributes of multimodal systems are independent production stages and/or multiple process modes.

In both cases, the plant can be described by an extended input vector $\widehat{\mathbf{x}} = x_{t1}^1 \ldots x_{tS}^1 \ldots x_{t1}^m \ldots x_{tS}^m \ldots x_{t1}^M \ldots x_{tS}^M$, where the index t denotes the instant of discrete system operation, m is the mode (manufacturing stage, operating mode, etc.) number, s is the number of the input vector’s component. The mode is characterized by input vector’s belonging to one of disjoint domains in R^S space.

Here:

- plant operation in a specific mode m characterized by certain input parameters such as flowrates, pressures or temperatures presumes that all input vector’s components except for $x_{t1}^m \ldots x_{tS}^m$ are equal to zero;
- for a multistage process, the input vector’s components may have different nature and possess different values dependent on the process stage. In particular, specific groups of input variables may change while the others remain constant or exceed the bounds of a certain subspace.

In order to predict the object’s violation of safe operating boundaries the following scheme is applied:

(1) Associative search technique is used to build a linear predictive model of a nonlinear object with extended input vector $\widehat{\mathbf{x}}$.
(2) The object with predicted properties is investigated.

In case of time-varying plant, it makes sense to examine the spectrum of a multiresolution wavelet decomposition of the forecast of the object’s output signal.

The stability of linear dynamic objects can be investigated by means of the method described in (4.2) and (4.3), or using Gramian technqiue. According to the latter, the approach to the operating boundary is associated with unrestricted growth of Frobenius controllability gramian for object’s certain state-space realization.

Associative search allows to apply this technique to the nonlinear plant study. It was proved in Sukhanov et al. (2012) that the investigation of the Frobenius norm of dynamic plant’s transfer function would be sufficient.

4.8 Conclusion

Associative search algorithms enabling deeper investigation of dynamic time-varying objects were considered. The associative impulse is formed as requirements imposed on the coefficients of wavelet expansions of input signals. The paper showed that the associative search in the time domain is a special case of the algorithm offered above. Associative search procedures based on wavelet analysis open up new effective approaches to the identification of time-varying processes.

In the present work, the sufficient conditions of the stability of time-varying object's predicted output were formulated in terms of transfer function's wavelet spectrum.

Wavelet transformation coefficients reveal the signal's fluctuating structure in various scales and instants of time. This is especially important for time-varying plants. The sufficient conditions of stability formulated in this paper were based on the investigation of associative predictive model's wavelet spectrum.

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Chapter 5
Multiple Criteria Decision Support System for Tender Consortium Building Within the Cluster Organization

Bartłomiej Małachowski

Abstract The article focuses on the process of contractors' consortium building that can be observed within cluster organizations. The problem of building a consortium is modeled as a multiple-criteria decision problem. Decision about consortium composition relays on many qualitative and quantitative criteria, from which qualitatively expressed criterion of competence seems to have significant importance. The formalization of such a criterion is presented. The paper proposes two step reduction method that decreases complexity of decision making in case of larger consortia. The case of group decision making within consortium is also covered in the paper.

Keywords Business cluster · Project team building · Multiple criteria decision analysis · Analytic hierarchy process · Group decision making · Competence modeling

5.1 Introduction

In recent years, clusters have become relatively popular form of business cooperation. Companies normally competing on common market join clusters and cooperate with each other to benefit from several opportunities created within cluster. The nature of these benefits is different. It could be easer migration of employees, common promotional events or access to skilled labor and reliable subcontractors. One of the activities observed frequently among cluster members is building a consortium of contractors in order to prepare a joint offer and apply for a tender. Companies by joining their potential can gain access to bigger contracts that

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alone would be beyond their reach (Anderson et al. 2006; Cluster Management Guide 2006).

In this article the author proposes the method that supports companies in building consortium of contractors in a way that can increase their chance to win a tender.

5.2 Aims and Benefits of Collaboration Within Cluster Initiatives

The notion of cluster appeared in the literature in the early 80s, but the theoretical background for it was given almost 60 years earlier by Marshall (1920), who introduced the concept of external economies as the positive effects for companies whose growth depends on the development of the sector in which they exist. A. Marshall emphasized the benefits of scale and agglomeration, such as specific industrial atmosphere that promotes certain formal and informal practices, entrepreneurship, organizational culture, development of complementary industries, access to skilled labor and specialized manufacturing equipment.

One of the most popular definitions of cluster is the definition proposed by Porter (2001): cluster is a geographically concentrated group of interconnected companies, specialized suppliers, service providers, firms in related industries and associated institutions that compete with each other and cooperate at the same time. This means that in the certain geographic area (region or within the limits of two or more provinces), there is a high concentration of companies that cooperate and compete at the common market. These related institutions can work together to achieve specific benefits, such as acquisition of new markets, joint promotion, brand building, human resource training or even running some joint projects. Greater efficiency of enterprises belonging to a cluster is achieved through greater intensification of information flows, reduced transaction costs, complementary services and access to business supporting institutions, universities and research centers. This can lead to greater capacity for innovation, understood as the implementation of new technologies and know-how as well as stimulation of experience and skills exchange between employees at various operational levels.

Cluster initiatives can consist of different types of organizations, referred in the literature as actors of the cluster. These could be:

- large enterprises and SMEs, private companies, including competitors, suppliers of goods and services, customers, suppliers or technology related companies sharing knowledge and experience,
- financial institutions: national banks, commercial banks, venture capital, business angels and private equity,
- government ministries, agencies involved in shaping legislation, investment, education, regional agencies and local government bodies, local community,

- universities: education, R&D institutions, technology transfer, science parks,
- public and private-public non-governmental organizations, trade, networking, such as joint venture, cluster organizations,
- media.

In order to succeed cluster initiatives need to meet a number of success factors (Solvell et al. 2003). These are: presence of existing networks, partnerships and linkages, a strong innovation base with R&D support, the existence of strong base of skills, adequate technical infrastructure, presence of large companies, strong organizational culture, convenient access to financing. The range of actions that could be taken by cluster initiative is very broad. The model of CIPM (Cluster Imitative Performance Model), which is the result of analysis of 500 initiatives situated all over the world, distinguishes twenty one activities. The CIPM determines the degree of relevance of the actions carried out by members of the cluster. Initiatives adopt activities according to their abilities and needs, which varies at different stages of cluster development, starting from embryonic stage, when they arise through phase after phase up to the end stage of maturity when they disappear. In order to be able to effectively manage such a wide range of activities, they have been divides into five main activities carried out with varying frequency and intensity (Cluster Management Guide 2006):

(1) information and marketing communication: an updated database, analysis of consumer needs, website, initiatives, suppliers and services directory, newsletter, regular meetings, study tours, company visits,
(2) training skills: an analysis of educational needs and employment, promoting and mentoring talented workers, action aimed at improving the qualifications of personnel at various levels of management, regular meeting for workshop and seminar, education for employees of one industry, working with R&D unites and others that affect the educational profile workers,
(3) initiating and supporting projects which increase cooperation in the cluster, to develop contacts between members and outside the cluster the desire to take the initiative to R&D, scientific and special service providers, the establishment of pro-grams to support the participant, the implementation of innovation,
(4) marketing and PR: material information—promoting of regional identity building, marketing and public relations on a national and international level, the measurement of brand strength, participation in fairs, prestigious conferences, company visits, presentations to major customers, lobbying,
(5) internationalization: access to international knowledge, conferences, meetings, analysis of consumer trends, supporting the process of establishing coo-petition and business participating, setting up networks between international initiatives, making more attractive foreign visits in the cluster.

Figure 5.1 shows cluster activities, which may be used during the tender preparation process. Cluster members may be active in one, two or more activities. Preparing a tender for request means choosing, from all cluster members and their

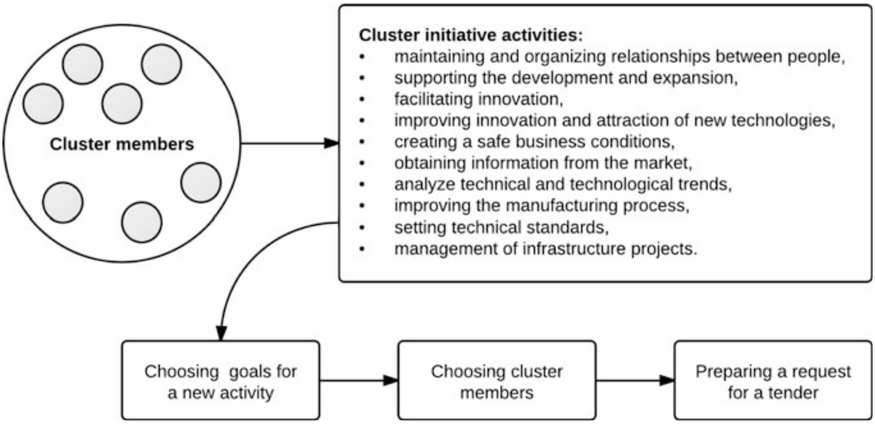

Fig. 5.1 Preparation of cluster members for a request for a tender

activities a new activity and goals which is needed to be done for the cluster growth. Some activities are based on a request for a tender. The next step is choosing partners, which are managed to work on a tender. If goals and partners are found a request for tender is going to be done.

The diversity of cluster initiative activities shows, that there are a lot of reasons why cluster members could prepare a request for a tender. Tenders are chances for SME to reach the next level of growth. Tenders help to achieve individual as well as cluster initiative goals. Preparing tenders in a cluster usually is much easier, because they are built on a trust and relationships among familiar business partners such as companies, R&D and government.

5.3 Competence-Based Methods in Project Management

Companies, whose main part of core business activities is creation and processing of knowledge, treat knowledge of their employees as their most valuable resources. In some sectors of business (e.g. ICT, semiconductor engineering, architecture and construction design etc.) knowledge and the ability to efficiently use it is a crucial factor for obtaining competitive advantage over other companies present on a given market. Such companies, described as knowledge-based organization, very often use project-oriented management as their main management model. Organizations of this type manage portfolio of projects and their main potential are human resources with their intellectual capital, which has to be assigned to tasks spread across projects of the company. This situation creates specific requirements for management methods, among which the methods for human resource management seem to have the strategic importance (Gareis and Huemann 2000).

The importance of knowledge treated as a resource allocated to tasks of a project can be seen in many works on this subject (Gareis and Huemann 2000; Huemann et al. 2007; Małachowski 2011; Różewski and Małachowski 2011). Allocation of human resources to intellectual task of a project requires knowledge representation model, which allows selection of worker according to their competence to accomplish the project task. The term 'competence' is understood in this context as demonstrated ability to apply knowledge and skills. This definition of competence is in conformity with definition introduced by International Standard Organization in ISO 9000:2005. ISO (2005) and Project Management Institute (association of project management practitioners) (2004) recommend that decisions about project members selection should be carried out in a formalized manner, according to some precisely defined criteria. This approach to project team building can be found in many works in project management and operational research (Gareis and Huemann 2000; Huemann et al. 2007; Małachowski 2011). Some of these works use mathematical formalization of competence that is based on methods of fuzzy competence sets (Yu and Zhang 1989, 1990; Wang and Wang 1995; Kushtina et al. 2009). This approach uses fuzzy sets (Zadeh 1965) to model collection of competences and methods of graph theory to analyze competence expansion process. Analysis of competence expansion process is used in many applications (Małachowski 2011; Różewski and Małachowski 2011; Kushtina et al. 2009; Wang and Wang 1995) to provide quantitative measures of how personal competences match competences required to solve a given task.

Business clusters has some similarities to the project-oriented organizations. They both are groups of partners that join to reach common goals. Naturally, cooperation within project-oriented organizations is more intense and can be managed in more effective way but some processes can be supported by the same or similar methods.

In this paper the author proposes the multiple-criteria decision support method of contractors' consortium building basing on the analogy to project management methods used to support project team building within project-oriented organizations. Decision about consortium composition and setup relays on many qualitative and quantitative criteria, from which qualitatively expressed criterion of competence seems to have significant importance.

5.4 Multiple-criteria Decision Analysis of Contractors' Consortium Composition Process

Many solutions to consortium building problem model it as the classic assignment problem recognizing agent qualification (Caron et al. 1999; Pentico 2007) where not every agent is qualified to do every task, which is regulated by the binary parameter. However, this approach is insufficient to model complex decision made by consortium as in real-life problems the decision is made basing on preference of the decision maker influenced by many qualitative and quantitative criteria.

In this article the author proposes approach based on multiple-criteria decision modeling and graph-based formal model of project work breakdown structure. Similar approaches can be found in (Małachowski 2011; Różewski and Małachowski 2011; Kushtina et al. 2009; Wang and Wang 1995; Harbi KMAS 2001).

5.4.1 Formal Representation of the Consortium Building Problem

Formalization of some quantitative criteria requires a project model that provides information on project work breakdown structure (WBS) as well as on time interdependency of project work packages (WP). In this approach the author proposes the model based on oriented graph (digraph). Thus, we have (Fig. 5.2):

$P = \{p_i\}$—the set of project work packages, $i = 1, \ldots, I$

$Z = \{z_j\}$—the set of companies willing to enter the consortium, $j = 1, \ldots, J$

$V = \{v^n\}$—the set of all possible consortium variants (company to work package assignments), $n = 1, \ldots, N$, where:

$v^n = \left(v_i^n\right)_{i=1}^{I} = \left(v_1^n, v_2^n, \ldots, v_i^n, \ldots, v_I^n\right)$—sequence of assignments in the nth consortium variant, $v_i^n \in Z$

$D(S, P)$—Project relation digraph, where:

$S = \{s_k\}$—set of project states, $k = 1, 2, \ldots, K$

$init(p_i)$—initial state of a work package p_i

$ter(p_i)$—final state of a work package p_i

5.4.2 Integration of Qualitative and Quantitative Decision Criteria

The decision about the composition and assignment of the consortium can be influenced by many possible criteria, like for example: competence of its members, their experience, technical resources, financial resources, etc. In some cases,

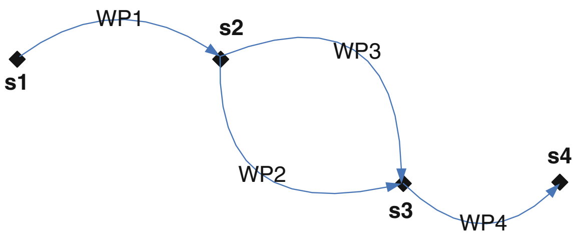

Fig. 5.2 Example project relation digraph for a project consisting of four work packages

decision makers use even very subjective criteria like reliability or punctuality. Therefore, the set of decision criteria can be a mixture of qualitative and quantitative, criteria with different scales, values (continuous, discrete, linguistic) (Figueira et al. 2005a, b):

$K = \{k_m\}$—set of decision criteria, $m = 1, \ldots, M$

For the set of decision criteria K the set of decision alternatives V (the set of all possible consortium variants) we can define the performance matrix E that reflects performance measures of every consortium variant for every decision criterion.

$$E = [e_{nm}] = \begin{bmatrix} e_{11} & \cdots & e_{1m} & \cdots & e_{1M} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ e_{n1} & \cdots & e_{nm} & \cdots & e_{nM} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ e_{N1} & \cdots & e_{Nm} & \cdots & e_{NM} \end{bmatrix}$$

where:

e_{nm}—performance measure of nth variant according to mth criterion.

The variant with the highest value of decision maker preference obtained through the analysis of its performance measures according to every criterion can be selected for the tender. However, not every MCDA is able to incorporate qualitative and quantitative criteria in one decision model. The method that has well proven background for such a case is Analytic Hierarchy Process (AHP) (Saaty 2001). Therefore, the author choses this method to find the solution to the given problem (Guitouni and Martel 1998; Harbi KMAS 2001; Figueira et al. 2005a, b; Perego and Rangone 1996).

5.4.3 Formalization of the Competence Criterion

In the Sect. 5.3 of the article the necessity of using formal quantitative criterion of competence in the problem of consortium building was explained. Such a criterion can be formalized by using methods of fuzzy competence sets provided in Wang and Wang (1995). Because projects are broken down into several independent work packages, the global criterion function must aggregate local criterion function values for every company to work package assignment. Moreover, this function must take into account the fact that personal competences can change throughout the project, so it is necessary to use dynamic programming to formalize this function. Such a model can be found in Małachowski (2011), where the aggregation of competence obtained as follows:

$$c^{\mathrm{K}}(v^n) = \sum_{i=1}^{I} c^{\mathrm{K}}\left(Sk\left(v_i^n, init(p_i), v^n\right), Tr(p_i)\right)$$

where:

$Tr(p_i)$—set of competences required to successfully accomplish a work package p_i

$Sk\left(v_i^n, init(p_i), v^n\right)$—set of competences of a company selected for a work package p_i measured in the initial state of p_i

c^K—measure of the lack of competence to successfully accomplish a task with given set of competences.

5.5 Model of the Decision Support System for Contractors' Consortium Building

Finding the solution to the given problem requires choosing one variant among several other alternatives. In case of the selected AHP method this problem can be equivalently solved through preparing a ranking of all decision alternatives and picking the one with the highest rank (Figueira et al. 2005a, b).

Using MCDA ranking method like AHP requires evaluation of every decision alternative (consortium variant), thus even for small consortia this method requires relatively large number of evaluation operations (number of decision alternatives grows exponentially $N = J^I$), which have to be done for every decision criteria. Moreover, in case of the methods basing on pair-wise comparisons of all alternatives (AHP method) it is necessary to do $\binom{N}{2}$ comparisons of decision alternatives for each of M criteria.

5.5.1 Two-Step Reduction of the Problem Complexity

The large numbers of elementary operations required by AHP significantly reduce usability of the method (Harbi KMAS 2001; Figueira et al. 2005a, b; Perego and Rangone 1996). However, in real life situations evaluation of every consortium variant is not necessary as only several combinations of companies selected from the cluster can give valuable consortium.

Most of the variants can be removed from further analysis by introducing simple constraints. In case of every project work package it is possible to verify whether all companies fulfill pre-assignment conditions that allow them to candidate for the contractor of this work package. These conditions can be obtained by simple checking, whether the company:

- has any of the competences required to accomplish the work package;
- has minimal experience required by the work package;
- has technical resources required by the work package;
- has financial resources required by the work package, etc.

The proper choice of pre-assignment conditions can significantly reduce the number of consortium variants.

Further reduction can be achieved by certain constraints set for the whole setup of the consortium variant. General form of the constraint can be formalized as follows:

$$f(v^n) \leq f_{\max} \text{ or } f(v^n) \geq f_{\min}$$

where:

$f(v^n)$—constraint function value for nth consortium variant

$f_{\max}$ or $f_{\min}$—threshold value

Setting these types of constraints can increase further reduction of necessary analysis and leave only best suited variants. Depending on the decision maker the set of constraint functions and their thresholds can be chose individually (Fig. 5.3).

Example constraint functions:

- overall competence of the consortium,
- financial resources of the consortium,
- number of consortium members,
- number of work packages assigned to one company.

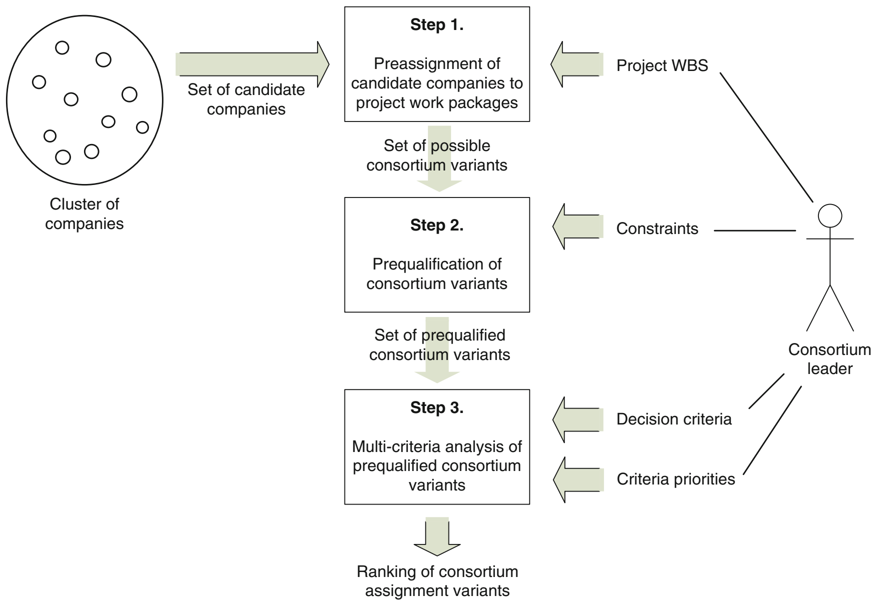

Fig. 5.3 Model of the decision support system for consortium members' selection

5.6 Group Decision Making in Case of Multiple Consortium Leaders

Tender consortia are usually built around one company called consortium leader. The leader is the company that initiates the process of consortium formation, pre-pares the offer and has a key impact on the form and composition of the consortium. The method presented in this article naturally suits this scenario. However, in case of some consortia there is a core group of companies which initiate formation of the consortium. Usually this is the case, when the core group does not have enough resources to make an offer to a tender. Such a group requires than to gain additional partners and form bigger consortium able to match tender requirements. However, this complicates the decision-making process because each of the partners of the initial group wants to have influence on the decision, which additional partners to select and how to assign them within consortium.

This problem can be easily solved with the AHP method, which provides support for group decision making. The AHP introduces procedures that can be applied in case of group decision making. If the group cannot find agreement on the final ranking the first technique is the Consensus. Consensus refers to the achievement of a consensus of group members on the initial preference. If a consensus cannot be reached, the group may than choose to vote or compromise on the initial judgment. Then, if the group do not find agreement on whether to vote or to compromise, than a geometric mean of individual judgment of all group members should be calculated. This means, that every core group member has to perform separate decision analysis based on AHP method and then individual outcomes has to be averaged to obtain final results (Figueira et al. 2005a, b; Lai et al. 2002).

5.7 Numerical Example

In order to illustrate the proposed method, let us consider a contract with the scope broken down into four work packages. The schedule of the project is similar to the one depicted in Fig. 5.1, thus there are two work packages that are run simultaneously. The call for consortium members issued within the cluster resulted in five candidate companies. This implies, that at least one candidate has to be rejected.

According to the method, every possible variant of companies to work packages assignment should be considered. This gives relatively high number of $5^4 = 625$ possible allocations. According to AHP method, making the decision on most preferable variant selection requires evaluation of every allocation variant against every other variant in series of pair-wise comparisons, that have to done for every decision criteria. This causes, that overall number of single decisions needed to be made by the decision maker amounts to M.195,000.

5.7.1 Pre-assignment of Candidates to Work Packages

Two conditions were chosen to verify, whether a candidate can be considered as a possible contractor for a work package: required competence and required technical resources. Using the method of fuzzy competence set analysis measures of the lack of competence (see Sect. 5.5) where computed for every candidate. This measures cannot be obtained if a candidate does not have any of required competences for a work package. In such cases a candidate is considered as incompetent for a work package and it has to be rejected (Table 5.1).

5.7.2 Prequalification of Consortium Variants

Taking into account the pre-assignment conditions the total number of decision variants can be significantly reduced. In case of the given example the possible number of consortium variants is: 3 • 1 • 1 • 3 = 9. The further reduction of the number of consortium variants that can enter multiple-criteria decision analysis phase of the method was obtained by introducing two prequalification constraints. Their analysis is shown in Table 5.2.

Table 5.1 Analysis of pre-assignment conditions

	Lack of competences					Required technical resources					Possible candidates
	z_1	z_2	z_3	z_4	z_5	z_1	z_2	z_3	z_4	z_5	
p_1	0.00	2.04	4.12	n.a.	n.a.	1	1	1	1	1	z_1, z_2, z_3
p_2	n.a.	n.a.	n.a.	0.00	1.15	0	1	1	1	0	z_4
p_3	1.81	n.a.	n.a.	n.a.	2.10	1	0	1	1	0	z_1
p_4	0	0	0.13	0	0.13	0	0	1	1	1	z_3, z_4, z_5

Table 5.2 Analysis of prequalification constraints

Consortium variant	Lack of competence < 5.0		No. of partners > 2		Prequalified
	Value	Fulfilled	Value	Fulfilled	
(z_1, z_4, z_1, z_3)	1.94	Yes	3	Yes	Yes
(z_1, z_4, z_1, z_4)	1.81	Yes	2	No	No
(z_1, z_4, z_1, z_5)	1.94	Yes	3	Yes	Yes
(z_2, z_4, z_1, z_3)	3.98	Yes	4	Yes	Yes
(z_2, z_4, z_1, z_4)	3.85	Yes	3	Yes	Yes
(z_2, z_4, z_1, z_5)	3,98	Yes	4	Yes	Yes
(z_3, z_4, z_1, z_3)	6.06	No	4	Yes	No
(z_3, z_4, z_1, z_4)	5.93	No	3	Yes	No
(z_3, z_4, z_1, z_5)	6.06	No	4	Yes	No

Selection of the most preferable from the five prequalified consortium variants requires performing the final multiple-criteria analysis using the AHP method and arbitrarily defined set of decision criteria. It is well known method, so due to limitations of article length the author decided not cover details of obtaining the AHP solution.

5.8 Conclusions and Future Work

The paper presented the method which supports a consortium leader in the process of consortium building. The problem was modeled using methods of MCDA and competence modeling methods based on fuzzy sets and the graph theory. The article also covered the case, when the decision on consortium composition has to be made by the group of leaders. The main advantage of the proposed approach is the use of quantitative formal model of competences allowing precise selection and allocation of consortium members. The method provide formalized solution to the problem that in most real-life situation is solved using common-sense methods. Moreover, the method by introducing set of company pre-assignment conditions and set of variant qualification constraints significantly reduce the complexity of the necessary multiple-criteria decision analysis.

The proposed solution can be further extended with the game theory model of sharing payout among consortium members after the completion of the tender.

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Chapter 6
Guideline for MCDA Method Selection in Production Management Area

Jarosław Wątróbski and Jarosław Jankowski

Abstract Each decision situation is described by a set of certain characteristics—a factor which classifies it into a category of decision problems. Many times the chosen problematic determines the choice of the most suitable Multi-Criteria Decision Analysis (MCDA) method to be employed for supporting a decision maker. The following paper deals with directions developing in the literature on choosing the MCDA method best suited to solve a given decision problem. In the study, two sources of factors which influence the choice of the method were identified: a subject of the decision and a characteristic of dependencies in the problem description. When considering factors originating from the subject of the decision, the main focus is on case studies which support applying a particular method to a given problem. Dependencies between parameters describing a problem were analysed from the impact that the existence of various data sources has to them. The selected group of factors was consecutively generalised and its impact on the result of the decision support (using a collection of methods) was pointed out. The performed analysis constitutes the source of the strategy for choosing one method from the considered group of methods. Examples of applications in production management area are given.

Keywords Multicriteria decision aid · Choosing a multicriteria method · Decision support

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6.1 Introduction

B. Roy (1990) defined a decision problem as a representation of a component of a global decision, and while taking into consideration the progress of the decision process, a problem can be solved independently and used as a starting point (a milestone) of decision aiding.

The literature of the subject distinguishes various types of decision alternatives, which can be classified as real alternatives (which are completely described and the implementation is possible) and fictional alternatives (which are idealised, not completely described or even imagined). The other distinction differentiates feasible (projects which can be applied) and unfeasible (which fulfil contradictory goals and are suitable only for discussion) alternatives. Considering the analysed phenomena, global and partial alternatives can be outlined as well. Therefore, the main difficulty in solving multicriteria decision problems is to analyse decision alternatives (choice options) from different points of view, which is referred to as multicriteria evaluation (Mousseau and Slowinski 1998).

Hence, assume that when formulating a multicriteria problem, a set of decision alternatives (actions) A is a subject to judgments according to n criteria $c_1, c_2, \ldots, c_n$, forming a family of criteria $C = \{c_1, c_2, \ldots, c_n\}$. It can be assumed without loss of generality, that the higher is the value of a criterion function $c_i(a)$, the better an alternative $a \in A$ is, in means of the criterion c_i for all $i \in C$. The goal of a decision-maker (DM) or a system analyst is to isolate a minimal set of decision alternatives or to create a ranking (over the whole set or over the "isolated" set) from the best alternative to the worst one, in conformity with the DM's preferences.

A defined decision problem can be classified into one of representative decision problematics (Roy 1990):

(a) choice problematic (α)—finding a subset containing best solutions,
(b) sorting problematic (β)—assigning alternatives to defined "a priori" categories,
(c) ranking problematic (γ)—creating a ranking of alternatives from the best to the worst (Fig. 6.1).

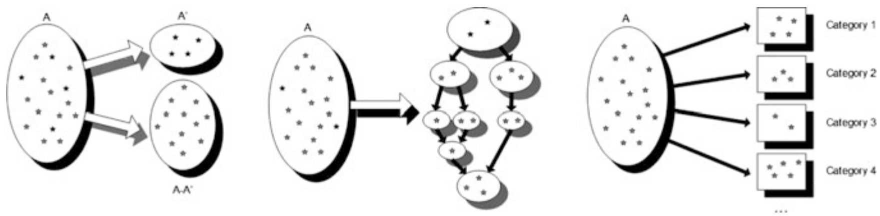

Fig. 6.1 Representative problematics (choice α, ranking γ, and sorting β respectively) in multicriteria decision aiding. *Source* Based on Roy (1991)

A description problematic (δ) was identified as a problematic of assigning alternatives from the set A into categories, where limited descriptions of alternatives and (or) its consequences exist. Hence, the process shall be directed in such a way so as to explore information about potential alternatives.

According to Roy (1990), an MCDA process can be divided into following four levels:

- the level of defining the subject of a decision and the scope of participation of an analyst,
- outlining criteria and analysing consequences of a decision,
- modelling global preferences of a DM,
- selecting research procedures (Fig. 6.2).

Roy's model points out that the choice of a MCDA method is a crucial element for solving a decision problem. Choosing a multicriteria method only on the basis of decision issues and an operational approach, seems to be too general, since in this way in order to solve the given decision problem one can select many methods. It results from a significant number of MCDA methods and their diversity (Hanne 1999; Wasielewska et al. 2014). Furthermore, it is difficult to identify which method is most suitable for solving a given problem (Bouyssou et al. 1993; Watrobski et al. 2014). Therefore, decision-makers are usually not able to justify the choice of the method they applied to solve a decision situation, often adapting their decision problem to the chosen multicriteria method (Guitouni and Martel 1998). Moreover, the choice of the multicriteria method is frequently made in an arbitrary manner and decision-makers are motivated by their knowledge about the given method or by

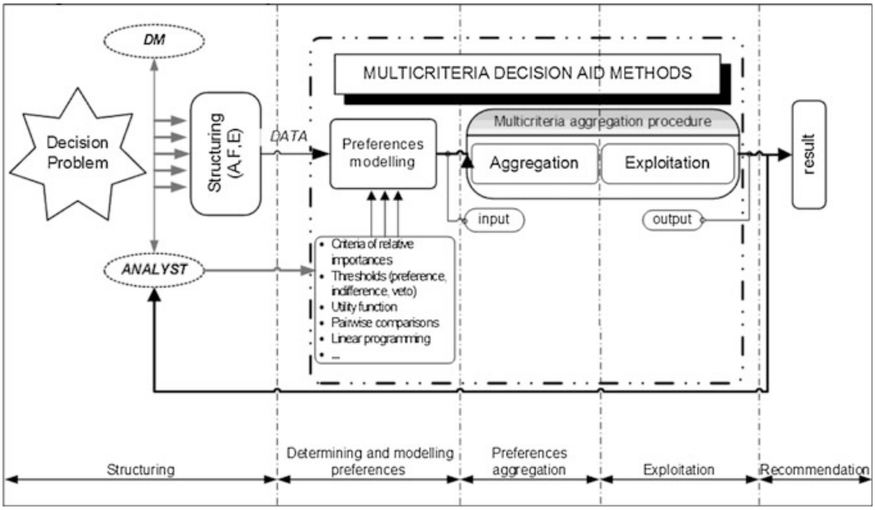

Fig. 6.2 The procedure of constructing solutions of a decision situation. *Source* Based on Guitouni and Martel (1998)

the availability of software which supports it (Kornyshova and Salinesi 2007; Li and Thomas 2014). However, the proper and reasoned selection of a proper MCDA method for a given decision situation is a vital issue, since different methods may give other solutions of the same problem (Wang and Triantaphyllou 2008).

6.2 Determinants of Suitability of a Method for Solving a Problem

The choice of a decision solving algorithm is determined by the subject of the decision situation. An analyst who is aiding a DM, sets a problem structure based on the nature of the decision, where nature is perceived as the area of reality which a decision applies to. An analyst is required to use his or her domain knowledge based on his or her experience in order to distinct the nature of a decision. An analyst should be able to understand a specific language of domains, where decisions apply to. Choosing one of the aforementioned problematics is the result of interaction between a DM and an analyst. Common determinants which decide about classifying a problem into one of problematics is availability of DM's resources or limitation to perform only single implementation of a decision (usually due to financial constraints). In practice, the aforementioned determinants are major reasons for categorising a decision into the problematic α or γ.

A problematic of a decision problem is the vaguest factor which determines a group of multicriteria methods which are suitable to solve the problem. In addition, the definition of a problem consists of a data model and a domain of the reality, where the subject of the decision situation is placed. An algorithm for calculating the performance function $c(\cdot)$ is defined by a DM in cooperation with an analyst and is based on the problem's domain of the reality. Performances can be calculated as judgements elaborated directly by a DM.

Hence, comparisons and aggregation are performed in different ways by multicriteria methods. Moreover, performance values, local and global preferences of a DM are included in the decision process using different approaches. Techniques of aggregation and dealing with preferences are distinctive features of a particular method. In order to isolate factors which influence choosing a particular approach, applications of various techniques based on outranking relations and aggregation to a common utility function were analysed further in the current paper.

A sort of a scale of preference information determines an amount of data which can be utilised to create an order of attributes which can be further exploited to make a recommendation. The main factor used to classify scales is the variety of possible comparisons within a scale and among other scales. In respect of the aforementioned determinants three main types of scales are distinguished (Bouyssou et al. 2006): ordered, interval and ratio scales. Following such a classification, criteria can be modelled on a respective scale according to the equation presented below (Meyer and Roubens 2005):

$$c_i \in \begin{cases} X_i := \left\{ c_1^i \prec \cdots \prec c_{s_i}^i \right\} \\ \mathbf{c}_i \\ c_i^- \le u \le c_i^+ \end{cases}$$

where s_i is a number of evaluations on an interval scale, $c_i \in \mathbf{c}_i$ describes a real value of a criterion, and u is a value of a level of membership to a linguistic set. An important factor considered when placing a value on a scale is to bond a relative scale with absolute values describing the reality. Relative utility of a factor described by a real value is an outcome of a decision situation. Choosing a technique to formalise calculations should be driven by characteristics of a chosen method and its suitability to a selected form of modelling the decision. Moreover, determining a category of a decision situation and selecting appropriate software is an absolute condition of obtaining a recommendation aligned to the definition of a decision situation.

6.3 Subject of a Decision Situation

A precise structure of criteria cannot be constructed when it is based only on the description of a decision situation. Furthermore, a difficulty arises due to tacit knowledge which is not elaborated by a decision maker in the problem definition, and which is not included in a mathematical model and covers practical, economical, or psychological areas of a decision situation. The unmodelled aspect of a decision has to be included by an analyst while choosing a method to solve a model (a MCDA method). Nonetheless, structuring such an aspect is cumbersome because important factors describing the domain of a problem may be considered unimportant and obvious by a DM, and he or she does not mention it during consultations with an analyst. The fundamental determinant of a decision situation is a multicriteria aspect of the problem, which can be described as fulfilling the following condition:

$$\underset{i \neq j}{\exists}\, c_i, c_j \in C : \max C \Rightarrow \max c_i \vee \max c_j$$

where: C is a set of criteria of a decision problem.

In order to choose a method to solve a problem, there have been developed numerous classifications of multicriteria methods which are based on various criteria (Moffett and Sarkar 2006; Guitouni et al. 1998; Munda 2005). Two main sources of classification determinants can be distinguished: an algorithmic approach and an application approach. The algorithmic approach determines the choice of the method based on characteristics of a problem description. Characteristics of a problem description consist of its problematic, a number of criteria, attributes and alternatives, scales where values are projected on and forms of these values. The second approach categorises methods on the basis of known applications for various types of problems which may include: economical, technological, social, financial, or interdisciplinary problems covering many specific domains.

In an enterprise organisation, decisions cover various aspects of operations which are influenced by different groups of factors. For example, financial factors describe a financial position of an organisation, economical factors describe an economical and business environment, and strategic factors allow to model the estimated impact of internal actions on relations between an organisation and the market environment (Spronk et al. 2005).

6.4 Dependencies Between Attributes

A values scale is a principal characteristic of the domain describing a decision situation. In accordance with a scale used, appropriate means are required to perform calculations and comparisons of $c(\cdot)$ function values. Moreover, a selected scale determines an amount of preferences information and a subset of MCDA techniques suitable for performing outranking tests. The need for using pseudo-criteria or fuzzy outranking relations is determined by the domain of values used in a problem description as well.

The ability to apply pairwise comparisons is determined by methods used to describe alternatives, particularly by domains of data which make up descriptions. Furthermore, applicability of pairwise comparisons is limited by the human brain capabilities. A human is not able to make reliable comparisons between two "very small" or two "very big" values. Another limitation is an outcome of human limitation to make comparisons only between values from the same scale. Hence, the application of methods which are based on pairwise comparisons is limited to situations where respective attributes of all alternatives are described with values of the same homogeneous scale (Saaty 2005).

6.5 Collaboration with an Analyst in Defining a Decision Situation

Considering the schema of the decision aiding process, presented in Fig. 6.2., the description of a decision situation has the most significant impact on the structuring phase. This phase involves cooperation between a DM and an analyst in order to determine relations between the internal preference structure of a DM (mental schema) and a developed decision model. However, an analyst is not aware of the real preference model of a DM. In order to discover relations between preferences, he or she asks a series of questions of a DM. Choices about preferred alternatives made by a DM are used by an analyst to determine dependencies among attributes and to create a model in an appropriate form. The purpose of developing a decision model is to reflect inter-attribute dependencies, while performance functions $c(\cdot)$ are defined in order to imitate mathematical operations performed within the internal utility model of a DM (Dyer 2005).

A source of a decision situation determines sources of requirements for a recommendation and characteristics of the data which can be used to develop a decision model. Moreover, the whole decision process is determined by characteristics of a decision situation. Hence, a decision aiding approach shall be selected with consideration of a decision situation's domain. Availability of data and DM's judgements depends on a type of a decision situation. Some decision aiding methods include the direct participation of a DM in the aggregation phase. Therefore that phase is described as "decision maker judgements' aggregation". Two aspects of diversity of values provided by a DM can be distinguished: the first aspect is diversity of scales where judgements are placed on, which results in different information capacity of these values; the second aspect describes dynamics of relations between values and DM's preference levels.

6.6 Impact of Factors on the Result of Decision Aiding

A description of a decision situation shall be provided in an appropriate form which depends on an expected outcome and may include: choosing the most preferred alternative or creating a simple or an interval ranking of alternatives. Choosing a method to solve a decision problem shall be based on DM's expectations and available data about the problem.

Hence a selected method articulates expectations for a recommendation and recognised availability of data about a decision situation. Following methods deliver an order of decision alternatives: ELECTRE II-IV (Figueira et al. 2005), PROMETHEE I (Brans and Mareschal 2005), MACBETH (Bana e Costa et al. 2005); as a simple ranking PROMETHEE II Brans and Mareschal (2005), AHP (Saaty 2005), UTA, UTASTAR (Siskos et al. 2005), MAUT (Dyer 2005) (as a ranking with utility values). Therefore, the aforementioned methods are suitable for decision or the problematic γ.

Pinpointing the best alternative among a considered set is the result obtained with the following methods: ELECTRE I, Iv and IS (Figueira et al. 2005), where a selection is made by finding an extremal point in the seeking space or by finding an alternative fulfilling appropriate outranking conditions. Such an outcome determines suitability of the above-mentioned methods for α problematic situations.

Methods ELECTRE TRI (Figueira et al. 2005) and UTADIS (Zopounidis and Doumpos 1999) deliver classifications based on proximity of analysed alternatives to specified categories. Hence, those methods shall be applied for aiding a situation of the problematic β.

The source of the description of a decision situation is not the only determinant of the type of preference information. The possible accuracy of the description and the level of DM's cognition of a problem are significant factors as well.

Table 6.1 Applicability of multicriteria methods for different types of preference information

Type of preference information	Multicriteria decision aid method
Deterministic	O_W, O_F, M_V, T_P, S_M, A_H, E_M, $E_{1–4}$, E_T, E_S, M_C, $P_{1–2}$, O_R, R_G, M_N, A_N, $A_H + T_P$
Non-deterministic	U_T, M_U, A_H, P_M, M_Z
Fuzzy	O_F, A_F, N_I, P_M, M_F, T_F, A_{NF}, $A_F + T_P$, $P_{1F–2F}$, $A_F + T_F$
Cardinal	O_W, M_V, T_P, U_T, M_U, S_M, A_H, E_M, $E_{1–4}$, E_T, E_S, $P_{1–2}$, N_I, M_Z, M_N, A_F, T_F, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$, $P_{1F–2F}$,
Ordinal	$E_{1–2}$, E_T, M_C, O_R, R_G, N_I, P_M, M_F

Applicability of multicriteria decision aiding methods according to available preference information is presented in Table 6.1. The table uses symbolics of MCDA methods considered in this paper. The translation of the aforementioned symbolics is presented below.

$E_{1–4}$—ELECTRE I-IV; E_S—ELECTRE IS; E_T—ELECTRE TRI; $P_{1–2}$—PROMETHEE I-II; $P_{1F–2F}$—Fuzzy PROMETHEE I-II; E_M—EVAMIX; N_I—NAIADE; P_M—PAMSSEM; T_C—TACTIC; O_W—OWA; O_F—Fuzzy OWA; M_X—Maximax; M_N—Maximin; M_F—Fuzzy Maximin; G_P—Goal Programming; AG—AGRUS; Q_F—QUALIFLEX; R_G—Regime; M_C—MELCHIOR; O_R—ORESTE; I_D—IDRA; P_C—PACMAN; M_P—MAPPAC; P_G—PRAGMA; M_B—MACBETH; A_H—AHP; A_M—Modified AHP; A_F—Fuzzy AHP; A_N—ANP; A_{NF}—Fuzzy ANP; T_P—TOPSIS; T_F—Fuzzy TOPSIS; $A_H + T_P$—AHP + TOPSIS; $A_F + T_P$—Fuzzy AHP + TOPSIS; $A_F + T_F$—Fuzzy AHP + Fuzzy TOPSIS; M_V—MAVT; M_U—MAUT; U_T—UTA; S_M—SMART; M_Z—Martel and Zaras.

The goal of decision aiding is to simplify describing a decision problem from the level of complex structure of attributes into the level of adapting estimated consequences of decision alternatives to DM preferences in a form appropriate for a chosen problematic of a decision situation. Hence, consequence analysis requires performing operations reflecting the real impact of attribute values on implementing an analysed alternative.

6.7 Conceptual Framework

A context of a decision situation determines not only a set of methods used to describe the reality, but the structuring process and the interpretation of values included in a model as well. A good decision is based on reliable analysis of available data and on predicting consequences of investigated phenomena which shall be as close as possible to real outcomes of implementation. Hence, cooperation between a DM and an analyst should be focused only on gathering the description of a decision situation from the DM. An analyst should possess knowledge about possible domains of reality which are covered by decision problems. Moreover, he or she should use his or her knowledge to pinpoint guidelines for decision-making techniques. A common professional language of DM–analyst relations helps to avoid misunderstanding in mutual communication which may cause distortion in drawing a picture of a decision situation. The description of a decision situation is a fundamental element of the consequence analysis of decision alternatives and it allows to determine DM's preferences both locally for particular criteria, and globally for considered alternatives.

Selecting a procedure of analysis should include considering not only parameters which describe a decision situation, but the whole context of a decision situation. Therefore, it is advisable to develop guidelines for selecting an appropriate method according to various aspects of a decision situation. To achieve such a goal a multidimensional applicability analysis is required. The analysis should investigate impact of types of preference information, linear and intra-criteria compensation, binary relations possible to identify, a problematic of a decision, forms of $c(\cdot)$ functions and manners of including them in a model, and veto properties. The result of such an analysis can be used to develop a rule based system, which validates the applicability of a suggested MCDA method. A sample set of rules is presented below.

The following approach of selecting a subset of multicriteria methods was developed: Let M be a set of all considered multicriteria methods, F a function defined as F(C, M) returning a subset $M^{*}\subseteq M$ of methods applicable to solve a decision problem described by a criteria set C. This work suggests defining the function F as a result of using decision rules presented in Table 6.3.

In the first step, based on results from Moffett and Sarkar (2006), a taxonomy of MCDA methods is proposed (Table 6.2), which operate on the set M defined as follows:

$$\begin{aligned} \mathrm{M} =(&\mathrm{E_1,\ E_2,\ E_3,\ E_4,\ E_S,\ P_1,\ P_2,\ P_{1F},\ P_{2F},\ T_C,\ M_X,\ M_N,\ G_P,\ A_G,\ Q_F,\ R_G,\ M_C,\ O_R,\ I_D,\ P_C,}\\ &\mathrm{M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ T_P,\ T_F,\ A_H + T_P,\ A_F + T_P, A_F + T_F,\ M_V,\ U_T)} \end{aligned}$$

Developed criteria $k_1(C)$, $k_2(C)$, $k_3(C)$, $k_4(C)$, $k_5(C)$ are defined as follows:

k_1 (C)—possibility of comparing all alternatives according to all criteria,

k_2 (C)—applying weights for criteria,

k_3 (C)—an ability to define quantitative importance of each criterion,

k_4 (C)—an ability to use relative quantitative importance of each criterion,

k_5 (C)—an ability to possibility of comparing all alternatives according to all criteria on quantitative scale.

On the basis of fulfilling requirements of each of criterion $k_f(C)$ by MCDA methods listed in Table 6.2, rules for selecting a function F(C, M) are presented in Table 6.3.

The rules presented above allows do determine the final set of methods suitable to solve the decision problem defined by the criteria set C.

Table 6.2 Taxonomy of MCDA methods

Set of MCDA methods (M)		k_1 (C)	k_2 (C)	k_3 (C)	k_4 (C)	k_5 (C)
		Possibility of comparing all alternatives according to all criteria	Applying weights for criteria	Ability to define quantitative importance of each criterion	Ability to use relative quantitative importance of each criterion	Ability to possibility of comparing all alternatives according to all criteria on quantitative scale
ELECTRE I	E_1	TRUE	TRUE	TRUE	FALSE	FALSE
ELECTRE II	E_2	TRUE	TRUE	TRUE	FALSE	FALSE
ELECTRE III	E_3	TRUE	TRUE	TRUE	FALSE	TRUE
ELECTRE IV	E_4	TRUE	FALSE	FALSE	FALSE	FALSE
ELECTRE IS	E_S	TRUE	TRUE	TRUE	FALSE	FALSE
ELECTRE TRI	E_T	TRUE	TRUE	TRUE	FALSE	TRUE
PROMETHEE I-II	P_{1-2}	TRUE	TRUE	TRUE	FALSE	TRUE
Fuzzy PROMETHEE I-II	P_{1F-2F}	TRUE	TRUE	TRUE	FALSE	TRUE
EVAMIX	E_M	TRUE	TRUE	TRUE	FALSE	TRUE
NAIADE	N_I	TRUE	TRUE	TRUE	FALSE	TRUE
PAMSSEM	P_M	TRUE	TRUE	TRUE	FALSE	TRUE
TACTIC	T_C	TRUE	TRUE	TRUE	FALSE	TRUE
OWA	O_W	TRUE	TRUE	TRUE	FALSE	TRUE
Fuzzy OWA	O_F	TRUE	TRUE	TRUE	FALSE	TRUE
Maximax	M_X	TRUE	FALSE	FALSE	FALSE	FALSE
Maximin	M_N	TRUE	FALSE	FALSE	FALSE	FALSE
Fuzzy maximin	M_F	TRUE	TRUE	TRUE	FALSE	TRUE
Goal programming	G_P	TRUE	FALSE	FALSE	FALSE	TRUE
AGRUS	A_G	TRUE	TRUE	FALSE	FALSE	FALSE
QUALIFLEX	Q_F	TRUE	TRUE	FALSE	FALSE	FALSE
Regime	R_G	TRUE	TRUE	FALSE	FALSE	FALSE
MELCHIOR	M_C	TRUE	TRUE	FALSE	FALSE	TRUE
ORESTE	O_R	TRUE	TRUE	FALSE	FALSE	TRUE
IDRA	I_D	TRUE	TRUE	TRUE	TRUE	TRUE
PACMAN	P_C	TRUE	TRUE	TRUE	TRUE	TRUE
MAPPAC	M_P	TRUE	TRUE	TRUE	TRUE	TRUE
PRAGMA	P_G	TRUE	TRUE	TRUE	TRUE	TRUE
MACBETH	M_B	TRUE	TRUE	TRUE	TRUE	TRUE
AHP	A_H	TRUE	TRUE	TRUE	TRUE	TRUE
Modified AHP	A_M	TRUE	TRUE	TRUE	TRUE	TRUE
Fuzzy AHP	A_F	TRUE	TRUE	TRUE	TRUE	TRUE
ANP	A_N	TRUE	TRUE	TRUE	TRUE	TRUE
Fuzzy ANP	A_{NF}	TRUE	TRUE	TRUE	TRUE	TRUE
TOPSIS	T_P	TRUE	TRUE	TRUE	FALSE	TRUE
Fuzzy TOPSIS	T_F	TRUE	TRUE	TRUE	FALSE	TRUE
AHP + TOPSIS	$A_H + T_P$	TRUE	TRUE	TRUE	TRUE	TRUE

(continued)

Table 6.2 (continued)

Set of MCDA methods (M)		k_1 (C)	k_2 (C)	k_3 (C)	k_4 (C)	k_5 (C)
		Possibility of comparing all alternatives according to all criteria	Applying weights for criteria	Ability to define quantitative importance of each criterion	Ability to use relative quantitative importance of each criterion	Ability to possibility of comparing all alternatives according to all criteria on quantitative scale
Fuzzy AHP + TOPSIS	$A_F + T_P$	TRUE	TRUE	TRUE	TRUE	TRUE
Fuzzy AHP + Fuzzy TOPSIS	$A_F + T_F$	TRUE	TRUE	TRUE	TRUE	TRUE
MAVT	M_V	TRUE	TRUE	TRUE	FALSE	TRUE
MAUT	M_U	TRUE	TRUE	TRUE	FALSE	TRUE
UTA	U_T	TRUE	TRUE	TRUE	FALSE	TRUE
SMART	S_M	TRUE	TRUE	TRUE	FALSE	TRUE
Martel and Zaras	M_Z	TRUE	TRUE	TRUE	FALSE	TRUE

Table 6.3 Rules for selecting an MCDA method on the basis of taxonomy

Rule	k_1(C)	k_2(C)	k_3(C)	k_4(C)	k_5(C)	Function F(C, M)
R1	1	0	0	0	0	E_4, M_X, M_N
R2	1	1	0	0	0	A_G, Q_F, R_G
R3	1	1	1	0	0	E_1, E_2, E_S
R4	1	0	0	0	1	G_P
R5	1	1	0	0	1	M_C, O_R
R6	1	1	1	0	1	E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T
R7	1	1	1	1	1	I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$

6.8 Empirical Research and Discussion

The practical verification of presented rules was carried out for referential sets of sample literature applications of MCDA in the field of production management. Studies (Garcia-Cascales and Lamata 2009; Marzouk 2011; Shanian et al. 2008; Cavallaro 2010; Abdi 2009; Wang et al. 2007, 2008; Li and Huang 2009; Mikhailov 2002; Ayag et al. 2009; Yu and Hu 2010; Nikolić et al. 2009; Khalil et al. 2005; Geldermann et al. 2000; Ertgrul and Gunes 2007; Rao and Davim 2008; Shanian and Savadogo 2006, 2009; Athanasopoulos et al. 2009; Huang et al. 2011; Yurdakul and Ic 2009; Dawal et al. 2013) were taken as referential literature sources. In the experimental part, the results of a selection of an MCDA research

Table 6.4 Practical verification decision rules with the use of referential sources (MCDA application in production management areas)

No.	K1—Comparisons of all variants relative to all criteria	K2—Weights of criteria	K3—Quantitative weights of criteria	K4—Relative quantitative weights of criteria	K5—Comparisons of variants relative to criteria on a quantitative scale	Remarks	Recommended MCDA method	Decision rule	Reference
1	1	1	1	1	1	selecting a system/a technique for cleaning an engine	A_H	$\{I_D, P_C, M_P, P_G, M_B, \mathbf{A_H}, A_M, A_F, A_N, A_{NF}, A_H + T_P, A_F + T_P, A_F + T_F\}$	Garcia-Cascales and Lamata (2009)
2	1	1	1	0	1	selecting glass for assembly	E_3	$\{\mathbf{E_3}, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T\}$	Marzouk (2011)
3	1	0	0	0	1	selecting glass for assembly	E_3	$\{G_P\}$	Marzouk (2011)
4	1	1	1	0	1	selecting a material for production	E_3	$\{\mathbf{E_3}, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T\}$	Shanian et al. (2008)
5	1	1	1	0	1	assessment of production processes of photovoltaic cells	E_3	$\{\mathbf{E_3}, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T\}$	Cavallaro (2010)
6	1	1	1	1	1	assessment of reconfigurable production devices	A_F	$\{I_D, P_C, M_P, P_G, M_B, A_H, A_M, \mathbf{A_F}, A_N, A_{NF}, A_H + T_P, A_F + T_P, A_F + T_F\}$	Abdi (2009)

(continued)

Table 6.4 (continued)

No.	K1—Comparisons of all variants relative to all criteria	K2—Weights of criteria	K3—Quantitative weights of criteria	K4—Relative quantitative weights of criteria	K5—Comparisons of variants relative to criteria on a quantitative scale	Remarks	Recommended MCDA method	Decision rule	Reference
7	1	1	1	1	1	selecting a device maintenance technique	A_F	{I_D, P_C, M_P, P_G, M_B, A_H, A_M,**A_F**, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$}	Wang et al. (2007)
8	1	1	1	1	1	production system selection	A_F	{I_D, P_C, M_P, P_G, M_B, A_H, A_M, **A_F**, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$}	Li and Huang (2009)
9	1	1	1	1	1	factory/manufacturer selection for producing a given product	A_F	{I_D, P_C, M_P, P_G, M_B, A_H, A_M,**A_F**, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$}	Mikhailov (2002)
10	1	1	1	1	1	assessment of design concept of a device	A_{NF}	{I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, **A_{NF}**, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$}	Ayag and Ozdemir (2009)

(continued)

Table 6.4 (continued)

No.	K1—Comparisons of all variants relative to all criteria	K2—Weights of criteria	K3—Quantitative weights of criteria	K4—Relative quantitative weights of criteria	K5—Comparisons of variants relative to criteria on a quantitative scale	Remarks	Recommended MCDA method	Decision rule	Reference
11	1	1	1	1	1	selecting a trigeneration system for energy production in a building	A_F+T_F	{I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $\mathbf{A_F + T_F}$}	Wang et al. (2008)
12	1	1	1	0	1	assessment of production plant productivity	T_F	{E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, $\mathbf{T_F}$, M_V, U_T}	Yu and Hu (2010)
13	1	1	1	0	1	ranking of copper concentrates	P_2	{E_3, P_1, $\mathbf{P_2}$, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T}	Nikolić et al. (2009)
14	1	0	0	0	1	hydrothermal treatment process in waste management	P_2	{G_P}	Khalil et al. (2005)
15	1	1	1	0	1	selecting a smelting technique in ironworks/steelworks	P_{1F}	{E_3, P_1, P_2, $\mathbf{P_{1F}}$, P_{2F}, T_C, T_P, T_F, M_V, U_T}	Geldermann et al. (2000)
16	1	1	1	0	0	selecting a machine for a production company	T_F	{E_1, E_2, E_S}	Ertgrul and Gunes (2007)

(continued)

Table 6.4 (continued)

No.	K1—Comparisons of all variants relative to all criteria	K2—Weights of criteria	K3—Quantitative weights of criteria	K4—Relative quantitative weights of criteria	K5—Comparisons of variants relative to criteria on a quantitative scale	Remarks	Recommended MCDA method	Decision rule	Reference
17	1	1	1	1	1	selecting a material for production	A_H+T_P	{I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, $\mathbf{A_H + T_P}$, $A_F + T_P$, $A_F + T_F$}	Rao and Davim (2008)
18	1	1	1	1	1	selecting a material for production	A_H+T_P	{I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, $\mathbf{A_H + T_P}$, $A_F + T_P$, $A_F + T_F$}	Rao and Davim (2008)
19	1	1	1	0	0	selecting a material for production	E_1	{$\mathbf{E_1}$, E_2, E_S}	Shanian and Savadogo (2006)
20	1	1	1	0	0	selecting a material for production	E_2	{E_1, $\mathbf{E_2}$, E_S}	Shanian and Savadogo (2006)
21	1	1	1	0	1	selecting a material for coating mechanical parts	T_F	{E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, $\mathbf{T_F}$, M_V, U_T}	Athanasopoulos et al. (2009)
22	1	0	0	0	1	materials selection in environmentally conscious design	T_P	{G_P}	Huang et al. (2011)

(continued)

Table 6.4 (continued)

No.	K1—Comparisons of all variants relative to all criteria	K2—Weights of criteria	K3—Quantitative weights of criteria	K4—Relative quantitative weights of criteria	K5—Comparisons of variants relative to criteria on a quantitative scale	Remarks	Recommended MCDA method	Decision rule	Reference
23	1	1	1	0	0	selecting a material for production of sensitive components	E_S	$\{E_1, E_2, \mathbf{E_S}\}$	Shanian and Savadogo (2009)
24	1	0	0	0	0	selecting a material for production of sensitive components	E_4	$\{\mathbf{E_4}, M_X, M_N\}$	Shanian and Savadogo (2009)
25	1	1	1	0	1	selecting a material for production of sensitive components	T_P	$\{E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, \mathbf{T_P}, T_F, M_V, U_T\}$	Shanian and Savadogo (2009)
26	1	1	1	0	1	selecting machine tools for a production company	T_P	$\{E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, \mathbf{T_P}, T_F, M_V, U_T\}$	Yurdakul and Ic (2009)
27	1	1	1	1	1	selecting CNC machine tools for a production company	A_F+T_P	$\{I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, A_H + T_P, \mathbf{A_F + T_P}, A_F + T_F\}$	Dawal et al. (2013)

method chosen by the authors were compared with the results of application of proposed taxonomy and decision rules suggested (Tables 6.2 and 6.3).

The MCDA method selection process consists of five steps and each of them requires carrying out a proper rule. It will be presented by means of a referential example in Table 6.4 in Point 6. The examined problem consists in assessing reconfigurable production devices. Three alternatives are being considered with regard to twenty-one criteria or sub-criteria. Therefore, one needs to select a method allowing to compare all alternatives relative to all criteria. Criterion $k_1(C)$ has a value 1 and the following methods can be considered:

$$k_1(C) = (E_1,\ E_2,\ E_3,\ E_4,\ E_S,\ P_1,\ P_2,\ P_{1F},\ P_{2F},\ T_C,\ M_X,\ M_N,\ G_P,\ A_G,\ Q_F,\ R_G,\ M_C,\ O_R,\ I_D,\ P_C,\ M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ T_P,\ T_F,\ A_H + T_P,\ A_F + T_P,\ A_F + T_F,\ M_V,\ U_T)$$

As far as the weights of the criteria are concerned, they should be quantitative even though it is difficult to determine their importance without a point of reference. Therefore, they are compared in pairs. Thus, a criterion k_2 has value 1 and selects MCDA methods which allow to attribute weights to the criteria, criteria k_3 and k_4 have also value 1 and determines methods which allow to apply quantitative weights and activates methods which make it possible to determine relative criteria weights.

$$k_2(C) = (E_1,\ E_2,\ E_3,\ E_S,\ P_1,\ P_2,\ P_{1F},\ P_{2F},\ T_C,\ A_G,\ Q_F,\ R_G,\ M_C,\ O_R,\ I_D,\ P_C,\ M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ T_P,\ T_F,\ A_H + T_P,\ A_F + T_P, A_F + T_F,\ M_V,\ U_T)$$

$$k_3(C) = (E_1,\ E_2,\ E_3,\ E_S,\ P_1,\ P_2,\ P_{1F},\ P_{2F},\ T_C,\ M_C,\ O_R,\ I_D,\ P_C,\ M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ T_P,\ T_F,\ A_H + T_P,\ A_F + T_P, A_F + T_F,\ M_V,\ U_T)$$

$$k_4(C) = (I_D,\ P_C,\ M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ A_H + T_P,\ A_F + T_P, A_F + T_F)$$

Alternatives are assessed on a quantitative scale, that's why 1 value of a criterion k_5 is obtained.

$$k_5(C) = (E_3,\ P_1,\ P_2,\ P_{1F},\ P_{2F},\ T_C,\ G_P,\ M_C,\ O_R,\ I_D,\ P_C,\ M_P,\ P_G,\ M_B,\ A_H,\ A_M, A_F,\ A_N,\ A_{NF},\ T_P,\ T_F,\ A_H + T_P,\ A_F + T_P,\ A_F + T_F,\ M_V,\ U_T)$$

Next, in order to select a proper MCDA method for solving a given problem rule R7 (Table 6.3) was used. According to Tables 6.2 and 6.3, a set of methods was determined: I_D, P_C, M_P, P_G, M_B, A_H, A_M, A_F, A_N, A_{NF}, $A_H + T_P$, $A_F + T_P$, $A_F + T_F$. This solution is in accordance with the authors' choice (Abdi 2009), who employed the method A_F to solve the decision problem.

When analyzing Table 6.4, one can notice that the recommendation of the method in conformity with the presented rules is not always in accordance with the method used by the authors of this publication. Such a case can be seen in Point 3 in Table 6.4. The selected method was E_3, whereas the set of criteria k_1–k_5 suggests selecting G_P. However, the presented criteria look for an MCDA method which is characterized by necessary features only, without excess functionalities. In the case discussed above, the authors of this publication (Marzouk 2011) chose a method which allows to attribute weights to criteria and then they defined them as equal. In this situation the method G_P, which did not employ the weights of the criteria, turned out to be sufficient. Obviously, applying a method which is functionally richer is correct, since it also allows to solve a decision problem (Guitouni et al. 1998). A similar situation takes place in literature recommendations, given in Table 6.4 in Positions 14, 16 and 22. As far as Positions 14 and 22 are concerned, a method, which would allow to compare criterial assessments of variants on a quantitative scale, was searched. Methods P_2 and T_P fulfil these expectations and also make it possible to attribute weights to criteria. Similarly, as other methods from the set $\{E_3, P_1, P_2, P_{1F}, P_{2F}, T_C, T_P, T_F, M_V, U_T\}$ defined by Rule 6 in Table Y are able to solve the given decision problem. Analogically, in Case 16 in Table 6.4 one may apply the same methods as mentioned, because formally they allow to work both on qualitative and quantitative data what makes it possible to compare variants with relation to both types of criteria.

6.9 Conclusion

Further research in the proposed direction should include not only methodical correctness, but the quality of received recommendations as well. The quality of the final recommendation is a resultant of the four elements described in Fortemps et al. (2004): the definition of the decision subject, the analysis of consequences of implementing decision alternatives, global preferences modelling, and choosing appropriate analysis procedures. Hence, the role of each factor is critical for the decision process entirely, whereas selecting appropriate analysis procedures is particularly important due to the fact it is a preliminary activity of the whole process and it determines the course of the decision situation analysis phase, which is often impossible to repeat.

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Part II
Applications: Production

Chapter 7
Declarative Modeling Driven Approach to Production Orders Portfolio Prototyping

Zbigniew Banaszak and Grzegorz Bocewicz

Abstract A set of unique production orders grouped into portfolio orders is considered. Operations executed along different production orders while following specified activity networks share available resources accessing them due to a mutual exclusion protocol. The main objective is to provide a declarative model enabling to state a constraint satisfaction problem aimed at multi project-like and mass customized oriented production scheduling. Its formal, declarative driven representation enables to formulate the straight and reverse problem scheduling of a newly inserted projects portfolio subject to constraints imposed by an enterprise multi-project environment. Its formal declarative framework driven representation enables to formulate the straight and reverse problems of multi-product scheduling. Considered problems correspond to the routine (faced by decision makers) questions that can be formulated either in the straight or reverse way, e.g. Does a given production orders portfolio specified by its resources allocation guarantee the production orders makespan do not exceed the given deadline? Does there exist a set of activities' operation times guaranteeing a given production orders portfolio completion time will not exceed the assumed deadline? In that context our contribution can be seen as an alternative approach to DSSs design allowing one to take into account both: straight and reverse problems formulation, while taking into account both distinct and imprecise character of the decision variables as well as to consider multi-criteria decision problems. Illustrative examples standing behind of proposed methodology are provided.

Keywords Production order · Projects portfolio · Scheduling · Declarative modeling · Customized production

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7.1 Introduction

Regardless of its character and scope of business activities a modern enterprise, has to build a project-driven development strategy in order to respond to challenges imposed by growing complexity and globalization. Managers need to be able to utilize a modern Decision Support System (DSS) as to undertake optimal business decisions in further strategic perspective of enterprise operations. Therefore, because of its fast prototyping capability the declarative modeling framework is more and more often considered (Reijers et al. 2013). It should be recalled that imperative models of computations are expressed in terms of states and sequences of state-changing operations simply describe *how* a solution is obtained. In turn, in declarative models focus is on *what* the solution is. In other words, imperative models take an "inside-out" approach; i.e. every possible execution sequence must be modeled explicitly. In contrast to imperative approaches, declarative models take an "outside-in" approach. Instead of describing how the process has to work exactly, only the essential characteristics are described.

Declarative approaches to systems and/or process modeling promise a high degree of flexibility. In that context, Constraint Programming (*CP*) framework can be considered as a well-suited framework for development of decision making software supporting small and medium size enterprises in the course of a variety, unique-product, i.e. multi project-like, production (Bocewicz and Banaszak 2013; Banaszak and Zaremba 2006; Banaszak et al. 2005). The considered problem concerns finding a computationally effective approach aimed at simultaneous routing and allocation as well as batching and scheduling of a new production order subject to constraints imposed by a multi-project environment. More precisely, allowing one to answer whether a given production order specified by its cost and completion time can be accepted in a manufacturing system specified by a given production capability and/or what manufacturing systems capability guarantee completion of a given production orders portfolio under assumed cost and time constraints.

The problems standing behind of the quoted questions belong to the class of so called project scheduling ones. In turn, project scheduling can be defined as the process of allocating scarce resources to activities over a period of time to perform a set of activities in a way taking into account a given set of performance measures. In practice, the generated schedules are subject to disturbances due to *uncertain data* (*fuzzy data*) such as the duration of activities and *random* (*stochastic*) *events* e.g. unforeseen situations and disturbances influencing the order specification (usually described by a probability density function). This makes it critical during the execution, to predict in real time, how one activity influences others with regards to resource consumption, estimated deadline and financial liquidity.

Existing methods assume that routing and allocation as well as batching and scheduling decisions are made independently, i.e. each production order is treated as an activity network and is assigned to processing units, and then divided into a number of batches (batching), and sequenced (scheduling). Several techniques have been proposed in the past 50 years, including MILP (Dang et al. 2014; Khayat et al. 2006; Linderoth and Savelsbergh et al. 1999), Branch-and-Bound (Beale 1979) or more recently Artificial Intelligence. The last sort of techniques concentrates mostly on fuzzy set theory and constraint programming frameworks.

Since the constraint programming treated as programming paradigm enables to specify both variables and relations between them in the form of constraints, then problems specified in that way can be easily implemented in the one of popular constraint logic languages such as: CHIP V5, ECL^{i}PS^{e} (Sitek and Wikarek 2014), or imperative constraint programming languages (assuming that a statement computation results in a program state change) such as: Choco (Prud'homme 2014), ILOG (Dang et al. 2014; Nielsen et al. 2014), or public domain concurrent constraint programming language as OzMozart (Bocewicz and Banaszak 2013; Bocewicz et al. 2015).

Constraint Programming/Constraint Logic Programming (*CP*/*CLP*) languages (Badell et al. 2004; Banaszak 2006; Barták 2004; Bocewicz et al. 2007; Groover et al. 2007; Krenczyk et al. 2012) seem to be well suited for modeling of real-life and day-to-day decision-making processes in an enterprise. Declarative modeling paradigm implemented in such kind of languages provides the framework allowing one to take into account both: distinct (crisp), and imprecise (fuzzy) data, as well as renewable and non-renewable resources in a unified way and treat it in a unified form of a fuzzy constraint satisfaction problem (Bach et al. 2008, 2010).

In that context our contribution provides a *CP*-driven reference model describing both an enterprise and a set of production orders portfolio as well as available amount of renewable and nonrenewable resources while taking into account crisp and/or imprecise character of decision variables. The proposed reference model can be seen as a new formal framework for developing a task oriented Decision Support Tool for Projects Portfolio Prototyping (Bocewicz et al. 2009) providing a prompt and interactive service to a set of routine queries formulated either in direct or reverse way. Such tools might be seen as person-computer systems with specialized problem-solving expertise supporting managers in the course of their decision making.

7.2 Mass Customization Oriented Modeling Framework

Mass Customization (MC) is an emerging production paradigm that seeks to manage the trade-offs between product variety and mass efficiency, while fulfilling individual customer requirements. The general purpose is to improve the effectiveness and efficiency of enterprises, usually Small and Medium sized Enterprises (SMEs) through high process agility, flexibility and integration (Nahmens 2007).

Facing with such requirements, i.e. variety of unique product production orders, the decision making in FMSs has to be supported by DSSs enabling to satisfy individual customer's needs with near mass production efficiency. In turn, MC oriented DSSs have to be equipped with the methods allowing one to prototype and evaluate different production flow scenarios, i.e. different ways of FMS resources allocation to both actually executed and newly introduced production orders.

An optimal assignment of available resources to production steps in a multi-product job shop is often economically indispensable. The goal is to generate a plan/schedule of production orders for a given period of time while minimize the cost that is equivalent to maximization of profit. In that context executives want to know how much a particular production order will cost, what resources are needed, what resources allocation can guarantee due time production order completion, and so on. So, a manager needs might be formulated in a form of standard, routine questions, such as: Does the production order can be completed before an arbitrary given deadline? What is the production completion time following assumed robots operation time? Is it possible to undertake a new production order under given (constrained in time) resources availability while guaranteeing disturbance-free execution of the already executed orders? What values and of what variables guarantee the production order will be completed following assumed set of performance indexes?

7.2.1 Declarative Modeling Framework

7.2.1.1 Constraint Satisfaction Problem

Since a constraint can be treated as a relation among several variables, each one taking a value in a given (usually discrete) domain, the idea of *CP* approach to solving problems can be employed. More formally, *CP* is a framework for solving combinatorial problems specified by pairs: (a set of variables and associated domains, a set of constraints restricting the possible combinations of the variables' values). In that context, the constraint satisfaction problem (*CSP*) (Bartak 2004) is defined as follows:

$$CS = ((X, D), C) \tag{7.1}$$

where

$X = \{x_1, x_2, \ldots, x_n\}$	a finite set of discrete decision variables,
$D = \{D_i \vert D_i = \{d_{i,1}, d_{i,2}, \ldots, d_{i,j}, \ldots, d_{i,ld}\}, i = 1, \ldots, g\}$	a family of variables' finite domains,
$C = \{c_i \vert i = 1, \ldots, L\}$	a finite set of constraints encompassing relations linking variables while limiting the variables domain.

Each constraint c_i can be seen as the relation defined on the relevant subset of variables $X_i \subset X = \{x_1, x_2, \ldots, x_n\}$. The solution to the *CS* is a vector $V = (v_1, v_2, \ldots, v_n) \in D_1 \times D_2 \times \cdots \times D_n$. such that the entry assignments satisfy all the constraints G. Consequently, the vector V is treated as the admissible solution of CS. Therefore, CSP can be seen as the triple (data, constrains, query), i.e. (the set of variables and family of variables domains, the set of constraints, and the question: Does there exist nonempty set off admissible solutions?).

Solution strategies are based on two subsequently used mechanisms, i.e. constraints propagation and variables distribution. Variables distribution can be executed either through systematic (e.g. breath-first-search) or stochastic search of the whole or constrained state space of potential solutions obtained from constraints propagation.

In other words, the inference engine consists of the following two components: constraint propagation and variable distribution. Constraints propagation uses constraints actively to prune the search space. The aim of propagation techniques, i.e., local consistency checking, is to reach a certain level of consistency in order to accelerate search procedures by drastically reducing the size of the search tree (Banaszak 2006). In general case however, the consistency techniques are incomplete. For instance, in the problem $CS = ((\{X, Y, Z\}, \{0, 1\}, \{0, 1\}, \{0, 1\}), \{X \neq Y, X \neq Z, Y \neq Y\})$ variables' domains are not reduced. Moreover a sufficient solution does not exist.

The searching strategies are implemented in constraint logic programming or constraint programming languages such as CHIP, OzMozart, ILOG, and so on.

7.2.2 Reference Model of Constraint Satisfaction Problem

Let us consider the reference model of a decision problem concerning of multi-resource task allocation in a multi-product job shop assuming imprecise character of decision variables. The model specifies both the job shop capability and production orders requirement in a unified way, i.e., through the description of determining them sets of variables and sets of constraints restricting domains of discrete variables. In other words, our a reference model sought, providing a decision problem encompassing equilibrium between possible expectations regarding potential orders completion (e.g. following a set of routine queries) and available production capabilities, focuses on resources conflict resolution, i.e. conflicts arising in case different activities simultaneously request their access to renewable and non renewable resources of limited quantity.

In the proposed model each fuzzy decision variable is described by a set of precise parameters (discrete alpha-cuts) and each fuzzy constraint is represented by the set of constraints describing relationships between parameters of fuzzy variables. Unfortunately standard CP platforms are not able to cope with fuzzy decision variables. Therefore the problems considered are stated in a new form of constraint satisfaction problems, i.e., Fuzzy Constraint Satisfaction Problem ($FCSP$). This kind of representation allows solving $FCSP$ as a standard CSP composed of parameters of fuzzy variables and their constraints. That is because, the $FCSP$ is defined as a triple: fuzzy decision variables, e.g. duration of activities, their fuzzy domains (families of the membership functions), and fuzzy constrains (fuzzy relations) a definition of their relationships representing for instance financial liquidity, etc.

Given a SME in which a set of production orders portfolio has to be executed while some parameters are uncertain (fuzzy), e.g. durations of activities. Consider the reference model aimed at the following routine questions: Do a given job shop capabilities and assumed resources allocation guarantee the production orders completion times do not exceed the deadline h? The model specifies both the job shop capability and production orders requirement in a unified way, i.e., through the description of assigning them sets of variables and sets of constraints restricting domains of discrete variables. Some conditions concerning the routine questions are included in the set of constraints.

7.2.2.1 Decision Variables *X*

Given number lz of renewable discrete resources ro_i (for instance robots and workers) specified by the sequence $Ro = (ro_1, \ldots, ro_{lz})$, and the sequence of resources availability $Zo = (zo_1, \ldots, zo_{lz}); Zo_i$—availability of the ith resource, value of Zo_i denotes available amount of the ith resource within the discrete time horizon $H = \{0, 1, \ldots, h\}$. Given a set of production routes $P = \{P_1, \ldots, P_{lp}\}$. Every particular route $p_i, (i = 1, 2, \ldots, lp)$ is specified by the set composed of lo_i activities, i.e., $P_i = \{O_{i,1}, \ldots, O_{i,lo_i}\}$, where

$$O_{i,j} = (x_{i,j}, t_{i,j}, Tp_{i,j}, Tz_{i,j}, Dp_{i,j}), \quad (7.2)$$

- $x_{i,j}$—means the starting time of the activity $O_{i,j}$, i.e., the time counted from the beginning of the time horizon H,
- $t_{i,j}$—the duration of the activity $O_{i,j}$,
- $Tp_{i,j} = (tp_{i,j,1}, tp_{i,j,2}, \ldots, tp_{i,j,lz})$—the sequence of time moments of the activity $O_{i,j}$ requires new numbers of renewable resources: $tp_{i,i,k}$—the time counted since the moment $x_{i,j}$ of the $dp_{i,j,k}$ (number of the kth resource allocation to the activity $O_{i,j}$). That means a resource is allotted to an activity during its execution period: $0 \le tp_{i,j,k} < t_{i,j}$; $k = 1, \ldots, lz$.
- $Tz_{i,j} = (tz_{i,j,1}, tz_{i,j,2}, \ldots, tz_{i,j,lz})$—the sequence of moments of the activity $O_{i,j}$ releases the subsequent resources: $tz_{i,j,k}$—the time counted since the moment $x_{i,j}$ the $dp_{i,j,k}$ number of the kth renewable resource was released by the activity $O_{i,j}$. It is assumed a resource is released by activity during its execution: $0 < tz_{i,j,k} \le t_{i,j}$; $k = 1, 2, \ldots, lz$, and $tp_{i,j,k} < tz_{i,j,k}$; $k = 1, 2, \ldots, lz$.

- $Dp_{i,j} = (dp_{i,j,1}, dp_{i,j,2}, \ldots, dp_{i,j,lz})$—the sequence of the kth resource numbers $dp_{i,j,k}$ are allocated to the activity $O_{i,j}$, i.e., $dp_{i,j,k}$—the number of the kth resource allocated to the activity $O_{i,j}$. That assumes: $0 \leq dp_{i,j,k} \leq zo_k$; $k = 1, 2, \ldots, lz$.

Consequently (using variables $x_{i,j}, t_{i,j}, tp_{i,j,k}, tz_{i,j,k}, dp_{i,j,k}$), every particular route $p_i (i = 1, 2, \ldots, lp)$ is specified by the following sequences of:

- starting times of activities in the route $p_i : X_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,lo_i})$; $0 \leq x_{i,j} < h$; $i = 1, 2, \ldots, lp$; $j = 1, 2, \ldots, lo_i$,
- duration of activities in the route $p_i : T_i = (t_{i,1}, t_{i,2}, \ldots,)$,
- starting times of the jth resource is allocated to the activity $O_{i,k}$ in the route p_i: $TP_{i,j} = (tp_{i,1,j}, \ldots, tp_{i,k,j}, \ldots, tp_{i,lo_i,j})$,
- starting times of the jth resource is released by the activity $O_{i,k}$ in the route P_i: $TZ_{i,j} = (tz_{i,1,j}, \ldots, tz_{i,k,j}, \ldots, tz_{i,lo_i,j})$,
- numbers of the jth resources allotted to the activity $O_{i,k}$ in the route P_i: $DP_{i,j} = (dp_{i,1,j}, \ldots, dp_{i,k,j}, \ldots, dp_{i,lo_{i,j}})$.

Assume some of chosen execution times are defined precisely, however a few of them are known roughly i.e., are treated as fuzzy variables specified by fuzzy sets. In case of imprecise variables such as activities execution times $\widehat{T}_i = (\widehat{t}_{i.1}, \widehat{t}_{i.2}, \ldots, \widehat{t}_{i,lo_i})$, where $\widehat{t}_{i,j}$ denotes execution time of the activity $O_{i,j}$, and starting times of activities $\widehat{X}_i = (\widehat{x}_{i,1}, \widehat{x}_{i,2}, \ldots, \widehat{x}_{i,lo_i})$, where $\widehat{x}_{i,j}$ denotes starting time of activity $O_{i,j}$. Therefore, the activity $O_{i,j} = (\widehat{x}_{i,j}, \widehat{t}_{i,j}, Tp_{i,j}, Tz_{i,j}, Dp_{i,j})$ is specified by the following sequences of:

- starting times of activities in the route p_i:

$$\widehat{X}_i = (\widehat{x}_{i,1}, \widehat{x}_{i,2}, \ldots, \widehat{x}_{i,lo_i}), \tag{7.3}$$

- duration of activities in the route p_i:

$$\widehat{T}_i = (\widehat{t}_{i,1}, \widehat{t}_{i,2}, \ldots, \widehat{t}_{i,lo_i}), \tag{7.4}$$

where

$\widehat{X}_i$	is a fuzzy set determining the starting times of activities $O_{i,j}$, $j = 1, 2, \ldots, lo_i$,
$\widehat{T}_i$	is a fuzzy set specifying the activities execution times,
$Tp_{i,j}, Tz_{i,j}, Dp_{i,j}$	the sequences defined as in the formulae (7.1).

Considered fuzzy variables are specified by fuzzy sets described by convex membership function (Piegat 1999; Zimmermann 1994). The distinct variables can be seen as a special case of imprecise ones, hence all the further considerations are focused on the imprecise (fuzzy) kind of variables.

7.2.2.2 Activities Order Constraints

Let us consider a set of production routes P_i composed of lo_i precedence and resource constrained, non-preemptable activities that require renewable resources. Assume lz renewable discrete resources are available and sequences $r_i = (ro_1, ro_2, \ldots, ro_f), i = 1, \ldots, lo_i$, determines fixed discrete resource requirements of the ith activity. The total number of units of the discrete resource j, $j = 1, \ldots, lz$, is limited by zo_j. The resource can be allotted (and constant within activity execution time) to activities in arbitrary number from the set $\{1, \ldots, zo_j\}$. The resources allotted to the ith activity have to be available at the moments $Tp_{i,j}, Ts_{i,j}$.

The production routes P_i are represented by activity-on-node networks, where activities state for nodes and arcs determine an order of activities execution. Consequently, the following activities order constraints are considered:

- the kth activity follows the ith activity:

$$\widehat{x}_{i,j} \widehat{+} \widehat{t}_{i,j} \widehat{\leq} \widehat{x}_{i,k}, \tag{7.5}$$

- the kth activity follows other activities:

$$\widehat{x}_{i,j} \widehat{+} \widehat{t}_{i,j} \widehat{\leq} \widehat{x}_{i,k}\ ,\ \widehat{x}_{i,j+1} \widehat{+} \widehat{t}_{i,j+1} \widehat{\leq} \widehat{x}_{i,k}, \ldots, \widehat{x}_{i,j+n} \widehat{+} \widehat{t}_{i,j+n} \widehat{\leq} \widehat{x}_{i,k}, \tag{7.6}$$

- the kth activity is followed by other activities:

$$\widehat{x}_{i,j} \widehat{+} \widehat{t}_{i,j} \widehat{\leq} \widehat{x}_{i,k+1}, \widehat{x}_{i,j} \widehat{+} \widehat{t}_{i,j} \widehat{\leq} \widehat{x}_{i,k+2}, \ldots, \widehat{x}_{i,j} \widehat{+} \widehat{t}_{i,j} \widehat{\leq} \widehat{x}_{i,k+n}. \tag{7.7}$$

The relevant fuzzy arithmetic operations $\widehat{+}, \widehat{\leq}$ are defined in the Appendix. Due to the formulas (7.8), (7.12), see the Appendix, any fuzzy constraint C_i (e.g. $\widehat{v}_i \widehat{\leq} \widehat{v}_l$) can be characterized by the logic value $E(C_i), E(C_i) \in [0, 1]$. In turn, values $E(C_i)$ allow to determine the level of uncertainty DE of reference model's constraints satisfaction, i.e. a kind of uncertainty threshold. For instance, $DE = 1$ means that all constraints hold, and DE = 0.8 means that they are almost satisfied. The level DE is defined by the formulae (7.7):

$$DE = \min_{i=1,2,\ldots,lo_c} \{E(C_i)\} \tag{7.8}$$

where lo_c—a number of reference model constraints.

7.2.2.3 Resource Conflict Constraints

Because of limited number of available discrete renewable resources, the constraints protecting against their allocation exceeding available outflows should also be considered. That means, the constraints taking into account imprecise character of such variables as activities execution times $\widehat{t}_{i,j}$ and the moments of activities beginning $\widehat{x}_{i,j}$ have to be considered. Note that cases regarding resources limit exceeding follow from conflicts arisen in result of bad resources allocation leading to the closed lops of resources requests. So, in order to be able to develop the constraints allowing one to avoid the exceeding of assumed limits imposed on available number of renewable resources, let us consider the following functions f_k^* and g_k^* determining available limits of the kth resource units required at the moment $\widehat{v}$:

- $f_k^*(\widehat{v}, \widehat{X}, DEf_k)$—determines the required number of the kth resource units at the fuzzy moment $\widehat{v}$, which depends on assumed fuzzy moments of activities beginning $\widehat{X} = \left(\widehat{X_1}, \widehat{X}_2, \ldots, \widehat{X}_{lp}\right)$. It is assumed, the set H is the domain of the membership function μv of the variable $\widehat{v}$ determining $DEf_k \in [0, 1]$. So, for the sake of simplicity in further considerations, the following phrase will be used: "the variable $\widehat{v}$ determined on the set H". Note, the function f_k^* is counted for a given level of uncertainty. That means for instance, if $DEf_k = 0.8$, then at the moment $\widehat{v}$ the number of required kth resource units do not exceed the number of resource units f_k^*, with uncertainty level equal to 0.8.
- $g_k^*(\widehat{v}, DEg_k)$—determines with uncertainty level $DEg \in [0, 1]$, the available number of the kth resource at the moment $\widehat{v}$. It is assumed, the considered available number of the kth resource is constant in the whole time horizon H, i.e. $g_k^*(\widehat{v}, DEg_k) = gv_k$ where $gv_k = const, \forall v \in H$.

Therefore, the above functions f_k^*, g_k^* can be seen as some generalization of functions f_k, g_k determining a number of required and number of available units of the kth resource in case variables considered are precise (Banaszak et al. 2008).

The occurrence of the closed loops of resource requests implies the following inequality $f_k(v_b, X) > g_k(v_b)$ (Banaszak et al. 2008). So, assuming the variables are treated as imprecise the inequality $f_k(v_b, X) > g_k(v_b)$ can be seen as a consequence of closed loop of resources request occurrence with an uncertainty level $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right) > gv_k$. Such generalizaton leads to the following Property 1.

Property 1 *The inequality* $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right) > gv_k$ *is a necessary condition for the occurrence of closed loop of resources request with the uncertainty level* DEf_k.

Moreover, assuming that activities cannot be stopped (suspended) during their execution, the following Lemma 1 holds.

Lemma 1 *If resources allocation to activities in the projects portfolio P at the moment follow the condition* $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right) \le gv_k, \forall k \in \{1, 2, \ldots, lz\}$, *for assumed* $\widehat{X}, \widehat{T}, \widehat{TP}_{i,j}, TZ_{i,j}, DP_{i,j}, H$, *then activities execution do not lead to the deadlocks with uncertainty level* $DEf = \min_{k \in \{1,2,\ldots,lz\}}\{DEf_k\}$.

Property 2 *If at any fuzzy moment* $\widehat{v}$ *in the time horizon H considered, the following condition holds* $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right) \leq gv_k$, $\forall k \in \{1, 2, \ldots, lz\}$, *then activities execution is deadlock-free with the uncertainty level* $DEf = \min_{k \in \{1,2,\ldots,lz\}}\{DEf_k\}$.

Due to the above introduced assumptions the functions f_k^* and g_k^* have the following form:

$$f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right) = \sum_{i=1}^{lp}\sum_{j=1}^{lo_i}\left[dp_{i,j,k} \cdot \widehat{\widehat{1}}\left(\widehat{v}, \widehat{x}_{i,j} \widehat{+} tp_{i,j,k}, \widehat{x}_{i,j} \widehat{+} tz_{i,j,k}, DEf_k\right)\right] \quad (7.9)$$

where

$tp_{i,j,k} < tz_{i,j,k}$, lp the number of projects,

lo_i the number of activities in the *i*th project,

$dp_{i,j,k}$ the number of resources of the *k*th resource busy by the activity $O_{i,j}$,

$\widehat{1}\left(\widehat{v}, \widehat{a}, \widehat{b}, DEf_k\right) = \widehat{1}(\widehat{v}, \widehat{a}, DEf_k) - \widehat{1}\left(\widehat{v}, \widehat{b}, DEf_k\right)$—an unary fuzzy function determining the time of recourse occupation, where $\widehat{1}(\widehat{v}, \widehat{a}, DEf_k)$—the unary fuzzy function.

The following unary fuzzy function is considered:

$$\widehat{1}(\widehat{v}, \widehat{a}, DEf_k) = f, \quad f \in \{0, 1\}, DEf_k \in [0, 1] \quad (7.10)$$

where f is a precise number for which the logic value of the following expression equals to DEf_k:

$$\left[\left(\widehat{v} \widehat{\geq} \widehat{a}\right) \vee (f = 0)\right] \wedge \left[\left(\widehat{v} \widehat{<} \widehat{a}\right) \vee (f = 1)\right] \quad (7.11)$$

that means:

$$E\left[\left[\left(\widehat{v} \widehat{\geq} \widehat{a}\right) \vee (f = 0)\right] \wedge \left[\left(\widehat{v} \widehat{<} \widehat{a}\right) \vee (f = 1)\right]\right] = DEf_k \quad (7.12)$$

The following propositions $\beta_1 \wedge \beta_2$; $\beta_1 \vee \beta_2$; $\neg\beta_1$ lead to the formulae below:

$$E(\beta_1 \wedge \beta_2) = E(\beta_1) \cdot E(\beta_2), \quad (7.13)$$

$$E(\beta_1 \vee \beta_2) = E(\beta_1) + E(\beta_2) - E(\beta_1) \cdot E(\beta_2) \quad (7.14)$$

$$E(\neg\beta_1) = 1 - E(\beta_1), \quad (7.15)$$

The formulae (7.10) leads to:

$$E\left(\widehat{v} \widehat{\geq} \widehat{a}\right) + E(f = 0) \cdot \left[1 - 2E\left(\widehat{v}_i \widehat{\geq} \widehat{a}\right)\right] = DEf_k \tag{7.16}$$

and finally:

$$E(f = 0) = \frac{DEf_k - E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}{1 - 2E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}. \tag{7.17}$$

Taking into account $E(f = 0) = 1 - f, f \in \{0, 1\}$ the following formulae holds:

$$f = 1 - \frac{DEf_k - E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}{1 - 2E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}. \tag{7.18}$$

Finally, the unary fuzzy function has the following form:

$$\widehat{1}(\widehat{v}, \widehat{a}, DEf_k) = 1 - \frac{DEf_k - E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}{1 - 2E\left(\widehat{v} \widehat{\geq} \widehat{a}\right)}. \tag{7.19}$$

where $\widehat{1}(\widehat{v}, \widehat{a}, DEf_k) \in \{0, 1\}, DEf_k \in [0, 1]$.

Let us assume the value $\widehat{a}$ of the function $\widehat{\widehat{1}}\left(\widehat{v}, \widehat{a}, \widehat{b}, DEf_k\right)$ is a distinguished so called characteristic point. In the formulae (7.9) two unary functions determining the recourse occupation time are added, the characteristic point determines the fuzzy moments $(\widehat{x}_{i,j} \widehat{+} tp_{i,j,k})$ where a number of the kth resource units become alloted to an activity. In further consderetaions such points will be called the characteristic points of the function $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right)$. Note that increasing of the function $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right)$ value can be done only in characteristic points of this function.

- Function $g_k^*(\widehat{v}, DEg_k)$:

$$g_k^*(\widehat{v}, DEg_k) = gv_k = zo_{k,1} \tag{7.20}$$

where
$Zo_{k,1}$ the available number of the kth renewable resource.

Therefore, since (7.9) and (7.20) hold, hence the following Theorem is also true.

Theorem *Given the projects portfolio P. Consider assumptions imposed by the reference model regarding activities specification* $\widehat{X}, \widehat{T}, TP_{i,j}, TZ_{i,j}, DP_{i,j}, H)$, *and functions* $f_k^*\left(\widehat{v}, \widehat{X}, DEf_k\right)$ and $g_k^*(\widehat{v}, DEg_k)$ *following formulae (7.9), (7.20). If for any moment* $\widehat{v}$ *in assumed time horizon H and for each* kth *resource* $(k = 1, 2, \ldots, lz)$, *conditions (7.21) hold, then projects portfolio execution will be deadlock free with the uncertainty level* $DEF = \min_{k \in \{1,2,\ldots,lz\}}\{DEf_k\}$.

$$\begin{cases} \sum_{i=1}^{lp}\sum_{j=1}^{lo_i}\left[dp_{i,j,k}\cdot\widehat{1}\left(\widehat{x}_{1,1}\widehat{+}tp_{1,1,k},\ \widehat{x}_{i,j}\widehat{+}tp_{i,j,k},\widehat{x}_{i,j}\widehat{+}tz_{i,j,k},E_{\widehat{1},i,j,1}\right)\right]\leq zo_k \\ \ldots \\ \sum_{i=1}^{lp}\sum_{j=1}^{lo_i}\left[dp_{i,j,k}\cdot\widehat{1}\left(\widehat{x}_{1,lo_1}\widehat{+}tp_{1,lo_1,k},\ \widehat{x}_{i,j}\widehat{+}\ tp_{i,j,k},\widehat{x}_{i,j}\widehat{+}tz_{i,j,k},E_{\widehat{1},i,j,lo_1}\right)\right]\leq zo_k \\ \sum_{i=1}^{lp}\sum_{j=1}^{lo_i}\left[dp_{i,j,k}\cdot\widehat{1}\left(\widehat{x}_{2,1}\widehat{+}tp_{2,1,k},\ \widehat{x}_{i,j}\widehat{+}\ tp_{i,j,k},\widehat{x}_{i,j}\widehat{+}tz_{i,j,k},E_{\widehat{1},i,j,lo_1+1}\right)\right]\leq zo_k \\ \ldots \\ \sum_{i=1}^{lp}\sum_{j=1}^{lo_i}\left[dp_{i,j,k}\cdot\widehat{1}\left(\widehat{x}_{lp,lo_{lp}}\widehat{+}tp_{lp,lo_{lp},k},\ \widehat{x}_{i,j}\widehat{+}\ tp_{i,j,k},\widehat{x}_{i,j}\widehat{+}tz_{i,j,k},E_{\widehat{1},i,j,lo_1+lo_2+..+lo_p}\right)\right]\leq zo_k \end{cases} \tag{7.21}$$

for $k = 1, 2, \ldots, lz$, where lz—a number of renewable resources $E_{\widehat{1},i,j,q}$—uncertainty threshold of the i, jth fuzzy unit step function of the resource allocation. Due to (7.8) the value $E(Co_q)$ of the particular constraint Co_q from the set (7.20) is calculated as follows (7.22):

$$E(Co_q) = \min_{i=1,2,\ldots lp}\left\{\min_{j=1,2,\ldots,lo_i}\left\{E_{\widehat{1},i,j,q}\right\}\right\}, \tag{7.22}$$

where lp—a number of production routes, lo_i—activities number in the ith production route.

In the course of decision making based on constraints assuming fuzzy variables, an uncertainty threshold (e.g. following an operator's experience) should be assumed. That means, the decision maker should be able to decide about the membership functions of the variables used as well as uncertainty thresholds of fuzzy constraints employed.

7.3 Production Orders Portfolio Prototyping

Traditionally-stated multi-criteria planning problems formulated as direct ones address standard questions as: is it possible to undertake the given project portfolio under a given resource availability while guaranteeing disturbance-free execution of activities? Such a formulation, however, may cause rejecting projects, which could actually be approved by the system if a satisfactory solution could be found by changing the levels of the constraints.

Therefore, an alternative problem statement formulated as a reverse planning problem can be as follows: Which values of the system parameters guarantee that the set of orders will be completed while giving a certain set of values for performance indexes? In case of any new event, caused e.g. by including a new project, a new system state has to be considered to determine a new project portfolio schedule. In that context, the proposed approach involves solving both direct and reverse problems for systems where project portfolios (specified by fuzzy data) change over time as a result of random occurring events. The methodology standing behind of this approach takes into account the following contributions:

- a method for follow up planning and online control subject to financial, time and resource capacity constraints, in an uncertain multi-project environment,
- an approach solving the reverse problem for project portfolio planning by integrating fuzzy logic and the constraint programming methods.

7.3.1 Direct Versus Reverse Problem Formulation

Our approach using the novel form of fuzzy variables representation (*the discrete α-cuts*) enables this and finally enables us to *solve reverse/direct problems* (modeled in terms of *FCSP*) while using standard *CP* environments. Therefore, the approach assumes the portfolio rescheduling takes place at states, where *FCSP* (representing *reverse/direct problem* of the considered *system*) is transformed to *CSP* and then solved using *CP*-based techniques. Its distinct advantage is that it separates the problem statement and its resolution methods. In addition, integrating the cash flows and the resource allocations with data describing the stochastic nature of possible disturbances are considered in the online control.

Consider the reference model provided in the Sect. 7.2.2. Depending on the questions stated the relevant context dedicated constraint satisfaction problem can be considered.

7.3.1.1 Problems Formulation

Given the time horizon $H = \{0, 1..., h\}$, the set of production orders (specified by the set of production routes) p, the set of resources and their availabilities Zo within H. Given are distinct and imprecise variables treated as fuzzy numbers, i.e. the sequences $\widehat{T_i}$, $\widehat{TP}_{i,j}$, $\widehat{TZ}_{i,j}$. The following questions should be answered:

- Does a given resources allocation guarantee the production orders makespan do not exceed the deadline h? Response to this question results in the following sequences $\widehat{X}_1, \widehat{X}_2, \ldots, \widehat{X}_{lp}$ determination.

- Does there exist resources allocation such that production orders makespan do not exceed the deadline h? Response to this question results in determination of the sequences: $\widehat{T}_1, \ldots, \widehat{T}_{lp}$. In that context variables $\widehat{X}_1, \widehat{X}_2, \ldots, \widehat{X}_{lp}$ and/or $\widehat{T}_1, \ldots, \widehat{T}_{lp}$ are treated as decision variables (the variables whose values are searched in order to achieve a required result).

The questions stated above correspond to the straight and reverse problems of multi-product scheduling. That means the routine (standard) questions can be formulated either in the straight or reverse way, i.e. as to determine:

- the criteria values implied by the assumed variables and constraints, for instance:
  Do the given activities' times guarantee completion of the project portfolio within assumed time horizon H?
- the variables guaranteeing expected values of the assumed goal functions, for example:
  What are the beginning times T_i of activities guaranteeing the project portfolio completion time does not exceed a given time horizon H?

The above questions belong to the class of so called problems formulated in a direct and reverse way. Some examples illustrating the above mentioned perspectives are stated below:

- **a straight way** (i.e. corresponding to the question: What results from premises?
  - What the portfolio makespan follows from the given project constraints specified by activity duration times, resources amount and their allocation to projects' activities?
  - Does a given resources allocation guarantee the production orders makespan do not exceed the given deadline?
  - Does the projects portfolio can be completed before an arbitrary given deadline?
  - Does there exist a schedule following constraints assumed on availability of renewable and non-renewable resources and $NPV > 0$ such that production orders completion time not exceeds the deadline H?
- **a reverse way** (i.e. corresponding to the question: What implies conclusion?)
  - What activity duration times and resources amount guarantee the given production orders portfolio makespan do not exceed the deadline?
  - Does there exist resources allocation such that production orders makespan do not exceed the deadline?
  - Does there exist a set of activities' operation times guaranteeing a given projects portfolio completion time will not exceed the assumed deadline?
  - What values and of what variables T_1, T_2, T_3, T_4, guarantee the makespan of the projects portfolio does not exceed a given deadline subject to limits imposed on available amounts of renewable and non-renewable resources as well as $NPV > 0$?

Above mentioned categories encompass the different reasoning perspectives, i.e. deductive and abductive ones. The corresponding queries can be stated in the same model that can be treated as composition of variables and constraints, i.e. assumed sets of variables and constraints limiting their values. In that context both an enterprise and the portfolio of production orders can be specified in terms of distinct and/or imprecise variables, discrete and/or continuous variables, renewable and/or non-renewable resources, limited and/or unlimited resources, and so on.

The introduced *CP*-based reference model provides a formal framework allowing one to formulate the projects portfolio planning problems in direct and reverse way. In other words it provides a base to an interactive task oriented decision support tools designing. That offers a possibility to respond to the questions like: What values and of what variables guarantee the production orders will complete due to assumed values of performance indexes? What is the shortest project portfolio completion time?

The main idea standing behind of this approach lies in searching for the conditions guaranteeing the existence of responses to the standard queries as well as for conditions guaranteeing the employed search strategies can be used in on-line mode for the given size of project planning problems. Therefore, the reference model of decision problems can be seen as a knowledge base kernel of a methodology aimed at designing of dedicated and interactive decision support systems.

7.3.2 DSS Driven Production Orders Prototyping

In multi-project planning the main focus is on deciding on a schedule for all activities of projects and allocating resource in order to finish projects before or due to their deadlines. One of our objectives is to propose a method that allows generating a schedule for set of production orders execution with resource allocation for a given period of time, guaranteeing a solution meeting a set of enterprise specific goals. Therefore, another of our objectives is to develop a method for rescheduling the project portfolio and reallocating resources with the consideration of budget, cash flow, resource capacity, new projects, etc.

When an unforeseen event occurs, it can make the current schedule infeasible. Thus, it is necessary to reschedule project portfolio and to reallocate resource in online mode. To be able to achieve this requires solving the problem in two steps: first, as a reverse problem and then as a direct problem. The reverse problem is formulated to establish the range of values of parameters guaranteeing a feasible plan exists. Therefore, the result from the reverse problem will guarantee finding a feasible solution in the direct problem and significantly reduce computational time. Moreover, the solution of the reverse problem could be used as input parameter for the direct problem which aims to find a new plan for projects with minimum cost.

Consider a DSS aimed at production orders portfolio prototyping, while implementing above introduced reference model, equipped with interactive interface module supported by *Drag and Drop, Touch Screen Panel*, and *Virtual Table* technologies. The menu composed of a set of tabs and folders allows one to specify parameters and decision variables describing both enterprise's capability (e.g., following from its structure and possible ways of work flows organization), and requirements imposed by production orders at hand (determining for instance the batches size, production cycles, work-in-progress, and so on). In turn, introduced parameters formulate a set of queries response to which can be seen via the same multi-board interface. Therefore, the presented concept of production orders portfolio prototyping can be seen as a kind of admissible solution searching through navigation between solutions delivered by iteratively stated problems see Fig. 7.1. An idea of navigation-like driven searching for admissible production orders portfolio schedule illustrated on his figure encompasses an iterative schema where soutions to direct and reverse decision problems are alternatively formulated and evaluated while giving input data to a newly stated, solved and then assessed problems.

Due to a kind of decision problem considered the relevant tabs are selected and structured on the board as to encompass the one of the following problems formulation:

- a straight planning problem (e.g., Is it possible to undertake the given project portfolio under a given resource availability while guaranteeing disturbance-free execution of already processed activities?),
- a reverse planning problem (e.g., What values of parameters of enterprise at hand guarantee that assumed production orders portfolio will be completed while following assumed performance indexes values?).

Note, that in the course of interactive solution searching any change in parameters describing SME capabilities results in different values of criteria matching-up production orders requirements. In turn, any change in parameters describing the criteria specifying production orders requirements, results in suggestion of change of parameters specifying the SME structure.

7.4 Illustrative Example

Consider the set of production routes $P = \{P_1, P_2\}$ composed of two routes P_1, P_2 corresponding to products W_1 and W_2 respectively, see Fig. 7.2. The manufacturing activities (sets $\{O_{1,1}, \ldots, O_{1,5}\}$ and $\{O_{2,1}, \ldots, O_{2,5}\}$) are serviced by the workers trained to perform specialized the following three roles: role 1—(ro_1, ro_2, ro_3); role 2—(ro_4, ro_5); and role 3—(ro_6, ro_7), see Table 7.1.

Given are activity times as well as associated moments of relevant resources allocation. Such decision variables, e.g. execution times of activities performed by robots or workers, can be specified either as distinct or imprecise ones.

Note that, since the number of common shared resources is limited, hence their allocation to simultaneously executed activities has to avoid an occurrence of

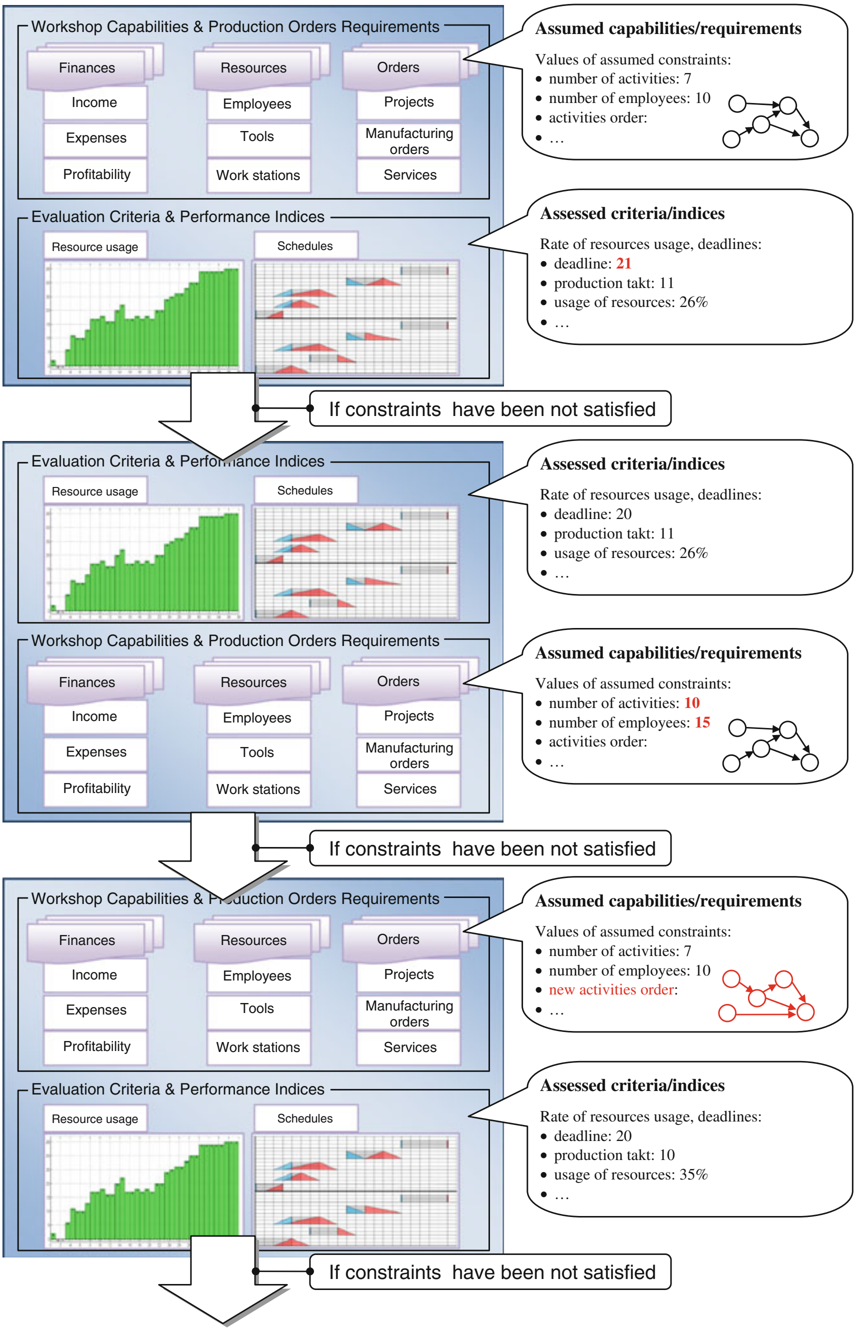

Fig. 7.1 Idea of navigation-like, iterative searching strategy

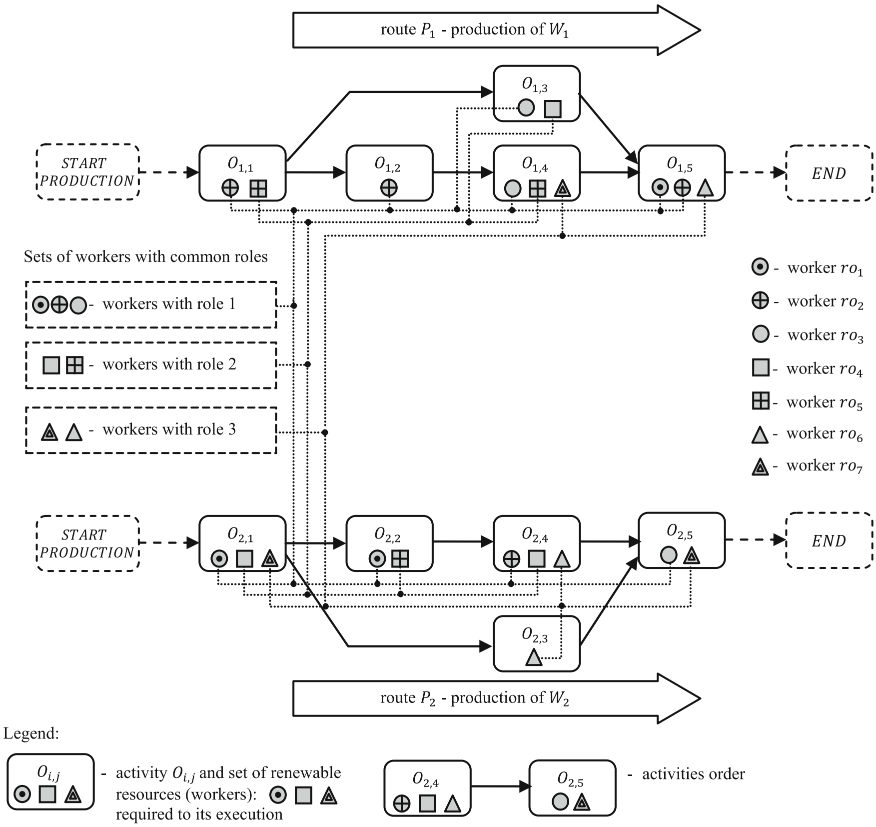

Fig. 7.2 Exemplary job shop structure with activity networks following products W_1 and W_2

Table 7.1 Workers allocations to activities executed along the production routes P_1 and P_2

		$O_{1,1}$	$O_{1,2}$	$O_{1,3}$	$O_{1,4}$	$O_{1,5}$	$O_{2,1}$	$O_{2,2}$	$O_{2,3}$	$O_{2,4}$	$O_{2,5}$
Role 1	ro_1	0	0	0	0	1	1	1	0	0	0
	ro_2	1	1	0	0	1	0	0	0	1	0
	ro_3	0	0	1	1	0	0	0	0	0	1
Role 2	ro_4	0	0	1	0	0	1	0	0	1	0
	ro_5	1	0	0	1	0	0	1	0	0	0
Role 3	ro_6	0	0	0	0	1	0	0	1	1	0
	ro_7	0	0	0	1	0	1	0	0	0	1

closed loop resource request, i.e. the deadlocks. Moreover, an imprecise nature of decision variables implies an imprecise (fuzzy) character of the performance evaluating criteria, e.g., an imprecise value of completion time of products W_1 and W_2. Consequently, because the constraints linking imprecise variables are also imprecise, the relevant membership function grades should be taken into account. In that context, the problem of multi-robot task allocation in a multi-product job shop reduces to a class of the dispatcher's routine questions, such as: Does a given way of resource allocation guarantee the production orders completion times do not exceed the deadline h? Is there a way of resources allocation such that production orders completion time not exceeding the deadline h is guaranteed? What values and of what variables guarantee the production orders will be completed due to assumed values of performance indexes?

Consider production routes P_1, P_2 composed of ten activities (see Fig. 7.2) where two products W_1 and W_2 are manufactured. The problem of production flow prototyping can be seen as an iterative process of decision variables adjustment and goal functions evaluation.

7.4.1 Case of the Straight Problem

The activities times are treated as fuzzy variables and determined by α-cuts:

$$\widehat{T}_1 = (\widehat{t}_{1,1}, \widehat{t}_{1,2}, \ldots, \widehat{t}_{1,5}),\ \alpha = \{0; 0.5; 1\}:$$
$$\widehat{t}_{1,1} = (\{[2,6],[3,5],[4,4]\},\alpha),\ \widehat{t}_{1,2} = (\{[3,5],[3,4],[3,3]\},\alpha),\ \widehat{t}_{1,3} = (\{[1,5],[2,4],[3,3]\},\alpha),$$
$$\widehat{t}_{1,4} = (\{[2,4],[2,3],[2,2]\},\alpha),\ \widehat{t}_{1,5} = (\{[5,5],[5,5],[5,5]\},\alpha).$$
$$\widehat{T}_2 = (\widehat{t}_{2,1}, \widehat{t}_{2,2}, \ldots \widehat{t}_{2,5}),\ \alpha = \{0; 0.5; 1\}:$$
$$\widehat{t}_{2,1} = (\{[1,3],[2,3],[3,3]\},\alpha),\ \widehat{t}_{2,2} = (\{[1,3],[1,2],[1,1]\},\alpha),\ \widehat{t}_{2,3} = (\{[1,5],[2,4],[3,3]\},\alpha),$$
$$\widehat{t}_{2,4} = (\{[2,4],[3,4],[4,4]\},\alpha),\ \widehat{t}_{2,5} = (\{[5,5],[5,5],[5,5]\},\alpha).$$

Seven different renewable resources ro_1, ro_2, ro_3, ro_4, ro_5, ro_6, ro_7 are used. The resources allocation follows Table 7.1. Therefore $DP_{i,j} = (dp_{i,1,j}, \ldots, dp_{i,k,j}, \ldots, dp_{i,lo_{i,j}})$:

$$DP_{1,1} = (0,1,0,0,1,0,0),\ DP_{1,2} = (0,1,0,0,0,0,0),\ DP_{1,3} = (0,0,1,1,0,0,0,0),$$
$$DP_{1,4} = (0,0,1,0,1,0,1),\ DP_{1,5} = (1,1,0,0,0,1,0),$$
$$DP_{2,1} = (1,0,0,1,0,0,1),\ DP_{2,2} = (1,0,0,0,1,0,0),\ DP_{2,3} = (0,0,0,0,0,0,1,0),$$
$$DP_{2,4} = (0,1,0,1,0,1,0),\ DP_{2,5} = (0,0,1,0,0,0,1).$$

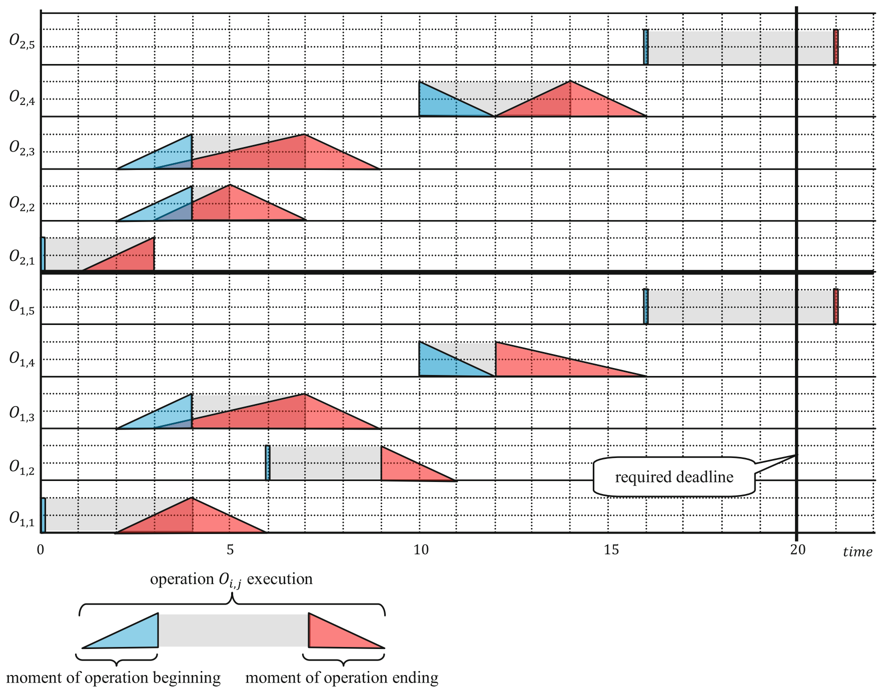

Fig. 7.3 Solution for the time horizon H $= \{0, 1, \ldots, 21\}$

It is assumed the moments of resources allocation and release follow both: the moments of activities beginning and completion. Therefore, $tp_{1,j,k} = tp_{2,j,k} = 0$, $j = 1, 2, .., 5$, $k = 1, 2, \ldots, 7$. The following sequences: $\widehat{tz}_{i,j,k} = \widehat{t}_{1,j}$, $j = 1, 2, \ldots, 5$, $k = 1, 2, \ldots, 8$, ($\widehat{tz}_{i,j,k}$- means the fuzzy variable $tz_{i,j,k}$) as well as $Zo = (zo_1, \ldots, zo_7)$ such that $Zo_1 = \ldots = zo_4 = zo_8 = 1$ are considered. Given the discrete time horizon $H = \{0, 1, \ldots, 20\}$, and the uncertainty threshold $DE \geq 0.8$.

The question considered: Does there exist a production schedule makespan which does not exceed a given deadline of 20 units of time? Expected response concerns of makespans $\widehat{X}_1 = (\widehat{x}_{1,1}, \widehat{x}_{1,2}, \ldots, \widehat{x}_{1,5})$, $\widehat{X}_2 = (\widehat{x}_{2,1}, \widehat{x}_{2,2}, \ldots, \widehat{x}_{2,5})$ where the moments $\widehat{x}_{i,j}$ are fuzzy numbers with triangle membership function as follows. Any admissible solution however does not exist (i.e., guaranteeing deadline of 20 units of time holds). The closest sufficient makespans, $\widehat{X}_1$, $\widehat{X}_2$ following the time horizon $H = \{0, 1, \ldots, 21\}$, (see Fig. 7.3) were obtained within 5 min (AMD Athlon(tm)XP 2500 + 1.85 GHz, RAM 1,00 GB):

$\widehat{x}_{1,1} = \{\{[0,0],[0,0],[0,0]\},\{0;0.5;1\}\}$, $\widehat{x}_{1,2} = \{\{[6,6],[6,6],[6,6]\},\{0;0.5;1\}\}$,
$\widehat{x}_{1,3} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\}$, $\widehat{x}_{1,4} = \{\{[10,12],[10,11],[10,10]\},\{0;0.5;1\}\}$,
$\widehat{x}_{1,5} = \{\{[16,16],[16,16],[16,13]\},\{0;0.5;1\}\}$,

$\widehat{x}_{2,1} = \{\{[0,0],[0,0],[0,0]\},\{0;0.5;1\}\}$, $\widehat{x}_{2,2} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\}$,
$\widehat{x}_{2,3} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\}$, $\widehat{x}_{2,4} = \{\{[10,12],[10,11],[10,10]\},\{0;0.5;1\}\}$,
$\widehat{x}_{1,5} = \{\{[16,16],[16,16],[16,13]\},\{0;0.5;1\}\}$.

7.4.2 Case of the Reverse Problem

Consider the production routes P_1, P_2 composed of ten activities (see Fig. 7.2) where two products W_1 and W_2 are manufactured. The activities execution times are fuzzy variables and determined by z-cuts $\widehat{T}_1 = \left(\widehat{t}_{1,1}, \widehat{t}_{1,2}, \ldots, \widehat{t}_{1,5}\right)$, $\widehat{T}_2 = \left(\widehat{t}_{2,1}, \widehat{t}_{2,2}, \ldots, \widehat{t}_{2,5}\right)$. Duration times of activities are unknown, however constraints limiting their duration are given (7.23):

$$C_1:\ \widehat{t}_{2,1} \widehat{+} \widehat{t}_{2,2} \widehat{=} \widehat{8}\,,\ C_2:\ \widehat{t}_{1,1} \widehat{+} \widehat{t}_{1,4} \widehat{=} \widehat{5}\,,\ C_3:\ \widehat{t}_{1,2} \widehat{+} \widehat{t}_{2,4} \widehat{=} \widehat{7},\ C_4:\ \widehat{t}_{1,3} \widehat{+} \widehat{t}_{1,5} \widehat{=} \widehat{3}$$
$$C_5:\ \widehat{t}_{2,3} \widehat{+} \widehat{t}_{2,5} \widehat{=} \widehat{3} \tag{7.23}$$

where $\widehat{8} = \{\{[6,8],[7,8],[8,8]\},\{0;0.5;1\}\}$,
$\widehat{5} = \{\{[5,5],[5,5],[5,5]\},\{0;0.5;1\}\}$, $\widehat{7} = \{\{[5,7],[6,7],[7,7]\},\{0;0.5;1\}\}$,
$\widehat{3} = \{\{[3,5],[3,4],[3,3]\},\{0;0.5;1\}\}$.

In the case considered, the constrains assumed belong to the following set $\{a\widehat{t}_{i,j} \widehat{+} b\widehat{t}_{k,1} \widehat{=} \widehat{c} : a, b \in N \wedge \widehat{t}_{i,j}, \widehat{t}_{i,j}, \widehat{c}\}$ are the fuzzy numbers}. For instance, the constraint C_1 determines a fuzzy relationship linking durations of activities $O_{2,1}$ and $O_{2,2}$. That means any change in activity $O_{2,1}$ duration implies corresponding change in duration of the activity $O_{2,2}$.

Seven different renewable resources ro_1, ro_2, ro_3, ro_4, ro_5, ro_6, ro_7 are used. The resources allocation follows Table 7.1. Therefore:

$DP_{1,1} = (0,1,0,0,1,0,0), DP_{1,2} = (0,1,0,0,0,0,0)$, $DP_{1,3} = (0,0,1,1,0,0,0,0)$,
$DP_{1,4} = (0,0,1,0,1,0,1)$, $DP_{1,5} = (1,1,0,0,0,1,0)$,
$DP_{2,1} = (1,0,0,1,0,0,1)$, $DP_{2,2} = (1,0,0,0,1,0,0)$, $DP_{2,3} = (0,0,0,0,0,0,1,0)$,
$DP_{2,4} = (0,1,0,1,0,1,0)$, $DP_{2,5} = (0,0,1,0,0,0,1)$.

Let us assume the moments of resources allocation and release follow the moments of activities beginning and completion. Therefore, $tp_{1,j,k} = tp_{2,j,k} = 0$,

j = 1,2,..,5, k = 1,2,…,7. The following sequences: $\widehat{tz}_{i,j,k} = \widehat{t}_{1,j}$, $j = 1, 2, .., 5$, $k = 1, 2, \ldots, 8$, ($\widehat{tz}_{i,j,k}$—means the fuzzy variable $tz_{i,j,k}$) as well as $Zo = (zo_1, \ldots, zo_7)$ such that zo_1 = ... = zo_4 = zo_8 = 1, are considered. Given the discrete time horizon $H = \{0, 1, \ldots, 21\}$, and the uncertainty threshold $DE \geq 0.8$.

The following question is considered: What activities duration guarantee the given production orders portfolio makespan does not exceed the deadline h? The solution results in determining of the following sequences: $\widehat{T}_1 = (\widehat{t}_{1,1}, \widehat{t}_{1,2}, \ldots, \widehat{t}_{1,5})$, $\widehat{T}_2 = (\widehat{t}_{2,1}, \widehat{t}_{2,2}, \ldots, \widehat{t}_{2,5})$ and $\widehat{X}_1 = (\widehat{x}_{1,1}, \widehat{x}_{1,2}, \ldots, \widehat{x}_{1,5})$, $\widehat{X}_2 = (\widehat{x}_{2,1}, \widehat{x}_{2,2}, \ldots, \widehat{x}_{2,5})$, where duration $\widehat{t}_{i,j}$ of the ith activity and beginning $\widehat{x}_{i,j}$ of the jth activity are described by a triangle membership function. The activities order (7.5–7.7), resource conflict (7.21) and activities duration limits (7.23) constraints have been implemented in OzMozart. First sufficient solution $\widehat{T}_1 = (\widehat{t}_{1,1}, \widehat{t}_{1,2}, \ldots, \widehat{t}_{1,5})$, $\widehat{T}_2 = (\widehat{t}_{2,1}, \widehat{t}_{2,2}, \ldots, \widehat{t}_{2,5})$, and $\widehat{X}_1 = (\widehat{x}_{1,1}, \widehat{x}_{1,2}, \ldots, \widehat{x}_{1,5})$, $\widehat{X}_2 = (\widehat{x}_{2,1}, \widehat{x}_{2,2}, \ldots, \widehat{x}_{2,5})$ (see Fig. 7.3) was obtained within 3 min (AMD Athlon(tm)XP 2500 + 1.85 GHz, RAM 1,00 GB). The activity durations are treated as fuzzy variables and determined by z-cuts:

$$\widehat{T_1} = (\widehat{t}_{1,1}, \widehat{t}_{1,2}, \ldots, \widehat{t}_{1,5}), \alpha = \{0; 0.5; 1\}:$$
$$\widehat{t}_{1,1} = \{\{[3,3],[3,3],[3,3]\},\{0;0.5;1\}\}, \widehat{t}_{1,2} = \{\{[3,3],[3,3],[3,3]\},\{0;0.5;1\}\},$$
$$\widehat{t}_{1,3} = \{\{[2,2],[2,2],[2,2]\},\{0;0.5;1\}\}, \widehat{t}_{1,4} = \{\{[2,2],[2,2],[2,2]\},\{0;0.5;1\}\}$$
$$\widehat{t}_{1,5} = \{\{[1,3],[1,2],[1,1]\},\{0;0.5;1\}\},$$
$$\widehat{T_2} = (\widehat{t}_{2,1}, \widehat{t}_{2,2}, \ldots, \widehat{t}_{2,5}),\ \alpha = \{0; 0.5; 1\}:$$
$$\widehat{t}_{2,1} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\}, \widehat{t}_{2,2} = \{\{[4,4],[4,4],[4,4]\},\{0;0.5;1\}\},$$
$$\widehat{t}_{2,3} = \{\{[2,2],[2,2],[2,2]\},\{0;0.5;1\}\}, \widehat{t}_{2,4} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\},$$
$$\widehat{X}_1 = (\widehat{x}_{1,1}, \widehat{x}_{1,2}, \ldots, \widehat{x}_{1,5}),\ \alpha = \{0; 0.5; 1\}:$$
$$\widehat{x}_{1,1} = \{\{[0,0],[0,0],[0,0]\},\{0;0.5;1\}\}, \widehat{x}_{1,2} = \{\{[3,3],[3,3],[3,3]\},\{0;0.5;1\}\},$$
$$\widehat{x}_{1,3} = \{\{[10,12],[10,11],[10,10]\},\{0;0.5;1\}\}, \widehat{x}_{1,4} = \{\{[7,9],[7,8],[7,7]\},\{0;0.5;1\}\},$$
$$\widehat{x}_{1,8} = \{\{[11,13],[12,13],[13,13]\},\{0;0.5;1\}\},$$
$$\widehat{X}_2 = (\widehat{x}_{2,1}, \widehat{x}_{2,2}, \ldots, \widehat{x}_{2,5}),\ \alpha = \{0; 0.5; 1\}:$$
$$\widehat{x}_{2,1} = \{\{[0,0],[0,0],[0,0]\},\{0;0.5;1\}\}, \widehat{x}_{2,2} = \{\{[2,4],[3,4],[4,4]\},\{0;0.5;1\}\},$$
$$\widehat{x}_{2,3} = \{\{[10,12],[10,11],[10,10]\},\{0;0.5;1\}\}, \widehat{x}_{2,4} = \{\{[6,8],[7,8],[8,8]\},\{0;0.5;1\}\},$$
$$\widehat{x}_{2,5} = \{\{[11,13],[12,13],[13,13]\},\{0;0.5;1\}\}.$$

Requirements following intuitive decision making imply the transformation of the fuzzy schedule obtained (see Fig. 7.4a) into the crispy-like one, e.g. providing results with the grade ≥0.5 (see Fig. 7.4b). That means, the completion time of products W_1, W_2 do not exceed 16 units of time for the uncertainty threshold $DE \geq 0.8$.

Provided example illustrates a way of the reference model implementation into the constraint programming environment as well as capabilities of their usage in reverse problem solution.

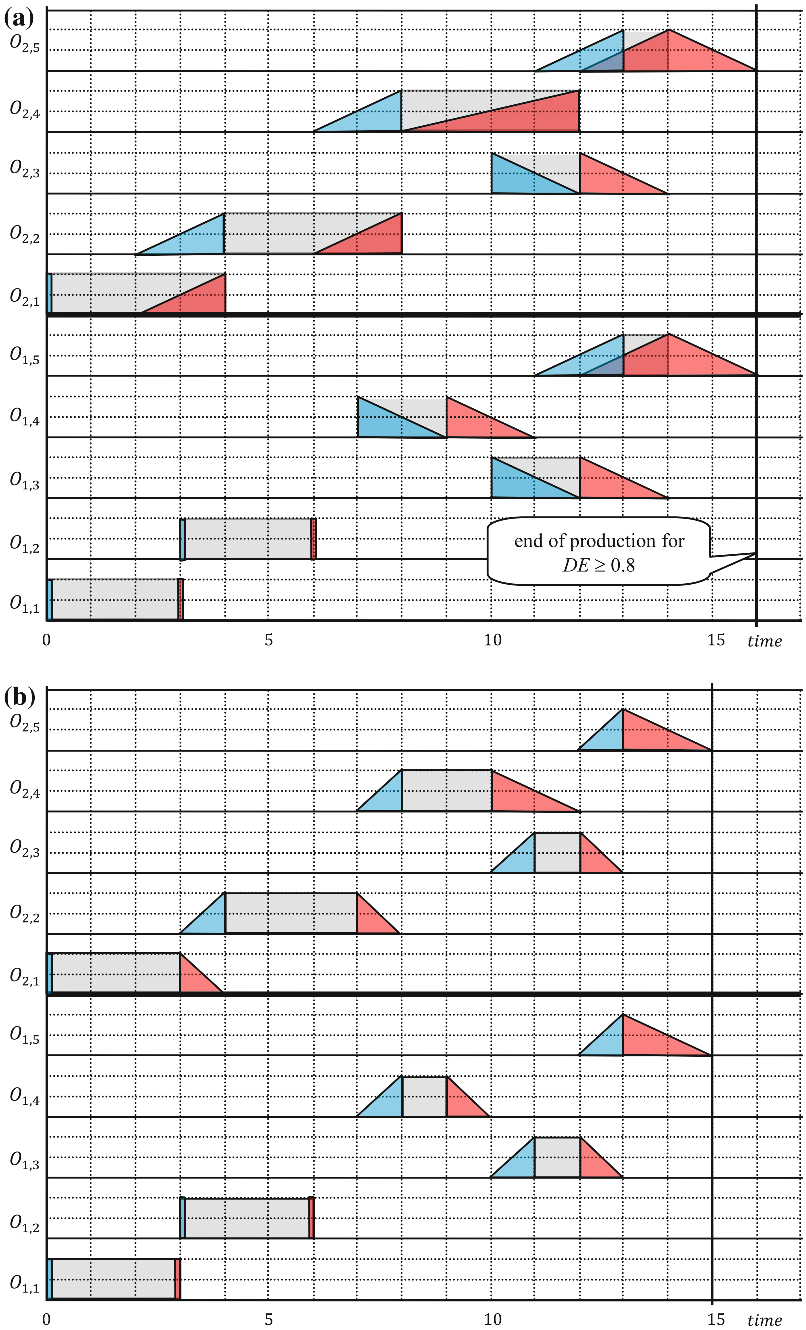

Fig. 7.4 Fuzzy schedule of production W_1, W_2, for the uncertainty threshold $DE \geq 0.8$ (**a**) and its reduction to 0.5 grade of membership function (**b**)

7.5 Concluding Remarks

It seems obvious, that not all functionalities are reachable under constraints imposed by a given system's structure. The similar observation concerns the system's behavior that can be achieved in systems possessing specific structural constraints. So, since system constraints determine its behavior, both the system structure and the desired behavior have to be considered simultaneously. In that context, our contribution provides a discussion of some solubility issues concerning structural properties providing conditions guaranteeing assumed system behavior (direct problem formulation) as well as behavioral requirements imposing conditions that have to be satisfied by system structure (reverse problem formulation).

In that context our contribution can be seen as an approach to DSSs design allowing one to take into account both: straight and reverse problems formulation. This advantage can be seen as a possibility to response (besides of such standard questions as Is it possible to complete a given set of production orders at a scheduled project deadline?) to the questions like: What variables value guarantee the production orders makespan follows the assumed deadline? Constraint programming paradigm standing behind of the methodology aimed for such tools designing allows to take into account both distinct and imprecise character of the decision variables as well as to consider of multi-criteria decision problems.

Better planning, in the manner supported by proposed approach, can improve companies' competitiveness through satisfying budgetary constraints and improving utilization of resources from a cash-flow perspective. A computer implementation of the proposed methodology should provide a new generation DSS supporting one in cases of online resource allocation and tasks scheduling as well as production orders batching and routing. Such a tool should be especially helpful in cases when actually processed products portfolio do not spend all company's capability reserves, i.e. there is a room for additional work order considerations.

Appendix

Imprecise variables specified by fuzzy sets and determined by convex membership function can be characterized by α-cuts (Piegat 1999; Zimmermann 1994), and then defined by pairs (7.24):

$$\{A_i, \alpha\} \tag{7.24}$$

where $A_i = \left\{A_{z_i,1}, A_{z_i,2}, \ldots, A_{z_i,lz}\right\}$ finite set of so called z-cuts,

$\alpha_{i,j} = \left\{\alpha_{i,1}, \alpha_{i,2}, \ldots, \alpha_{i,lz}\right\}$—is a set $A_{z_i,1}, A_{z_i,2}, \ldots, A_{z_i,lz}$ of values corresponding to α-cuts at levels $\alpha_{i,j}$, lz—a number of z-cuts. And

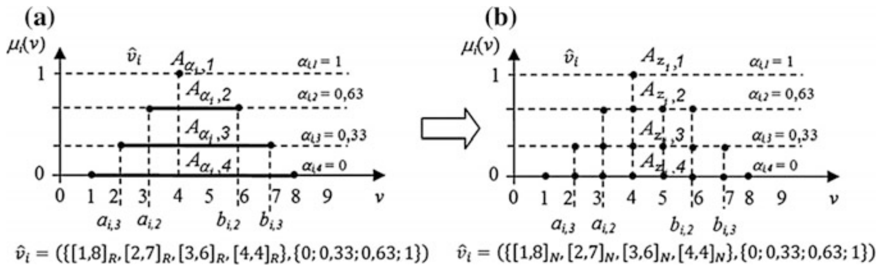

Fig. 7.5 Fuzzy set $\hat{v}_i$ specified by: **a** α-cuts, **b** discretized α-cuts, i.e., z-cuts

$$A_{z_i,k} = [a_{i,k}, b_{i,k}]_N \tag{7.25}$$

where $a_{i,k}$, $b_{i,k}$—is the smallest and the highest value of the *k*th α-cut, $a_{i,k}, b_{i,k} \in N$

The z-cut can be seen as a discretized form of the α-cut, i.e. $A_{z_i,k} = A_{\propto_i,k} \cap N$, see Fig. 7.5.

Note, that under assumed specification the distinct values are represented by singletons.

Imprecise character of decision variables, e.g. $\widehat{x}_{i,j}$, $\widehat{t}_{i,j}$, implies imprecise character of employing them constraints, which in turn can be considered as a consequence of implementation of assumed operations. Therefore, the set of fuzzy operations is considered: "$\widehat{=}$", "$\widehat{<}$", "$\widehat{>}$", encompassing standard algebraic operations such as: = , ≠ , < , > , ≥ , ≤ . Of course, the considered fuzzy operations linking two fuzzy variables $\widehat{v}_i$, $\widehat{v}_1$ have to follow the condition (7.26):

$$E\left(\widehat{v}_i \widehat{<} \widehat{v}_l\right) + E(\widehat{v}_i \widehat{=} \widehat{v}_l) + E\left(\widehat{v}_i \widehat{>} \widehat{v}_l\right) = 1 \tag{7.26}$$

where $E(a)$—the fuzzy logic value of the proposition a, $E(a) \in [0,1]$.

In order to define fuzzy operations used for description of the deadlock avoidance conditions (7.33) the following auxiliary sets v_i^L, v_i^*, v_i^P and v_l^L, v_l^*, v_l^P are defined as well as the concept of a size of fuzzy variable $S_i$and the size of subsets $S_i^L, S_i^P, S_l^L, S^*, S_i^P$ of S_i.

For each pair of fuzzy variables $\widehat{v}_i$, $\widehat{v}_l$ defined by $\{\mu_l(v), v\}$,$\forall v \in K_i$, where K_i is the domain of the variable $\widehat{v}_i$, the following sets can be distinguished: v_i^L, v_i^*, v_i^P i v_l^L, v_l^*, v_l^P. For instance, for the set $\widehat{v}_l$ the following subsets can be determined:

v_i^L—the set composed of elements v being less (smaller) than all elements from $\widehat{v}_l$,

$v_{i,j}^*$—the set of elements shared with $\widehat{v}_l$,

v_i^P—the set composed of elements v being greater (bigger) than all elements from $\widehat{v}_l$. The sets v_i^L, v_i^*, v_i^P are defined as follows:

$$v_i^L = \left\{\left(\mu_i^L(v), v\right)\right\}, \ \forall v \in K_i, \tag{7.27}$$

where

$$\mu_i^L(v) = \begin{cases} \mu_i(v) - \mu_l(v) & \text{if } \mu_i(v) \geq \mu_l(v), v < w_{min} \\ 0 \quad \text{if } \mu_i(v) < \mu_l(v), v < w_{min} \text{ or } v \geq w_{min}, \end{cases}$$
$$w_{min} = \min\{K_w\},\ K_w = \{v : v \in K_i, \mu_l(v) = 1\},$$

$$v_i^* = \left\{ \left(\mu_i^*(v), v \right) \right\},\ \forall v \in K_i, \tag{7.28}$$

where
$\mu_i^*(v) = min\{\mu_i(v), \mu_l(v)\}$

$$v_i^P = \left\{ \left(\mu_i^P(v), v \right) \right\}, \forall v \in K_i \tag{7.29}$$

where

$$\mu_i^P(v) = \begin{cases} \mu_i(v) - \mu_l(v) & \text{if} \mu_i(v) \geq \mu_l(v), v > w_{max} \\ 0 \quad \text{if } \mu_i(v) < \mu_l(v), v > w_{max} \text{ or } v \leq w_{max} \end{cases}$$
$$w_{max} = \max\{K_w\},\ K_w = \{v : v \in K_i, \mu_l(v) = 1\},$$

Corresponding to the fuzzy variable $\widehat{v}_l$ subsets v_l^L, v_l^*, v_l^P are defined in the same way.

To each fuzzy variable $\widehat{v}_i$, $\widehat{v}_l$ and the corresponding subset, v_i^L, v_i^*, v_i^P, v_l^L, v_l^*, v_l^P an associated size value can be determined. For instance, the size value S_i corresponding to the fuzzy variablev_i, and specified in terms of z-cuts can be defined as (7.30):

$$S_i = \sum\nolimits_{k=1}^{lz} \parallel A_{z_i,k} \parallel, \tag{7.30}$$

where $\parallel A_{z_i,k} \parallel$—a number of elements of the set $A_{z_i,k}$.

In the similar way the size values $s_l, s_i^L, s_i^*, s_i^P, s_l^L, s_i^*, s_i^P$., corresponding to the sets, $v_i^L, v_i^*, v_i^P, v_l^L, v_l^*\ , v_l^P$ are defined. In the case considered because the decision variables $\widehat{v}_i$, $\widehat{v}_l$ concern of the time domain the equation $S_l^* = S_i^*$ holds for the given v_i^*, v_l^*. Therefore, for the sake of simplicity in further considerations the sizes S_l^*, S_i^* will be denoted by the same symbol S^*.

Given fuzzy variables $\widehat{v}_i$, $\widehat{v}_l$. Consider algebraic-like fuzzy operations following the condition (7.26). Fuzzy logic value of the proposition $\widehat{v}_i \widehat{=} \widehat{v}_l$ is defined by (7.31):

$$E(\widehat{v}_i \widehat{=} \widehat{v}_l) = \frac{2S^*}{S_i + S_l}, \tag{7.31}$$

where S_i—the size of $\widehat{v}_i$, S_l—the size of $\widehat{v}_l$, S^*—the size of the common part of sets $\widehat{v}_i$, $\widehat{v}_l$.

Fuzzy logic value of the proposition $\widehat{v}_i \widehat{<} \widehat{v}_l$ is defined by (7.32):

$$E\left(\widehat{v}_i \widehat{<} \widehat{v}_l\right) = \frac{S_i^L + S_l^P}{S_i + S_l}, \tag{7.32}$$

where S_i—the size of $\widehat{v}_i$, S_l—the size of $\widehat{v}_l$, S_i^L—the size of v_i^L, S_l^P—the size of v_l^P,

Fuzzy logic value of the proposition $\widehat{v}_i \widehat{>} \widehat{v}_l$ is defined by (7.33):

$$E\left(\widehat{v}_i \widehat{>} \widehat{v}_l\right) = \frac{S_i^P + S_l^L}{S_i + S_l}. \tag{7.33}$$

Fuzzy logic value of the proposition $\widehat{v}_i \widehat{\geq} \widehat{v}_l$ is defined by (7.34):

$$E\left(\widehat{v}_i \widehat{\geq} \widehat{v}_l\right) = \frac{2S^* + S_i^P + S_l^L}{S_i + S_l}. \tag{7.34}$$

Fuzzy logic value of the proposition $\widehat{v}_i \widehat{\leq} \widehat{v}_l$ is defined by (7.35):

$$E\left(\widehat{v}_i \widehat{\leq} \widehat{v}_l\right) = \frac{2S^* + S_i^L + S_l^P}{S_i + S_l}. \tag{7.35}$$

Formulae (7.31–7.35) allow one to design constraints describing basic relations among two fuzzy variables, such as equality, less than, greater than, less or equal, and greater or equal. In order to allow one to consider other constraints, e.g., taking into account distinct variables, the fuzzy operations such as fuzzy addition and fuzzy subtraction have to be employed as well. The relevant operations "$\widehat{+}$", "$\widehat{-}$" can be found in (Piegat 1999; Zimmermann 1994).

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Chapter 8
A Knowledge-Based System for New Product Portfolio Selection

Marcin Relich

Abstract This chapter is concerned with designing and developing a knowledge-based system for evaluating concepts of new products and selecting product portfolio. The model of measuring the product success includes metrics identified by an expert, such as duration and cost of product development or net profit from a product. The model contains a set of decision variables, their domains, and the constraints that can be described in terms of a constraint satisfaction problem (CSP). Knowledge base is specified according to CSP framework and it reflects the company's resources, performance metrics, and relationships identified. The presented knowledge discovery process consists of the stages such as data selection, data preprocessing, and data mining in the context of an enterprise system database. In order to identify the patterns, fuzzy neural networks have been used and compared with the results from artificial neural networks and linear regression. The illustrative example presents the use of fuzzy neural networks to the identification of patterns that are translated into rules understandable by users. The proposed knowledge-based system helps the managers in selecting the most promising product portfolio and reducing the risk of unsuccessful product development.

Keywords Knowledge acquisition · Data mining · Fuzzy neural networks · Constraint satisfaction problem · Project management · New product development

8.1 Introduction

A dynamic and turbulent environment imposes organizations to be smart, agile, and responsive to fast changes of business needs. Faced with uncertain environment, companies are seeking new ways to improve their performance and flexibility for

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the changing business requirements. In order to maintain survival and development, organizations have paid attention towards expert systems to develop knowledge management systems that can provide the basis for future sustainability and competence (Malhota 2001).

In recent years, the knowledge-based economy has become the major trend in international society (Hsu et al. 2008; Ullman 2009; Li et al. 2011). Knowledge is a combination of information and experience, context, interpretation and reflection (Davenport 1998). Product knowledge, as a type of knowledge, is important to support manufacturing activities (Kulon 2006). Product knowledge has played increasingly significant roles in the new product development process especially in the development of one-of-a-kind products (Li et al. 2011).

New product development (NPD) is one of the most important processes in maintaining company's competitive position and continuing business success. New products and innovations impact on sales volume, employment, technological process, and economic progress. Contribution of NPD to the growth of the companies, its influence on profit performance, and its role as a key factor in business planning has been widely considered (e.g. Benedetto 1999; Cooper and Edgett 2008; Ulrich and Eppinger 2011). Nevertheless, it is still reported that the success rate of product development projects is unsatisfactory, with more cost and time than expected having been consumed to achieve the project goals. A key challenge faced by new product development projects is how to acquire knowledge, sustain success rate among the products, and manage the project in order to reduce the risk of failure of the product (Cooper 2003).

The main reasons of failures concerning new product development derive from extrinsic and intrinsic problems. Extrinsic problems include flops in the market, changes in regulations or simply competition develops product first (Cooper 2003). Intrinsic problems concern the limited resources (e.g. money, highly qualified employees) and result in the difficulties to meet the project goals, including product innovativeness. Unsatisfactory success rate of product development projects can also be considered from the perspective of inherent feature of NPD, i.e. it is a relatively risky activity (Kahraman et al. 2007), as market competition and product technology advancement are often intense (McCarthy et al. 2006).

Although the success of a new product depends on the environmental uncertainties that are beyond a firm's control, companies should take into account both external and internal indices and try to improve the NPD process. Internal indices can be acquired from company's databases, including enterprise resource planning (ERP) system, project management software, customer relationship management (CRM) system, and computer aided design (CAD) system. The advancement of information technology helps today's organisations in business management processes and collecting data. As a result, enterprise systems generate and store a huge amount of data that is potential source of information (Doskočil 2013; Relich 2013). Knowledge creation and management through the new product development and management processes is of significant interest in the context of recent technology and infrastructure changes. Data mining applications have vastly increased the amount of information available and the ease of manipulating and using it (Zahay et al. 2004).

The effective management of NPD projects is a challenging goal, due to factors such as intensive research and development investment, long and uncertain development times, low probability of technical success, and uncertain market impact and competition (Zapata 2008). One of the most important decisions that impact on business success is the selection of concepts for further development. Companies usually develop a set of new products simultaneously, what requires a task-oriented tool to support the decision-makers. Although knowledge-based systems have been proposed to support product development activities and new knowledge modelling methodologies have been developed, there is a scarcity in the context of new product portfolio selection.

This chapter aims to develop an approach that identifies the relationships between the success of a product and the key factors that are stored in an enterprise system and that influence on this success. The proposed approach takes into account data of the previous projects that can be retrieved from an enterprise system, including the fields such as marketing and sales, production, project management and the customers' complains. The relationships between the product success and metrics of the NPD process are sought with the use of a fuzzy neural network that enables the description of the identified relationships in form of if-then rules. The proposed knowledge-based system uses these rules to estimating net profit for the products that are considered for development, and proposing a set of the most promising products according to the decision-maker's preferences. The knowledge-based system can also be used to generating and evaluating the alternative NPD portfolios, and identifying such changes in project environment that can increase the chance to develop a successful product. The set of potential products for development is determined with the use of constraint programming taking into account the company's constraints.

The novelty of this research includes the model of measuring product success that is specified in term of a constraint satisfaction problem as a set of variables, domains, and constraints. The constraint satisfaction problem can be considered as a knowledge base enabling the design of a knowledge-based system that includes the identified patterns, expert knowledge, and routine queries, for example, what is the most promising set of products for development, or what resources are required to implement the NPD project portfolio and to ensure the desired success rate of new products? Knowledge base and inference engine of the proposed knowledge-based system has been developed with the use of constraint programming environment.

The remaining sections of this chapter are organised as follows: Sect. 8.2 presents the literature review regarding new product development, performance metrics in the NPD process and the use of knowledge-based systems in new product development. A model of measuring product success in terms of constraint satisfaction problem is presented in Sect. 8.3. The proposed method of product portfolio selection is shown in Sect. 8.4. An illustrative example of the proposed approach is illustrated in Sect. 8.5. Finally, some concluding remarks are contained in Sect. 8.6.

8.2 Literature Review

8.2.1 New Product Development

The new product development literature emphasizes the importance of introducing new products on the market for continuing business success. New products influence on employment, economic growth, technological progress, and high standards of living (Bhuiyan 2011; Spalek 2014). As new product development helps firms to survive and succeed in dynamic markets, it is a crucial process in maintaining a company's competitive position (Chin et al. 2009). However, market competition and product technology advancement is often intense (McCarty et al. 2006), resulting that NPD is a relatively risky activity (Kahraman et al. 2007). Consequently, companies try to meet customer requirements by improving product attributes and processes. To survive and succeed in the current business environment, companies usually focus on several areas to improve their new product development, such as identifying customer needs for continuous new product development, improving product quality, and accelerating the process of commercialization (Chan and Ip 2011).

New product development is a complicated and time-consuming process in which several different activities are involved. The NPD process consists of the stages, in which an initial product concept is evaluated, developed, tested, and launched on the market. Many NPD models have been developed over the years taking into account the above-mentioned stages of the NPD process. Sun and Wing (2005) presented the NPD process in the context of the following phases: ideas generation and conceptual design, definition and specification, prototype and development, and commercialization. According to Ulrich and Eppinger (2011), overall concept development process includes identify customer needs, establish target specification, concept generation, concept selection, test the concept, set final specification and develop product development plan.

The concept selection aims to choose the most promising set of products for further development. As the stage of concept selection precedes the more expensive and long-term development of the selected products, it is the critical stage of the NPD process and one of the most important decisions that impact on business success. In this stage, the proposed concepts are evaluated and optimized with the use of relevant performance metrics. This study considers the performance metrics for selecting a set of concepts for further development in the context of the predicted success of a product, and the factors that impact on the successful NPD. These factors derive from the fields of research and development (R&D), marketing and sales, production, and they can be retrieved from an enterprise system database.

8.2.2 Performance Metrics in the NDP Process

Performance metrics allow companies to measure the impact of process improvement over time resulting enhancement their NPD efforts. A successful NPD project is usually considered in the literature as the fulfilment of a fixed goal, the compliance with budget progress, or achieving an acceptable level of performance (Chang and Chen 2004). Cooper and Kleinschmidt (1995) presented the NPD performance with 10 measures: success rate, percent of sales, profitability relative to spending, technical success rating, sales impact, profit impact, success in meeting sales objectives, success in meeting profit objectives, profitability relative to competitors, and overall success. In turn, Sounder and Song (1997) proposed seven criteria in making overall judgments about the new product development in the context of actual performance versus the original expectations: sales, market share, return on investment, profit, customer satisfaction, contribution to technology leadership, and contribution to market leadership.

Metrics and critical success factors can refer to the entire NPD process or to its stages such as idea generation, concept selection, development, and testing. Metrics for idea generation include number of ideas generated from the customer, number of ideas retrieved and enhanced from an idea portfolio, number of ideas generated over a period of time, and the value of ideas in idea collection. Among all of these metrics, the number of ideas generated from the customers seems to be especially important due to identification of customer needs, and finally, customer satisfaction with a new product. Metrics for concept selection can be based on the expected return of investment (commercial value, net present value, internal rate of return), export rate, market share, or sales growth. Taking into account the product lifetime and return on product development expense, the net profit from a product in the first year after launch is further considered as a metric of the product success.

Metrics for development include mainly time and resources that impact on time frame. Reduction of development time is critical for business sustainability because companies that develop products quickly gain many advantages over their competitors (e.g. premium prices, valuable market information, leadership reputation, lower development costs, accelerated learning). In the stage of product testing, metrics can refer to product functionality (e.g. testing physical features, perceptual features, functional modes) and customer acceptance (e.g. customer-perceived value).

8.2.3 Knowledge-Based Systems in New Product Development

A knowledge-based system is a computer-based information system that represents knowledge of experts and manipulates the expertise to solve problems at an expert's level of performance (Jadhav and Sonar 2011). Such a system has three main components: knowledge base, inference engine, and user interface. The knowledge base consists of highly specialized knowledge of problem areas as provided by experts or/and data mining techniques. It includes facts, rules, concepts, and relationships that describe a given problem (Leung and Chuah 1998). The inference engine is the knowledge processor that works with the available information of the problem, coupled with the knowledge stored in the knowledge base, to draw conclusions or provide recommendations (Durkin 1994).

Development of a knowledge-based system involves capturing domain knowledge and knowledge about problem adjusting methodology to real world problems associated with the particular domain of application. Rule based reasoning and case based reasoning are two fundamental and complementary reasoning methods of knowledge-based systems (Pal and Campbell 1997). Knowledge-based systems have widely been adopted to solve decision-making problems in many domains, such as manufacturing (Kathuria et al. 1999), help desk operations (Chan et al. 2000), make or buy decision (McIvor and Humphreys 2000), technology investments (Tan et al. 2005), software effort estimation (Park and Baek 2008), resource allocation in project portfolio (Bocewicz et al. 2009), product safety and recalls (Kumar 2014).

The application of knowledge-based systems in the field of new product development can be considered from the perspective of stages in the NPD process including generation and selection of new product idea. In creating new ideas for products, designers often use creative problem solving techniques (Wu et al. 2006), where the brainstorming method is one of the most widely used. However, the use of the brainstorming method for generating new product ideas encounters some difficulties. Namely, this method has been developed for a team and its performance highly depends on the capacities of team members. Moreover, the brainstorming method facilitates team members to generate new ideas through a free-association mechanism that is not always customer-oriented or user-centered. As a result, some ideas good for users might be ignored in the brainstorming method (Wu et al. 2006). Therefore, to overcome these drawbacks the computer-aided techniques to create new product ideas have been developed. For instance, in the process of generating new product idea and product design can be used case-based reasoning (Tseng et al. 2005; Wu et al. 2006), TRIZ method (Yang and Chen 2011), and design structure matrix (Tang et al. 2010).

A number of new product ideas is usually larger than the financial and production capacity in an enterprise to develop all new products. Therefore, a set of product concepts should be reduced towards selecting the most promising product portfolio. Among approaches to selecting product portfolio can meet association rule mining (Jiao and Zhang 2005), multi-objective genetic algorithm (Yu and Wang 2010), integrating technology roadmapping (Oliveira and Rozenfeld 2010), fuzzy multi-criteria group decision (Wei and Chang 2011), or visual product architecture modeling (Ulonska and Welo 2014). Recent development of knowledge-based systems in the context of one-of-a kind production includes web-based, ontology-based, STEP-based, and case-based approaches (Li et al. 2011). STandard Exchange of Product model data (STEP) is an international standard defined to provide a complete, unambiguous and computer readable definition. With the use of a set of standards, STEP can improve the level of knowledge exchange and sharing in different formats appearing in CAD, CAE, CAM, PDM/EDM and other CAx systems.

The NPD process includes tasks such as scheduling, estimating and monitoring, which involve considerable skills and experience to plan the activities, time, people, equipment, material and the money required. A task-oriented knowledge-based system may assist project managers in indicating what is likely to happen in future, presenting facts in a manner that makes judgment easier, retaining project managers' expertise for future uses, and showing what has happened and why. This system is an aid to decision-making and problem solving, as well as it may be useful in training inexperienced project managers (Leung and Chuah 1998).

8.3 Model of Measuring Product Success

The product design process can be divided into the customer, functional, physical and process domains (Yu and Wang 2010). These domains concern the customer satisfaction, functionality, technical feasibility, and manufacturability/cost issues connected with the products. In general, new product development encompasses three successive stages (Jiao and Zhang 2005): (1) product definition connected with mapping of customer needs in the customer domain to functional requirements in the functional domain; (2) product design connected with mapping of functional requirements to design parameters in the physical domain; (3) process design connected with mapping of design parameters in the physical domain to process variables in the process domain.

Within the context of mass customization, product design and process design are embodied in the respective product lines and process platforms. Product portfolio represents the functional specification of product families, i.e. the functional view of product lines and process platforms (Jiao and Zhang 2005). The specification of the previous product lines, customer requirements, design parameters, and product portfolios is stored in an enterprise system that can include ERP, CRM and CAD system. Figure 8.1 illustrates the principles of model of measuring product success on the basis of an enterprise system.

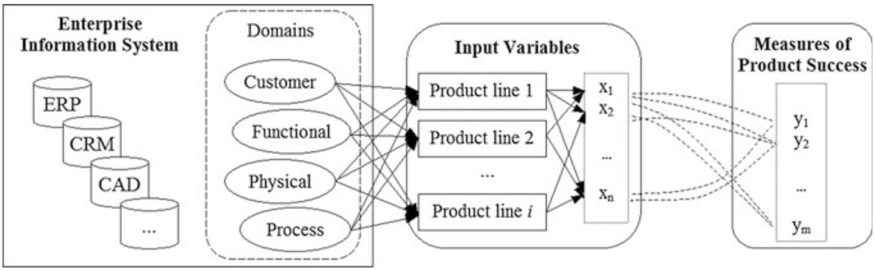

Fig. 8.1 Model of measuring product success

The proposed model consists of output variables that describe the product success and input variables that are suspected of significant impact on this success. The set of variables can be selected from an enterprise database with the use of variable reduction methods or specified by an expert. It is noteworthy that a variable selection method should take into account the nature of the problem because automatic variable selection is not guaranteed to be consistent with the assumed goals (Relich and Muszyński 2014). In this study, an expert approach is applied for selecting a set of variables for each product line. As a result, an expert experience is used to developing a knowledge-based system.

The success of a product can be evaluated according to the measures such as sales growth, export rate, market share, return of investment, and customer satisfaction (Sounder and Song 1997). Taking into account the product lifetime and return on product development expense, as the output variable and the measure of the product success, the net profit from a product in the first year after launch is chosen. In turn, the input variables derive from the fields such as marketing, customer, project management and production, and they are as follows: duration of marketing campaign of the product and cost of marketing campaign of the product, number of customer's complains (requirements, comments) for the previous products that have been used to developing a new product, number of project team members, number of activities in the project, percentage of existing parts used in new products, production cost of the product. These variables can be easily retrieved from an enterprise system database.

The presented model contains a set of decision variables, their domains, and the constraints that can be referred to the company's resources and performance indicators. The decision problem concerning the selection of the most promising set of products for development has been described in terms of a constraint satisfaction problem (CSP). The model description encompasses the limitations of a company, parameters of new products that are considered for development, and a set of routine queries (the instances of decision problems) that are formulated in the framework of CSP. The structure of the constraint satisfaction problem may be described as follows (Rossi et al. 2006):

$$\mathrm{CSP} = ((\mathrm{V},\ \mathrm{D}),\ \mathrm{C})$$

where:

$V = \{v_1, v_2, \ldots, v_n\}$—a finite set of n variables,

$D = \{d_1, d_2, \ldots, d_n\}$—a finite set of n discrete domains of variables,

$C = \{c_1, c_2, \ldots, c_k\}$—a finite set of k constraints limiting and linking variables.

Consider a set of new products for development $P = \{P_1 \ldots, P_i, \ldots, P_I\}$, where P_i consists of J activities. Moreover, the following variables are considered: duration of new product development (PD_i) and its cost (PC_i), number of project team members (PTM_i), technical innovativeness (percentage of existing parts used in a new product) (PEP_i), production cost of the product (PPC_i), duration of marketing campaign of the product (PMD_i) and its cost (PMC_i), number of customer requirements for a new product (PCR_i), percentage of customer requirements translated into technical specification (PTS_i), and net profit of the product (PNP_i). The company's limitations include the total number of R&D employees (project team members) $C_{1,t}$ and financial means $C_{2,t}$ in the tth time unit.

The constraint satisfaction problem can be considered in the context of a knowledge base. The knowledge base is a platform for query formulation as well as for obtaining answers, and it comprises of facts and rules that are relevant to the system's properties and the relations between its different parts. As a knowledge base can be considered in terms of a system, at the input of the system are led the variables concerning basic characteristics of an object that are known and given by user (Bocewicz et al. 2009). For instance, the available resources in the enterprise and parameters of new products occur in the knowledge base describing the enterprise-product portfolio model. The output of the system is described by the characteristics of the object that are unknown or are only partially known. For example, there is a value of the product success or a set of the most promising products for development.

The model description in terms of constraint satisfaction problem enables the design of a knowledge-based system taking into account the available specifications, routine queries, and expert knowledge. Consequently, the model integrates technical parameters, available resources, expert experience, identified relationships (rules) and user requirements in the form of knowledge base. Interpretation of such a model allows for using the logic-algebraic method as a reference engine (Bocewicz et al. 2009).

A distinction of decision variables that are embedded in the knowledge base as an input-output variable permits the formulation of two classes of standard routine queries that concern two different problems with respect to resources (Bocewicz et al. 2009; Relich et al. 2015):

- what products should be chosen to the product portfolio by a fixed amount of resources to ensure the optimal value of criterion of the purpose (e.g. the minimal cost and time of the product portfolio, the maximal net profit from the product portfolio)?
- what resources in which quantities are minimally necessary to be able to complete the product portfolio before a certain deadline, by a desired cost, or by a desired net profit from new products?

The method of finding admissible solutions (variants of product portfolio) for the above-described problem is presented in the next section.

8.4 Method of Product Portfolio Selection

The enterprise system generates routinely an enormous amount of data according to the business processes in a company. As the amount of available data in companies becomes greater and greater, companies have become aware of an opportunity to derive valuable information from their databases, which can be further used to

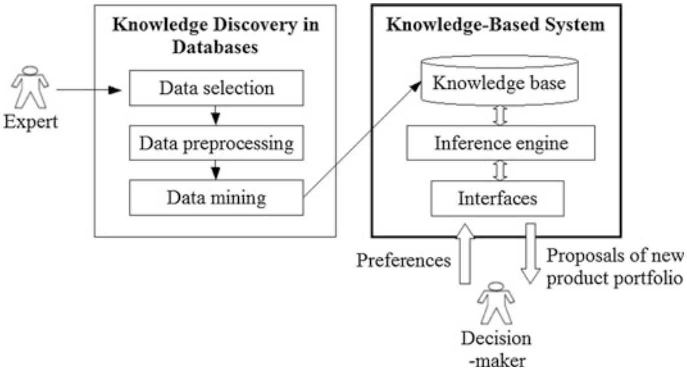

Fig. 8.2 Framework of a knowledge-based system for product portfolio selection

improve their business (Li and Ruan 2007). The process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data is known as knowledge discovery (Fayyad et al. 1996). The knowledge discovery process includes the stages such as data selection, data preprocessing, data transformation, data mining, and interpretation (evaluation) of the patterns identified (Fayyad et al. 1996; Jiao and Zhang 2005). Figure 8.2 illustrates the framework of the knowledge discovery in the context of developing a knowledge-based system for product portfolio selection.

Initially, an expert selects a set of variables from the enterprise databases, variables that are suspected of significant impact on the success of previous products. In the next step, data is preprocessed to the form that is suitable for a chosen data mining technique. As analysis of huge amount of data and knowledge acquisition with the use of manual methods is slow, expensive, subjective, and prone to errors, there is a need to automate the process through using data mining techniques (Han and Kamber 2006; Cios et al. 2007).

Pattern discovery from databases requires some data mining techniques that cope with the description of relationships among data and that solve the problems connected with e.g. classification, regression, clustering, and estimation that is further considered. These techniques include neural networks, fuzzy sets, rough sets, time series analysis, Bayesian networks, evolutionary programming and genetic algorithms, decision trees, etc. The artificial neural networks and fuzzy logic are complementary technologies and powerful design techniques that can be used in the identification of patterns from a large database and noisy data that is common for an enterprise system.

The fuzzy neural system has the advantages of both neural networks (e.g. learning abilities, optimization abilities and connectionist structures) and fuzzy systems (e.g. if-then reasoning, simplicity of incorporating expert knowledge). One of the possibilities to combine neural networks and fuzzy logic is to use a neural network as an inference engine to develop a classification system. In this case, the network can learn from training samples, and after learning it is possible to decode the network to extract fuzzy if-then rules. The outcome of a fuzzy neural system is a set of humanly understandable rules that can be used to perform nonlinear predictive modelling, simulation, and forecasting. One well-known structure of fuzzy neural networks is the adaptive neuro-fuzzy inference system (ANFIS).

The use of ANFIS requires preprocessing the data that is retrieved from enterprise systems (Relich 2015). One of the feature reduction methods is principal component analysis (PCA) that reduces the dimension for linearly mapping high dimensional data onto a lower dimension with minimal loss of information. Data preprocessing has been performed with the use of PCA that is the best, in the mean-square error sense, linear dimension reduction technique (Chizi and Maimon 2010).

The identified relationships between input and output variables are stored in a knowledge base and used to estimate the success of a potential product and further used to select the most promising products for development. The knowledge base stores the identified relationships as well as the resource constraints (financial, temporal, personal, etc.) that determine product portfolio.

The output of a knowledge-based system is the proposal of project portfolio that is adjusted to the decision-maker's preferences (e.g. the desired value of the total net profit from new products). The decision-maker can also carry out what-if analysis and check whether the product portfolio will be changed in the case of others values of the input variables. Moreover, the decision-maker should be able to check what resources and in which amount are needed to obtain the desired value of the total net profit from products.

A growing number of admissible solutions resulting from increase of the changed parameters requires taking into consideration more efficient algorithms in order to shorten time taken in the searching process of solution. Moreover, the impact of real-life constraints on decision-making is of significant importance, especially for designing an interactive knowledge-based system. In the case of extensive search space, the processing time of calculations can be significantly reduced with the use of constraints programming techniques (Banaszak et al. 2009; Sitek and Wikarek 2014).

The constraint programming (CP) environment seems to be particularly well suited to modelling real-life and day-to-day decision-making processes at an enterprise. CP is qualitatively different from the other programming paradigms, in terms of declarative, object-oriented and concurrent programming. Compared to these paradigms, constraint programming is much closer to the ideal of declarative programming: to state what we want without stating how to achieve it (Van Roy and Haridi 2004). CP is an emergent software technology for a declarative constraints satisfaction problem description and can be considered as a pertinent framework for the development of decision support and knowledge-based system software.

To sum up, the proposed method bases on a fuzzy-neural system that identifies the relationships between the input variables chosen by an expert from an enterprise system and the net profit from the previous products. These relationships are used to estimate the net profit for product concepts that are considered for development. In the next step taking into account the decision-maker preferences, the portfolio of the most promising NPD projects is selected with the use of constraint programming. The next section presents an illustrative example of the use of ANFIS and CP techniques that enable the development of a knowledge-based system in the context of knowledge base, inference engine and interfaces.

8.5 Illustrative Example

An illustrative example includes two parts: determination of the optimal product portfolio by the limited (fixed) resources and seeking the feasible set of product portfolio that ensures the desired value of total net profit from new products. These tasks refer to two types of questions presented in the model formulation section.

The output variable is net profit from a product (PNP) that is considered as a measure of product success. The input variables concern the fields of marketing, project management, research and development (R&D), and production. Among an enterprise database, the following input variables have been chosen:

- number of activities in the NPD project (J),
- duration of the NPD project (PD),
- cost of the NPD project (PC).
- number of project team members (PTM),
- percentage of existing parts used in a new product (PEP),
- unit cost of production for the product (PPC),
- duration of marketing campaign of the product (PMD),
- cost of marketing campaign of the product (PMC),
- number of customer requirements for a new product (PCR),
- percentage of customer requirements translated into technical specification (PTS).

The success of new product is estimated on the basis of information about the previous NPD projects. There are sought the relationships between the above-described input variables and net profit from a product. Moreover, some input variables can be used to estimate the duration of product development {J, PTM, PEP, PCR}, and the cost of product development {J, PD, PTM, PEP, PCR}. The R&D department considers five possible products {P1, P2, P3, P4, P5} for the development. The number of employees that can participate in the NDP projects equals 25 people. Other constraints concern the R&D budget (200 thousand Euros) and the budget of marketing campaign (250 thousand Euros).

The identification of relationships between the input variables and net profit from a product has been sought with the use of the adaptive neuro-fuzzy inference system (ANFIS) and compared with the artificial neural networks (ANN), linear regression model, and the average. In order to eliminate the overtraining (i.e. too strict function adjustment to data) of ANFIS and ANN and to increase the estimation quality, the data set has been divided into learning (27 past products) and testing sets (7 past

Table 8.1 RMSE for different models

Model	Learning set	Testing set
ANN—GDX	30.28	25.24
ANN—LM	1e–12	23.42
ANFIS—hybrid (RI = 0.9)	0.0032	24.32
ANFIS—hybrid (RI = 0.7)	9e-5	26.37
ANFIS—hybrid (RI = 0.5)	0.0004	17.19
ANFIS—hybrid (RI = 0.4)	0.0006	16.76
ANFIS—hybrid (RI = 0.3)	0.0014	12.54
ANFIS—hybrid (RI = 0.2)	0.0009	16.28
ANFIS—hybrid (RI = 0.1)	0.0005	21.19
ANFIS—back-propagation	1.10	49.13
Linear regression	11.08	30.47
Average	72.04	78.45

products). The data has been preprocessed before the learning stage with the use of principal component analysis.

In studies, the ANFIS has been trained according to subtractive clustering method by the use of the back-propagation (for 5000 iterations) and hybrid algorithm for the different values for range of influence (RI). In turn, a multilayer feed-forward neural network has been trained according to the back-propagation algorithm. Weights have been optimised according to the Levenberg-Marquardt algorithm (LM) and gradient descent momentum with adaptive learning rate algorithm (GDX). The neural network structure has been determined in an experimental way, by the comparison of learning and testing sets for the different number of layers and hidden neurons. The root mean square errors (RMSE) have been calculated as the average of 20 simulations for each structure of neural network with a number to the extent of 20 hidden neurons. After learning phase, the testing data has been led to input of the ANFIS, ANN and other models. The results have been calculated in the Matlab® software and presented in Table 8.1 as the root mean square errors for the learning and testing set.

The presented in Table 8.1 results indicate that the least error in the testing set has been generated with the use of the ANFIS trained according to the hybrid method and with the parameter of RI equals 0.3. The ANFIS obtained better results for the testing set (by RI between 0.1 and 0.5) than the artificial neural networks. The ANN trained according to the Levenberg-Marquardt algorithm generated the least RMSE for the learning set, but the results for the testing set are worse than for the majority of ANFIS models. This can result from the overtraining of the ANN in the learning phase and the lack of its ability to generalization. It is noteworthy that RMSE generated with the use of the ANFIS and ANN is smaller than RMSE for the average and the linear regression model (the exception is the ANFIS trained according to back-propagation method). The comparison of different forecasting models is especially recommended in the case of significant variance of an output variable.

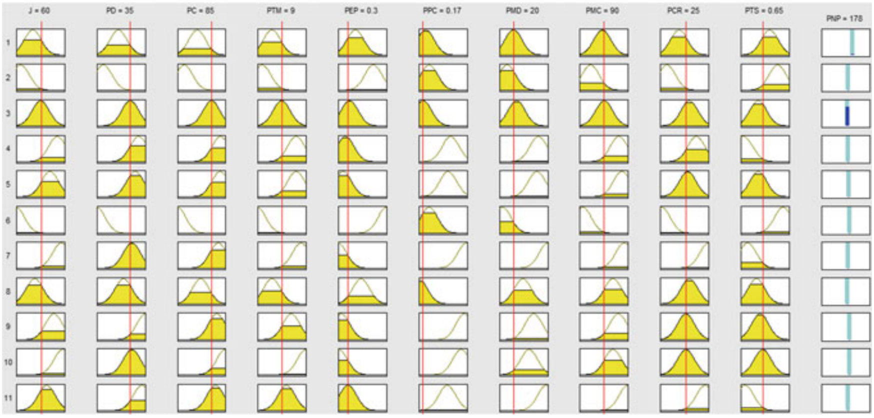

Fig. 8.3 Estimating net profit from product P1

The identified relationships between input and output data are stored in the structure of ANN and ANFIS. The fuzzy neural system identified 11 rules that have been used to compute the estimation of net profit for five products. In order to calculate the forecasts of net profit for the considered products, the planned values of ten input variables have been led to the trained ANFIS structure. Figure 8.3 illustrates the membership functions for the rules that are used for estimating net profit from product P1.

The estimated net profit for products P1, P2, P3, P4 and P5 equals 178, 115, 81, 251, and 154, respectively. The presented example include the following constraints: 35 weeks for duration of the NPD projects (all projects are developed simultaneously), 25 people involve directly in the NPD projects, 200 thousand Euros for the R&D budget, and 250 thousand Euros for the budget of marketing campaign. The maximal total net profit from new product is the criterion of project portfolio selection. From this point of view, the optimal product portfolio includes product P3, P4 and P5 with the total net profit equals 486. Figure 8.4 presents a user interface of the proposed knowledge-based system for product portfolio selection. Interface allows the decision-maker to assign the values of input variables for each product, the limits for resources, and consequently, to obtain the optimal product portfolio and the estimated values for the resources and total net profit for all products.

The presented knowledge-based system enables what-if analysis for the different values of input variables and constraints. This analysis can be extended towards a reverse approach, i.e. the determination such values of the input variables or/and resources to obtain the desired value of net profit from new product. Figure 8.5 presents a user interface of the proposed knowledge-based system for seeking the feasible product portfolios for the desired value of total net profit and the changes in the field of resources.

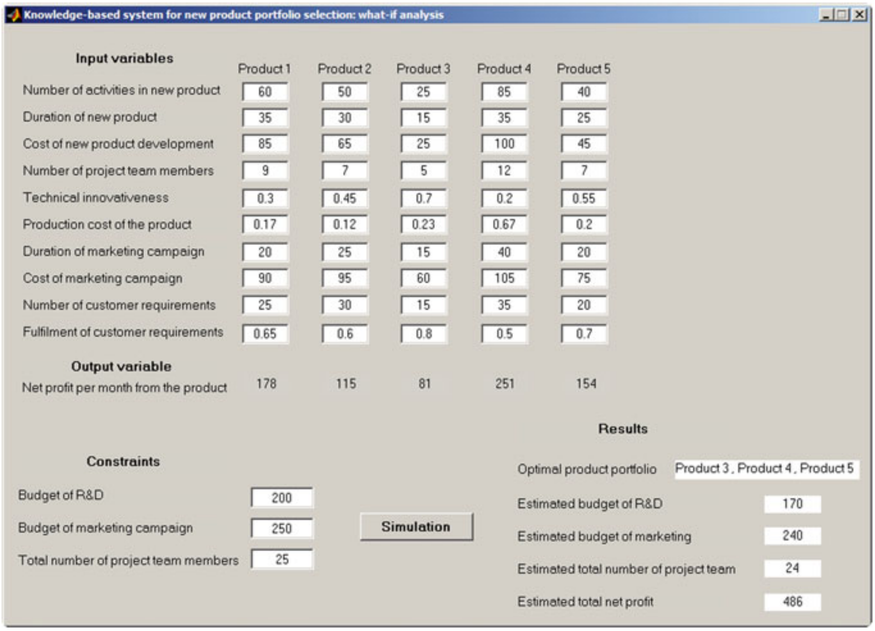

Fig. 8.4 User interface for product portfolio selection

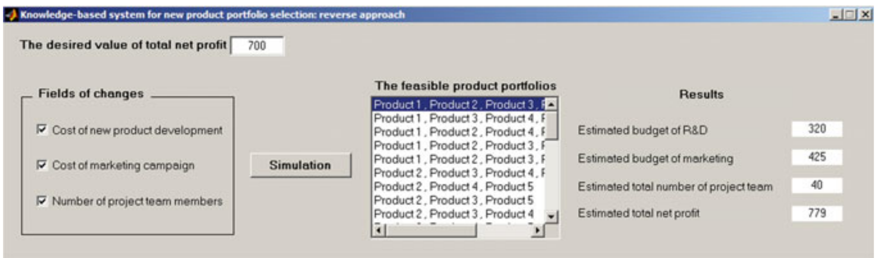

Fig. 8.5 User interface for product portfolio selection: a reverse approach

The reverse approach is connected with seeking an answer to the question what values should have the input variables or/and resources to reach the desired value of net profit from new product. In order to obtain a set of the feasible solutions, the constraint programming framework is used. This framework integrates the relationships identified by the ANFIS, technical parameters, expert experience, and user requirements into a knowledge base. Moreover, the constraint programming facilitates the implementation of model in terms of constraint satisfaction problem and the inference engine of the proposed knowledge-based system. In studies, the constraint programming framework has been implemented in Oz Mozart programming environment.

8.6 Conclusions

The continuous development and launching of new products is an important determinant of maintaining the company's success. However, due to its inherent features, new product development is a relatively risky activity. Failed NPD projects can decrease market share, profitability, and finally, lead to bankruptcy. The rapid evolving technology, the fast changing markets and the more demanding customers, require developing high quality new products more efficiently and effectively. To ensure these requirements, the identification of the key success factors of product is needed. As an enterprise system stores the data connected with the various areas of business, including customers' demand and NPD projects, its database can be used to seeking the relationships between these areas and the success of a product. These relationships can be further used to evaluating concepts for new products and selecting product portfolio for development.

The characteristics of the presented knowledge-based system includes the use of expert knowledge to select variables used in the knowledge discovery process, fuzzy neural networks to seek the relationships and their description in the form of if-then rules, and framework of constraint satisfaction problem to specify a knowledge base. This knowledge base includes the rules identified by fuzzy neural network or/and an expert, facts (including company's resources), and it allows the managers to obtain an answer to the routine questions such as what is the most promising set of products for development, or what parameters should have the NPD projects to increase their chances for the success? The use of constraint programming to describe the constraint satisfaction problem allows the development of a knowledge-based system in a pertinent framework.

This study presents the possibility of using an enterprise system database to the identification of relationships between the success of a product and the factors in the field of marketing, customer complaints, production, and project management. These relationships are sought with the use of fuzzy neural networks that have been compared with the results from artificial neural networks and linear regression. The results indicate that the least error in the testing set has been generated with the use of fuzzy neural network trained according to the hybrid method. Nevertheless, the learning of fuzzy neural network requires declaration of several parameters that are chosen in an experimental way, what can be considered as a drawback of the proposed approach.

The proposed approach has several advantages such as the low effort of data retrieval (the data are accessible in an enterprise system), the possibility of parameter change and what-if analysis, as well as the determination such values of resources to obtain the desired value of net profit from new products. Moreover, the recognized patterns are used in the knowledge-based system to help the managers in conducting simulation of the NPD projects, selecting the most promising product portfolio, and reducing the risk of unsuccessful product development.

The proposed approach gives new insights to the literature of pattern identification with the use of an enterprise system database that aims to improve development of new products, and finally, the success rate of products. On the other hand, the application of the proposed approach encounters some difficulties, for instance, by collecting enough amounts of data of the past similar NPD projects and ambiguous principles to build structure of fuzzy neural network. Nevertheless, the presented approach seems to have the promising properties for acquiring information from an enterprise system and improving the decision-making process in the context of selecting new product portfolio.

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Chapter 9
Knowledge-Based Models for Smart Grid

Igor B. Yadykin and Evgeny M. Maximov

Abstract At the plant level, a smart grid unifies power grids, consumers and generating facilities in a single automated system which enables real-time tracking and monitoring the regimes of all participants. It responds automatically to the changes of all parameters in the power grid and maintains no-break power with maximum benefits and lower human involvement. The most effective control can be attained in smart grids by using intelligent agents. Their functionalities should be based on intelligent control algorithms with predictive models featuring high-precision treatment of process knowledge and adaptive learning. This chapter offers a concept of developing an intelligent multi-agent system that maintains stability of Russia's Smart Grid incorporating an active analytical network (AAN) and new algorithms to determine the degree of the system's stability by using Gramians.

9.1 Multi-agent Systems in Power Engineering

Stability control is a critical aspect the synthesis of multimodal large-scale energy network. The control systems of national power grids consist of various subsystems performing their own functions and interacting with numerous remotely located engineers. With this in mind, the present authors believe that some control elements should be taken over by the system's periphery with their scopes and access to data strictly delineated. A today's energy facility control system must be intelligent, multimodal and dynamic. For the grid frequency and power control to operate efficiently, the facility functioning is assumed to be adjustable in real time. This kind of control needs systems that would predict the facility state by relying on a database on power generation, consumption and reserves so as to carry out dynamic stability analysis and prevent contingencies at various levels (Bakhtadze et al. 2011a, b). Network control with predictive models for plants of various levels that perform various functions needs multi-agent technologies.

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9.1.1 Multi-agent Control Systems for Energy Facilities

At present multi-agent systems (MAS) are employed in control of energy facilities in the U.S., Japan, India, China and the European Union. They tackle quite a few power engineering tasks but not yet control of national power grids, even though such designs are already being developed and to some extent implemented.

What follows are show cases of MAS used in power engineering:

- Transmission networks (standard automation hardware in power grids).
  Energy facilities are controlled now by various monitoring and control systems. In particular, Britain's National Grid Transco (NGT) serves a grid of 244 substations of 275 or 400 kW that are subsequently distributed among 132 kW and lower tension substations (NGT web site 2011) substations are now equipped with distributed intelligent electronic devices (IEDs) which are in charge of various data transfer and processing functions in a corporate network.
- Monitoring smart grids and data processing and control multi-agent systems.
  Today's electric facilities rely on three basic types of substation automation: Supervisory Control And Data Acquisition (SCADA) systems, EMS (Energy Management Systems) and Substation Automation Systems (SAS) (Bricker et al. 2001). They make up a hierarchical structure, with an EMS at the topmost level. A medium level SCADA that is directly dependent on the EMS and a SAS system for every substation at the lowermost level. Centralized processing of large amounts of technological data and extraction of technological knowledge from them for subsequent use in intelligent control systems become inefficient. What is needed is an open access to substation data through a global network of the power company. This is the reason why MAS super-imposed over standard automation hardware in power grids are used on an increasing scale.
- Controlling commutation equipment (Preiss and Wegmann 2001).
  The system employs aiding agents, equipment engineers and distribution agents. Equipment engineers work using transformers, buses, and transmission lines and look after their operational state, service time and the service time of their elements. Distribution agents operate switches or bunches of switches.
- Supervision of bills and power supply service bills.
  Nagata et al. (2002) outlines a sequence of negotiations between agents who represent independent system operators and companies that transmit power to consumers.
- Optimizing power distribution (Vishwanathan et al. 2001).
  The negotiation medium system includes consumers and their representatives as agents who share in the energy auctions. Such systems must be able to flexibly follow price variations over several auction steps. They must be able to interact with large-scale systems and a set of applications.
  The Foundation for Intelligent Physical Agents (FIPA) was set up in 2005 under whose auspices basic guidelines on multi-agent systems, in particular in the power engineering industry, are being worked out. Experts note (FIPA web site 2005) that technologies and ways to analyze data are urgently needed to give

concrete substance to the document "European Smart Grids Technology Platform". MAS will make it possible, for instance, to overcome differences in monitoring key indices such as the duration of the average system interruption (SAIDI index) in the U.S.A. and customer minutes lost in Britain. A methodology needed to resolve this problem could be a MAS where the large-scale system is made up of subsystems performing various functions.

9.1.2 Development of Standards and Specifications

Compliance with standards is especially important for the systems under development. All applications in control systems must comply with data exchange standards such as the Common Information Model (CIM) and IEC 61850 (Documents IEC 61850). FIPA has developed a set of special standards covering all kinds of interaction between agents in a power grid. These standards are legitimate for multi-agent systems in the power engineering industry.

- Message delivery to MAS is regulated by the FIPA's standard Agent Management Reference Model that in fact regulates a logical model of agent interaction.
- The FIPA Agent Communication Language (FIPA-ACL) standard regulates the structure and flow of messages between agents on the FIPA agent platform.
- Message contents are described by the FIPA Semantic Language (FIPA-SL) that specifies the syntax.
- and semantics, or grammar and lexicology of the message content and also the ontology language.

Reasoning formalization technology development for various agents and MAS is specific.

Certain standard solutions are known such as standard planners in artificial intelligence systems or systems based on Belief-Desire-Intention (BDI) architecture. Special solutions based on use of neuron network and various pattern recognition models are used .

MAS architecture development. Architectures of multi-agent systems that are employed in today's control systems may be conveniently classified as follows:

- Architectures relying on artificial intelligence principles and methods (deliberate agent architectures).
- Reactive architectures based on the behaviour and responses to events in the exogenous world (reactive agent architecture).
- Hybrid multi-level architectures based on artificial intelligence (AI) behaviour and methods (hybrid agent architectures).

Designs of global MAS. The special literature has on an increasing number of occasions been mentioning the need to develop Smart Grids that would implement cross- system (inter-regional) integration through a multi-agent technology (Buse and Wu 2007) Numerous authors believe that this approach may combine the potential of a global control system to reason and to analyze the situation and to devise proper managerial decisions. The modelling of sophisticated control systems by using a multi-agent approach is termed Agent-based modelling (ABM).

- The U.S. National Institute of Standards and Technology (NIST) reports frameworks and a roadmap for Smart Grid interoperability standards. The European Union and numerous partner countries are sharing in field tests of possibilities that could be put to good use in cross-system Smart Grid technologies (Catterson et al. 2012).

China has successfully implemented its own Smart Grid programs such as the National 11–5th High-Tech Support Program of China (2006BAH02A0407) and Technology Support Program of the State Grid of China (WG1-2010-X). These programs place special emphasis on development of MAS for control of distributed cooperation between system elements and integration of applications resultant from technological knowledge.

MAS developed for intelligent control of actively adaptive networks will make it possible to have flexible control tools with modules which can be up-scaled, mobile and interoperable- all important features for knowledge-based control.

The architecture of a multi-agent system for intelligent energy installations will provide intelligent support to decision making on improving the operational reliability for the entire energy facility control at every level and also to optimize economic indices in power generation and consumption. Intelligent agents enable the system to restore its operability following a cascade of blackouts. The multi-agent subsystem that prevents loss of stability in the IES control system must become a major element in the system destabilization early warning subsystem, the global immune system that implements the pre-failure prevention strategy (Fig. 9.1).

9.1.3 Determining Energy Facility's Degree of Stability

Operational voltage instability is now regarded as the key cause of avalanche-like tension increases and cascade blackouts. The U.S. and Canada 1965–1987 statistics suggests that 17 blackouts featured voltage instability. Weakly-dampened energy facility modes and resonance properties of the power grid that lead to low frequency oscillations add up to another problem. If a perturbation arises in the power grid that is caused by a generation loss or a line disconnection, the resonance processes in the system lead to an amplitude increase and weaker dampening of the oscillations (Fig. 9.2).

Science has known the need to determine the stability degree of the power grid for over 50 years; this has remained an unresolved problem. The research in this field has chiefly concentrated around the direct Lyapunov method, modal analysis

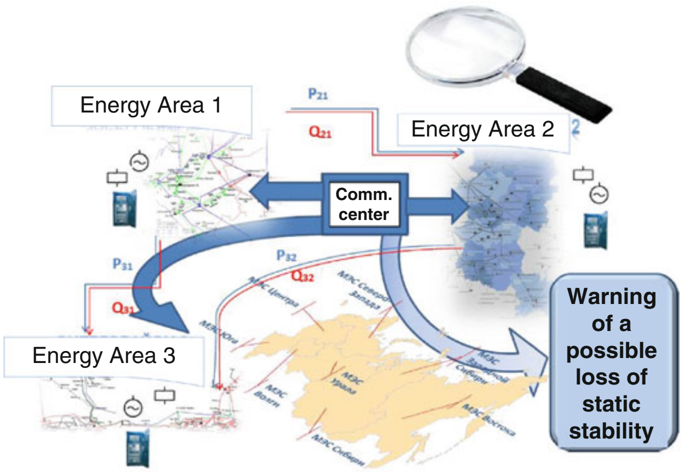

Fig. 9.1 A fragment of the MAS reliability control

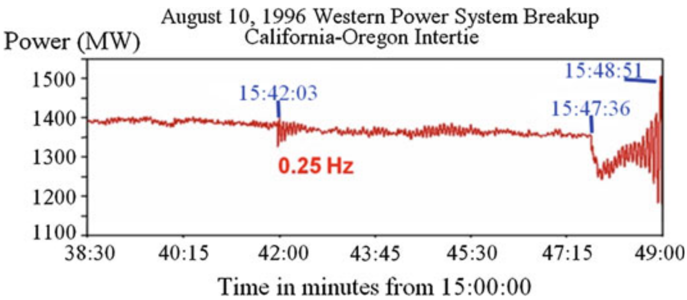

Fig. 9.2 Tension plots in the California-Oregon line: a 1966 California blackout (WSCC Breakup)

and studies of eigen values in characteristic equations of energy facility math model matrices. Various mathematical methods and their combinations have been used.

Spectral methods rely on the Alberti method, the method of computing the dominant spectrum poles and the matrix signum-function method. Modal analysis methods rely on the Prony's method, recursive robust method, the least squares method, the Yule-Walker algorithms, the wavelet analysis, neuron nets and genetic algorithms.

In practical terms, however, all these methods do not work very well, above all, because mathematical models of power grids are unwieldy in that they are non-linear, non-stationary and distributed; their slow and fast processes are described in different terms. Every method works only with certain system modes. The math models of power grids are high dimensional and so real time solution of such problems is out of the question.

9.1.4 Gramian Method of Determining the Degree of Static Stability

To determine the static stability of a power grid a report filed in Sukhanov et al. (2011) suggests a Gramian method based on a new mathematical technique of solving Lyapunov and Silvester differential and algebraic equations that was developed in the Institute of Control Sciences for analysis of the degree of stability in linear dynamic systems. The method operates by decomposing the Gramian matrix that is a solution to the Lyapunov or Silvester equations into a spectrum of matrices that make up these equations.

Optimal management of recovery plan may be executed by agents lower-level MAS, who perform preventive actions (joint actions), for example, by coordinated control systems of generators in neighboring segments. When an asynchronous way is arising (recognition) isolated power system MAS performs actions (formation of a group of agents and planning) to prevent landing generators to zero (the most severe systemic failure which may result from large active power deficit, the maintenance of the autonomous power supply and simultaneously to restore normal mode (joint actions).

The main advantage of multi-agent technologies usage in such a situation is to eliminate the human situational factors in modes management and improvement system reliability through timely and rapid reconfiguration control clusters after failures network or computer equipment. To develop immune system it is necessary to create virtual analyzer (soft sensor) of the stability loss threat. There are several approach to design such analyzer (Sukhanov et al. 2011):

- Ill-stable oscillation power measurement,
- Selective modal analysis,
- Modified Arnoldi method,
- Parametric identification methods,
- Kalman filter,
- Neural networks.

For soft sensor design one can use direct Lyapunov method, based on analysis of solution of the Lyapunov differential or algebraic equation in frequency domain. Let take up continuous dynamic system

$$\begin{aligned} \dot{x} &= Ax + Bu,\ x(0) = 0, \\ y &= Cx, \end{aligned} \tag{9.1}$$

where $x \in R^n, u \in R^r, y \in R^r$. We will consider real square finite dimension $A_{[n \times n]}$, matrices, where n are any positive integers. Assume that the systems are completely controllable and observable. The system controllability Gramian of the system (9.1) is known to be determined in a time and frequency domain

$$P^c(t) = \int_0^t e^{At}BB^{\mathrm{T}}e^{A^{\mathrm{T}}t}dt,\ P(\infty) = \int_0^\infty e^{At}BB^{\mathrm{T}}e^{A^{\mathrm{T}}t}dt.$$

Let take up continuous differential and algebraic Lyapunov equations of the form

$$\begin{aligned} &\frac{dP(t)}{dt} = AP(t) + P(t)A^{\mathrm{T}} + R,\ P(0) = 0_n, \\ &AP(\infty) + P(\infty)A^{\mathrm{T}} + R = 0. \end{aligned} \tag{9.2}$$

9.1.5 The Differential and Algebraic Lyapunov Equation Solution in Time and Frequency Domain

Let take up a matrix integral of the form $P(t) = \int_0^t e^{At}Re^{A_m t}dt$, where real quadratic matrices of finite dimensions $A_{[n\times n]} = [a_{ij}]$, $A_{m[r\times r]} = [a_{mij}], R_{[n\times r]} = [r_{ij}]$

Assume, that the conditions $s_k + s_l \neq 0, \forall k = 1,2\ldots n;\ \forall l = 1,2\ldots r.$ are met. Then the following statements are true: for all finite times $t \in [0,\infty)$ and all values of matrix elements $A, A_m \in \Sigma$, except those in which eigenvalues of both matrices become multiples and cases, in which the condition $s_k + s_l \neq 0, \forall k = 1,2\ldots n;\ \forall l = 1,2\ldots r$; does not hold, for cases where the spectra of the matrix A_m, A are plain, the following identities are true

$$\begin{aligned} P(s) \;=\; L\{P(t)\} &= -s^{-1}\sum_{k=1}^{n}\sum_{l=1}^{r}\sum_{j=0}^{n-1}\sum_{\eta=0}^{r-1}\frac{s_k^j s_l^\eta}{(s_l+s_k)N'(s_k)N'_m(s_l)}A_jRA_{m\eta} \\ &+\sum_{k=1}^{n}\sum_{\lambda=l}^{r}\sum_{j=0}^{n-1}\sum_{\eta=0}^{r-1}\frac{s_k^j s_l^\eta}{(s_l+s_k)N'(s_k)\frac{dN_m(s-s_k)}{ds}|_{s=s_k+s_l}}\times\frac{1}{(s-s_k-s_l)}A_jRA_{m\eta} \\ &= s^{-1}\sum_{\lambda=l}^{r}\sum_{j=0}^{n-1}\sum_{\eta=0}^{r-1}\frac{s_l^\eta(-s_l)^j}{N'_m(s_l)N(-s_l)}A_jRA_{m\eta} \\ &+\sum_{k=1}^{n}\sum_{\lambda=l}^{r}\sum_{j=0}^{n-1}\sum_{\eta=0}^{r-1}\frac{s_k^j s_l^\eta}{(s_l+s_k)N'_m(s_l)\frac{dN(s-s_l)}{ds}|_{s=s_k+s_l}}\times\frac{1}{(s-s_k-s_l)}A_jRA_m \end{aligned} \tag{9.3}$$

$$P(t) = L^{-1}[P(s)]. \tag{9.4}$$

Linearized model in small relative to the power system fixed mode is defined as the linear algebro-differential equations system

$$\begin{aligned} \dot{x}(t) &= A_1 x(t) + Bu(t), x(t_0) = 0, \\ Mx(t) &= Nu(t). \end{aligned} \tag{9.5}$$

Suppose that, matrix M is nonsingular one. Then (9.5) may be transformed as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), x(t_0) = 0, \\ A &= A_1 + M^{-1}N, \end{aligned}$$

Stability of the differential-and-algebraic equations for a power grid is analyzed by real time computation of the system's Gramian and by using the asymptotic Frobenius norms of the Gramian, that norm going to infinity as the real part of any root in the system characteristic equation goes to zero.

Experimental studies of the Gramian method for a four-generator and two-line system (the Kundur circuit) have led to the following findings:

- As they approach the real part of the real root or the real part of the pair of complex-conjugated roots of the power grid characteristic equation, Gramians go to infinity.
- The dangerous electric mode makes it possible to detect the approach to the critical point much earlier than the full Gramian norm would do.
- When a "critical" sub-Gramian is identified it is the dynamics of its behaviour, or its derivative, is important rather than its value.

9.1.6 Technology of Maintaining the Desired Degree of Stability

In line with the multi-agent approach, the desired degree of stability is maintained by on line monitoring the degree of static stability in the mains detecting and localizing the critical section of the network and FACTS Vector automatic control with devices by using the transient mode monitoring systems through monitoring and controlling the damping of low-frequency vibrations in the power grid.

The other technology implemented in line with the multi-agent approach stabilizes in real time the reserves of static stability in the power grid by monitoring and damping dangerous low-frequency vibrations on the basis of adaptive vector control of FACTS hardware that attach to the power grid the spots where stability is likely to be disturbed. The technology maintains the following functions:

(1) Current voltage and reactive power data reception, processing, filing and presentation to the personnel.
(2) FACTS hardware generation of local adaptive control.
(3) Generation of the coordinating adaptive control vector (on the basis of data from the transient mode monitoring system) for intelligent multi-agent systems for geographically close energy facilities.

(4) Adaptive on-line stabilization of static stability reserves with monitoring the parameters of dangerous low frequency vibrations (agent of adaptive stabilization of static stability reserves).
(5) On line monitoring of static stability reserves, frequency values and dampening degree of low frequency vibrations (agent for on line computing the static stability reserves, frequency and the dampening degree of dangerous inter-regional vibrations).

This technology lays the groundwork for a new generation of control systems aimed at preserving stability of intelligent adaptive systems. Its application is expected to significantly improve the throughput in the bandwidths of the network control systems.

9.1.7 An Intelligent System that Maintains the Specified Reliability Criterion N-k

(1) monitoring the current reliability state of the power grid by using a real-time digital modelling platform;
(2) diagnosis of the state, detection and localization of simultaneous failure of k power units;
(3) normal self-healing of the power grid.

This multi-agent system performs the following functions:

- data reception, processing, filing and presentation to the personnel (current voltages, active and reactive power values obtained from transient mode monitoring systems and SCADA value and telemetry data);
- formation of a probabilistic mathematical model of the power grid with adjacent distributed power generation and consumption, computation of current reliability indices (agent for generation of reliability indices);
- automatic adaptation of model parameters to the current mode (agent for model parameter adjustment);
- real-time model verification (agent for model verification);
- data reduction for an intelligent model self-restoration problem solver and bringing reliability indices to desired values;
- mode self-restoration (agent for intelligent mode self-restoration problem solver);
- initiation of commands to switch on automatic power grid self-reconfiguration (agent for power grid mode reconfiguration).

9.1.7.1 Agent for an Intelligent Mode Self-restoration Problem Solver

This subsystem may be implemented as a set of decentralized network control systems with the use of network clusters. Each network cluster consists of a decentralized computing part, a telemetry network containing a common bus, a data processing part and an executive part (first level agents). A decentralized part will be assumed to consist of a totality of multi-processor computing units of similar processors that are connected to the common bus with the aid of commutation network controllers.

If several power facilities in a network have simultaneously failed, the system may recover on its own if it possesses “hot” reserves of active or reactive bandwidth in relevant sections of the network. The agent will continuously update his knowledge base so as to create a current and a reference model of the network. This agent acts as a local switchboard of the multi-agent system and tackles the following tasks:

- detecting a dangerous deflection of the state from the predicted one of the reference model and localizing it (an agent for predicting a dangerous state of the system);
- predicting a potential failure situation (an agent for an associative search for a precedent);
- planning the process of control system reconfiguration.

It is obvious that for self-healing of an intelligent power grid the loads of failed power units should be transferred to generation sources that possess relevant reserves of active and/or reactive power provided that the network sections that connect the above loads to new generation sources possess throughput reserves in all above sections. What is also important is that the necessary reserves may be obtained by using the intelligent system of supporting the specified stability and self-healing of the power unit.

Quite operable decentralized network control systems (DNCS) that are not connected to the DNCSs of the operable part of the power grid. A power grid may self-heal in either of the two ways below. In the one the communication channels of failed power units are connected to associated operable power units; consequently, the control system may be reconfigured by reconfiguring the communication network. In the other technique the communication network need not be self-healed, if multi-agent technologies are used in the reconfiguration.

9.1.7.2 Agent (MAS) for Reconfiguring the Power Grid Mode

An agent is a multi-agent system where the reconfiguring planning and control are implemented by technical agents that are 6th level agents that act as the coordinating centre of the multi-agent system and perform the following tasks:

- determining the ordinal numbers of operable and, possibly, failed processing units;
- determining reserve DNCS processing units in the operable part of the power grid;
- transfer through the communication network the original DNCS codes if the failed part to reserve DNCS;
- processing units in the operable part of the power grid;
- resuming the power grid control.

There are several ways to make DNCS stable in face of processing unit failures:

- increasing the reserve production of the processing units;
- reservation of processing units;
- a combination of the two above techniques.

The probability of smooth operation in the commutative network is usually achieved by using various kinds of reserving the communication channels.

Using the proposed mathematical methods to develop and install MAS for early warning of the system losing stability will step up the network throughput by at least 3 %; this increase will improve the network company's profit, save capital investments in network construction and modernization and payment for various additional system services. Furthermore, losses of the active power in the electric network will be reduced, the range of admissible modes will be extended by limiting power flows and improving the system controllability and consequently the mode reliability. The development of a real time programmable sensor that would specify the point where the system stability may be lost will make it possible to start the tackling of the following new technological tasks:

- Development of an adaptive automatic vector dampening control of dangerous low frequency oscillations in a power grid;
- Development of a computation technique and program for real time emergency control devices;
- Development of a new generation of multi-agent systems that would counter stability disturbances in intelligent adaptive systems which maintain system stability.

9.2 Intelligent Multi-agent Optimization System in Smart Grids

9.2.1 Design of Multimodal Intelligent Immune System for Smart Grid

In the conditions of both increasing demands to reliability and quality of electric power supply and energy generation technologies development to solve regime optimization problems it is effective to use intellectual networks. The term "intelligent networks" means the aggregate of power and information/communication technologies providing the possibilities of effective power distribution and control of consumption through exchange and smart control of technical and marketing information. In a sense, smart grid is a multimodal network.

The smart power grid with active adaptive network is a new generation electric power system aiming effective use of different types of resources (natural, technological, human) for reliable, high quality and effective power supply of energy consumers through flexible interaction of its subjects (that is different types of energy generators, power networks and consumers) based on modern techniques and equipment and universal intelligent control system.

The complexity of control of united national smart grid of Russia is so high that centralized control becomes ineffective due to huge information streams when too much time take data transmission to the center for decision making. That is why certain functions of organizational control are to be delivered from center to periphery with the strict differentiation of information availability rights.

Analysis of modern design techniques, control soft and hardware of power grid technology devices gives the opportunity to use multi agent approach (Rehtanz 2003) as a basis of system solution. According to this concept the control system of upper level of electric energy systems (EES) is to be a coordinating information management system based on standard interaction protocols and interfaces. The control system architecture becomes modular, interoperable, and expansible.

It is constructed of imbedded network clusters of vertical integrated multi-agent system where intellectual autonomous agents of different purposes are functioning. The operation of intellectual control system is based on dynamic estimation and intellectual prediction of EES state aiming adaptive control and dynamic support of decision making.

The EES functioning is characterized by following factors:

- EES often is working in transient modes close to limiting with respect to stability loss;
- Short time interval is left for decision making by human operator;
- Coordination is necessary between control actions in local networks of large consumers and global network;
- Recovering of EES working conditions is to be done automatically.

The mentioned factors need to use new control strategies based on automatic holding of EES working conditions in safe state with necessary stability reserve. This strategy may be realized by use of both intellectual automatic system of EES static stability degree determination and intellectual automatic system of EES guaranteed stability support (Pourbeik et al. 2006). Using of multi agent approach allows to implement this complex control strategy what results in possible diminishing of normative stability reserve so increasing EES capacity.

Equal with providing EES guaranteed stability reserve the important control problem is inner and outer threats detection, their geographic localization and danger level determination.

Recently there has been increased an interest in the study of artificial immune systems. Artificial immune systems (AIS) may be determined as information methodology, using the concept of theoretical immunology to solve applied problems. AIS is an adaptive system for data processing and analysis, which are the mathematical structure that mimics some of the functions of the human immune system and possesses properties such as the ability to learn, forecasting and self-healing. Principles and mechanisms of the immune system are used to build data analysis algorithms, optimization, and pattern recognition systems, technology, computer and Internet security, risk assessment and other applications (Samigulina and Chebeiko 2003).

The first experiments in this area of investigations were made in the 70s. XX century; an extensive work began in the 90s.

This chapter discusses aspects of the smart grids creation using multi-agent technology for AIS implementation.

9.2.2 Inner and Outer Threats Detection and Their Geographic Localization

Principal advantage of smart grid with active adaptive system (SG AAS) is its ability to foresee inner or outer threats and react instantly eliminating them or diminishing their influence on SG AAS functioning in normal conditions, before, in time of, and after the breakdown conditions. Similar properties has immune system of animals (including the human race) so this intellectual multi agent subsystem of SG AAS may be called "immune" one.

The existing control system and breakdown protection system of SG do not possess these properties in full though certain functions of intellectual "immune" system may be realized in truncated form. Moreover, on the stage of working conditions planning, system is able to recover after arbitrary line switching off (that is, one has insensitivity property); the loads are chosen with certain reserve with respect to expected maximal values.

The main types of outer threats are as follows: terrorism; cyber threats; natural cataclysms; industrial catastrophes. The inner threats are: arising of unpredictable perturbations; possibility of cascade breakdown arising and development; stability loss in normal/transient conditions; violation of thermal stability; wrong decisions and/or actions of personnel.

Main functions of the subsystem are as follows: detection of place and determination of danger level of threat; threat localization and isolation; preventive adaptive control; control system reconfiguration.

The following functions also may be realized by the system:

- Information reception, processing, storage, and presentation to personnel (the monitoring agent of environment state and power system state using knowledge base);

- Current working conditions reference model design (agent constructing forecasting reference model);
- Detection of dangerous deviation of system state from predicted reference model state and its localization (predicting agent of dangerous system state);
- Forecasting of possible breakdown situation (agent for precedent associative search).

Note that variety of threat types makes impossible construction of universal intellectual immune system.

So increasing the energy efficiency of EES AAS can't be achieved without global immune system with AAS which permits both automatically system restoration after breakdown and to fulfill a number of preventive measures (Bakhtadze et al. 2008). Such approach realizes essential progress in implementation of breakdown anticipating control strategy with simultaneous efficiency increase.

The functions of intellectual immune system of EES AAS with AAS:

- Monitoring of environment state and EES AAS state with replenishment of technology knowledge base (information reception, storage, processing, and presentation to personnel).
- Real time monitoring of power grid static stability. The system calculates the static stability reserve of EES AAS on line and presents recommendations to dispatcher for conserving necessary reserves of EES AAS static stability and restoration of normal functioning mode after system breakdown. The technique is based on developed in Institute of Control Sciences Gramian method of calculation of linear dynamic system stability degree.
- Real time adjusting of prediction model of current operation mode dynamics.
- Detection of dangerous deviation of system state from predicted model state and its localization (forecasting agent of energy system dangerous state).
- Prediction of dangerous situations (using intellectual associative search of precedent).
- Determination of control actions and recommendation on threat development prevention and normal operation mode recovering (human operator intellectual assistant).

9.2.3 Dynamic State Estimation Algorithm and Predictive Model Design of Current Operation Mode

Under conditions of increasing demands to reliability and quality of power supply optimization of energy plants working conditions concludes in optimal loading, providing necessary stability reserve based on dynamic stability analysis, minimization of energy losses, elimination of idle water escapes, so guaranteeing high reliability of energy system.

These conditions can be met using control system with predictive dynamic models (Comacho and Bordons 1998). For example, in anti-crash control systems, short-term forecasts are to be used, which underlie the determination of dispatcher schedules and necessary values of power reserves and their localization in energy system. To implement such control, one needs the control system which allows to predict energy plant state by technological data on current production, consumption, and available reserve power units.

Control decision making support and/or control action determination while solving certain technological problems is carried out with the help of intellectual algorithms of nonlinear dynamic system identification. Those are based on inductive learning: associative search of analogues by intellectual analysis of both archives of energy system technology parameters (Data Mining) and the knowledge base of technologies.

The construction of predictive model by associative search of dynamic plant on each step is based on technological knowledge. This approach allows to use any available a priori information about the plant. To increase quickness of algorithm and to save computational resources, one is to learn the system (Hunt 1989). The criterion of input vectors choice from the archive for current virtual model building underlies clustering technique choice.

The linear dynamic model is:

$$y_t = a_0 + \sum_{i=1}^{r} a_i y_{t-i} + \sum_{j=1}^{s} \sum_{p=1}^{P} b_{jp} x_{t-l_j,p}, \quad l_j \leq t \tag{9.6}$$

where y_t is the object's output forecast at the tth step, x_t is the input vector, r is the output memory depth, s is the input memory depth, P is the input vector length. The Eq. (9.1) differs from the ordinary regression because $t - l_j$ are being selected not in chronological sequence but rather according to a certain criterion, which describes the proximity of input vectors with the index $t - l_j$ to the current input vector x_t. Such criteria are named associative impulses.

The original dynamic algorithm consists in the design of an approximating hypersurface in the input vector space and the related one-dimensional outputs at every time step (see Fig. 9.1). To build a virtual model for a specific time step, the vectors close in a manner to the current input vector are selected. This selection procedure is called *associative impulse*. The output value at the next step is further calculated using least-squares method (LSM).

To increase the speed of the virtual models-based algorithm, an approach is applied based on employing a model of process operator's associative thinking for predicting.

For modeling the associative search procedure imitating the intuitive prediction of process status by an analyst we assume that the sets of process variable values, which are the components of an input vector, as well as the system outputs at previous time steps altogether create a set of symptoms, making an image of the object output at the next step.

The associative search process consists in the recovery of all symptoms describing the specific object based on its images. Denote the image initiating the associative search by R_0 and the corresponding resulting image of the associative search by R. A pair of images (R_0, R) will be further called *association* A or $A(R_0, R)$. The set of all associations over the set of images forms the memory of the intelligent system's knowledgebase.

$X_N, X_{N-k} \ldots, X_{N-j}$ are the input vectors, and $Y_N, Y_{N-k} \ldots, Y_{N-j}$ are corresponded output signals.

At the system's learning phase, an archive of images is created. In our case, a set of input vectors selected form the process history will be considered as an image. At the prediction stage, the input vector x_t will be considered as an initial image R_0^a of the associative search, while approximating hypersurface formed by the input vectors from the process history will be the final image R^a of the associative search. The selected hypersurface is an image of the current input vector which is used for output prediction. The algorithm implements the process of image R^a recovery based on R_0^a, i.e., the associative search process, and can be described by a predicate $\Xi = \{\Xi_i(R_{0i}^a, R_i^a, T^a)\}$ where $R_{0i}^a \subset R_0$, $R_i^a \subset R$, and T^a is the duration of the associative search.

Here fuzzy algorithms techniques may be effectively used. So modern approaches suppose using for certain real plant identification, the simulation of the person who makes decisions based on technology knowledge.

9.2.4 Multi-agent Approach to Design of Intellectual Immune System for EES AAS

The design of intellectual immune system uses multi agent technology both for software implementation and as an instrument to coordinate different subsystems in general control system.

The multi agent techniques have principally new approach to solution of specific functional problems, that is, they are in fact self-organizing systems. It is important for control of large energy system in dangerous situations. The following factors are in favor of multi agent system using for control of EES AAS (Bakhtadze et al. 2011a, b) due to specific features of energy systems:

- the huge information flows together with complexity of system structure and its functional abilities;
- the problems to be solved and the systems to be designed are heterogeneous and distributed;
- in global multi agent control system of EES AAS the possibilities and means of adaptation to environment variation by changing its structure and parameters in real time;

- the system software evolution is characterized by developing of autonomous interactive modules;
- when information and relative processing means are distributed the parallel computation may be used so increasing computation speed and saving computing resources;
- the data base is distributed one.

Intellectual agents in control systems of EES AAS solve the problems by unconventional optimization techniques, in particular using on-line intellectual analysis of technology information.

9.2.5 Intellectual System of Group Control of Active and Reactive Power for Virtual Electric Power Station of Local Trading Area

Equally with the mentioned functions of global intellectual immune EES AAS it is useful to design group control systems which realize following functions:

- the support of given by system operator dispatcher schedules of voltage in prescribed “corridor “ emergency switching off the sources of distributed generation (for example, as a result of network or one of generation sources breakdown), that is, system service inside the local power system;
- to sell on wholesale electric energy market the power through distributed and transmission networks of reserve active and reactive distributed generation as external system service.

Let us indicate the following methods to achieve the mentioned aims:

- use of free distributed energy generation with fixed price to support necessary balance of virtual station active and reactive power;
- use the collective strategies of multi agent systems which are leasing certain power stations (sale of system service) to support mentioned balances and optimize operating mode.

In virtual power system, the reserve sources of distributed generation or large capacity energy accumulators are to be provided to stabilize frequency and support balance of active and reactive power.

9.2.6 Intellectual Automatic System of Frequency Control and Power Interflows Control

The loss of EPG operation stability due to load value and character changes, short circuit, etc., results in large economic losses owing to switching off the consumers supplying lines. To avoid such situations, automatic system of stability loss prevention is used which enlarges the capacity of transmission lines, readjustment of excitation controllers and turbo-generators, etc.

The architecture of these systems is a flexible structure of vertically integrated imbedded network clusters of multi agent systems. Let us choose following levels of hierarchy in which different multi agent subsystems are functioning: substations, centers of network management, center of regional segment management, center of coordinating (global) segment.

Together with vertical layers in multi agent system hierarchy, the horizontal layers are differentiated which determine the geographic localization of functionally identical multi agent systems.

9.2.7 The Mode of Detection of EPG Stability Loss (Safety Multi Agent System)

Safety multi agent system reveals the location and value of power misbalance and determines the responsibility zones for multi agent systems of regional information/control clusters, control clusters of distributed networks and consumers (formation of agent groups).

Very important is the function of geographical coordination of intellectual automatic systems of local EES static stability degree which monitors both stability degree of EES critical fragment and stability degrees of neighbor EES_i ($i = 1, 2 \ldots n$).

9.2.8 The Mode of Collective Preventive Action Planning

Several multi agent based systems can plan common actions in real time to recover working mode with guaranteed stability degree. These actions may include the analysis of possible scenarios of multi agent systems activity to recover normal operation mode, so optimizing the plan. To implement these scenarios one uses real time simulation/optimization platforms.

9.2.9 The Mode of Normal Functioning Recover

Optimal plan of management of normal mode recovering is to be realized by agents of the system lowest level which jointly fulfill preventive actions, for example through coordinate control of generators excitation systems in neighbor energy segments. In the case of asynchronous motion, the multi agent system of separate

EES fulfills specified actions (group of agents formation, planning) to prevent landing generators to zero (hard system breakdown which results from large deficit of active power) and support of autonomous power supply and synchronous motion recover by joint actions.

The main advantage of multi agent systems use in this conditions consists in elimination of human factor under situational control and system reliability increasing due to fast and timely control clusters reconfiguration in case of network/computing hardware failure.

9.2.10 Automatic Remote Diagnosis of Readiness for General Primary Frequency Control in the Power System

The use of transient mode monitoring technique to analyze dynamic property of EES AAS allows to solve many problems by multi agent systems in real time. This technique is realized by special hardware for information registration and transmission.

The energy system dynamics determines the transient modes dynamics for specified perturbation. Modern primary frequency control systems contain digital models of generator excitation, turbine rotation speed controllers, dynamic load models, models of safeguard and automation devices. Let consider multi agent approach for general primary frequency control in power system.

In case of dangerous situation resulting in voltage drop, primary frequency control is to be carried out by all power stations by means of power changing through automatic controllers of turbo aggregates rotation frequency, productivity of boilers, nuclear reactors, etc.

Normalized primary frequency control is to be carried out by fixed power stations (power units) which possess prescribed characteristics of primary control. In these plants, the necessary primary reserve is created and constantly supported.

It is important to estimate the generating equipment state with respect to its accordance to conventional standards. The participation of certain aggregate in primary frequency control is determined by parameter set which may change during equipment life time.

When equipment characteristics do not correspond to present requirement it may result in stability loss of whole energy system at large frequency oscillations. That is why very actual for energy system normal work becomes the diagnosis of current aggregates state and their readiness to primary frequency control.

The single mean of such diagnosis which is available today is the control testing. It requires switching off the generation process for all time of testing so being too expensive. The authors suggested methodology of remote diagnosis of generating facilities readiness for primary frequency control from aggregates reply on sudden frequency changes in normal working mode.

Control tests include checking-up of rotation frequency controllers for each turbine; combined testing of energy unit; section of thermal power unit with common steam pipe.

The generation equipment has to meet the following main conditions:

- the totality of basic and auxiliary equipment, power unit automation devices, power stations, and their working modes are to allow within the prescribed load limits primary control amplitudes up to 20 % of nominal power;
- for unique power change of turbo aggregate in the given range ±10 % from nominal value, the rotation frequency controller must provide prescribed transient time, and new power value must be provided by basic and auxiliary equipment, and power unit/station technological automation equipment for unlimited time.

The correspondence of experimental transient characteristic of primary frequency control to desired one (which is checked during certification tests) is achieved for each type of equipment by adjusting automatic control system of its working mode parameters: position of turbine's regulatory body, input turbine steam pressure, fuel consumption, and generator power.

Both, the results of certification tests (that is, empirical transient characteristics and aggregate parameter estimates) and turbine type, frequency droop and dead band of turbine speed controllers, droop and dead band of power regulators frequency offsets are put into technology knowledge base of automatic diagnosis system.

Further, one investigate the sample of frequency values with significant deviations, that is variation of frequency in the sample exceeding ±0.1 cycle per second for time period less than 1 min. Such data although are the elements of technological knowledge base.

Further, analysis of knowledge base current state is carried out including the evaluation of statistic and dynamic properties of certain parameters and their interconnections. Basing on this analysis one formulate (with respect to certain criterion) the set of input factors and respective outputs. This is done by associative search algorithm which is used to construct aggregate dynamic model (Fig. 9.3).

To construct the dynamic identification model by associative search technique, one uses the methods basing on-line associative analysis of technology knowledge. Method allows to obtain aggregate dynamic identification model for different specified sets of archive data. As technology knowledge base is replenished, one obtains the model coefficient set for given aggregate type. So one can calculate expected power and parameter values of certain aggregate for any input frequency. The model accuracy can be evaluated by responses proximity of model and aggregate under testing.

So far both power and parameter values of aggregate are known in process of model building, this model can be used to localize dead band.

During the aggregate life time, their state and their control system state do change. The use of intellectual algorithms of associative search allows to compare models based on archive data with on-line ones.

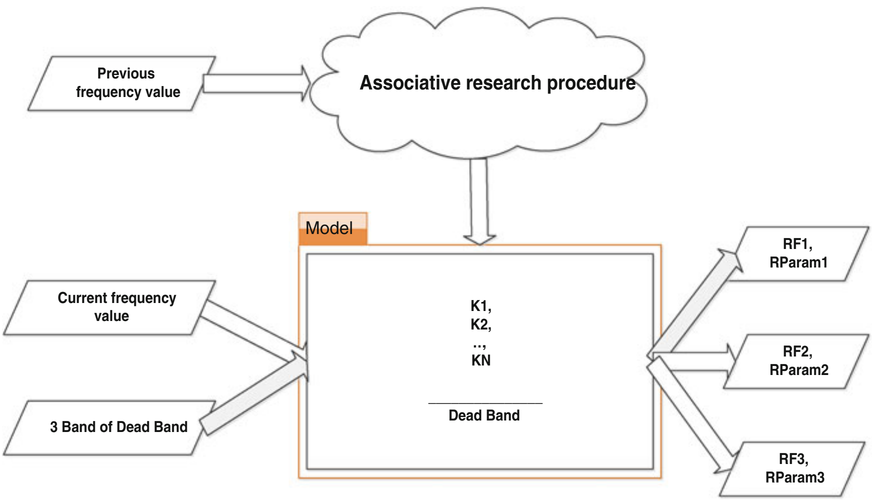

Fig. 9.3 Account of frequency by intelligent model. RP1, RP2, RP3 are specific values (from the process archive) of power realizations

Basing on parameter changes of aggregates identification models which are constructed from empirical data of real energy system functioning, one can find the significant changes in the functioning of certain aggregate and its control system which influence the quality of aggregate work in primary frequency control system.

9.3 Conclusion

The novelty of this work is that it presents a conceptual approach to the immune system design. Intelligent immune systems of new generation need the design and step-by-step implementation of:

- new intellectual electronic devices and hard/software (soft sensors) for early detection of different types of threats;
- soft/hardware for probabilistic risk evaluation of breakdown state;
- feeding networks with flexible reconfiguration opportunities;
- multi agent based software of wide destination;
- new techniques of threat visualization to provide rapid reaction of human operator on threat level.

Design of electric power grid with active adaptive system and developed immune functions demands large investment but final advantage for consumers, energy companies, state, and society will result in multiple investment revenue including also increasing of reliability, safety, vitality, electric energy quality, and slackening the environmental pressure.

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Part III
Applications: Information Systems

Chapter 10
Transformations of Standardized MLP Models and Linguistic Data in the Computerized Decision Support System

Jarosław Becker, Jarosław Jankowski and Jarosław Wątróbski

Abstract The content of the study presented two complementary issues, transformation of the data form and transformation of structures of MLP decision models, which constitute the basis of the construction of the computerized decision support system. (version DSS 2.0—authors Becker, Architecture of information system for generating multi-criteria decision-making solution (part. 1.), The concept of building a MLP model based on a decision tasks, in series of IBS PAN, 2008; Becker, Integration of knowledge sources in decision support system (methodological and design basics). The scientific monograph, 2008; Budziński, Architecture of information system for generating multi-criteria decision-making solution (part. 2.), Organization of information structures and the functioning of the system, 2015). The system supports the multi-faceted (multi-methodical) and multi-criteria decision analysis, which includes: the selection (MLP optimization), ranking (AHP) and grouping (Electre Tri) of decision variants (called the objects of analysis). The first part of the study focused on the transformation of the information structure of partial mathematical models, reflecting the objects of analysis, to the form of records of the database and on their connection into a more complex structure, so-called multi-model, in order to subject the method of multi-criteria optimization to calculations. There was also mentioned the possibility of transformation of these complex structures from data records to a simple, tabular form transferred on the inputs of method. In the second part discussed the issue of the

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bi-directional data transformation (from the linguistic form into numerical, and vice versa). Data transformations are based on the use of fuzzy set logic and specially developed for thus purpose scoring and linguistic scales of the ordinal nature.

10.1 Introduction

The process of building computerized decision support systems should take into account the idea of the method (knowledge) popularization in the most important moment of the civilization process—the decisive game, which is connected with the selection of the best available solutions. This involves the sharing of complicated methods in a simple and useful form to decision-makers. From the point of view of engineering of information systems, this task is not easy, because decision processes usually concern the future and are not fully predictable. One should also take into account the frequent changes of event structures and things in management, which cause that we are dealing with unstructured situations, unique, and therefore difficult to program.

An important attribute of the decision-making process, which affects its complexity, is the dispersion of data sources and evaluations of decision variants. This dispersion may be compatible with the structure of hierarchy of the decision problem. Units responsible for the definition of criteria (and/or sub-criteria) provide data and determine preferences. This feature may also be identified with the topics of attributes and occur in a situation, when their values come from many specialized external sources. For example: the expert knowledge, statistical data or economic and technical parameters. The mentioned phenomenon implies the occurrence of different types and data scales, inconsistent descriptions and their inaccuracies. Apart from this, in business practice very common are situations, in which information expressed orally are necessary to make a decision. This type of expression form is cognitive in nature and closer to the human perception of reality. By nature, we perceive and describe objects and phenomena in the imprecise and blurred way. Only the need to make precise calculations, for example, of the engineering nature, forces the use of right tools and measurement methods and expressing some properties using precise numerical values.

Literature contains a variety of procedures and methods of multiple criteria decision making (MCDM) (Bouyssou and Roy 1993; Greco et al. 2001, 2002; Słowiński 2007). According to Greco et al. (2001) they can be divided into methods based on the functional model (American school) and relational model (European school). The vast majority of these methods depends on the input data expressed numerically. The remaining group, constituting the complement in this context, are the research methods created on the basis of statistics, artificial intelligence and psychology, in which the numerical parameters characterising the research subject are not specified (phenomenon, object). On inputs of these methods are introduced data in the form of linguistic. They are called the non-parametric methods, often there are no assumptions in them as to the completeness or precision of data. This group, for example, includes the symbolic methods of data classification (Gatnar 1998) and most of the methods based on the theory of rough sets, applied to the analysis of data consistency, their grouping and induction of decision-making rules (Pawlak 1982). They apply in qualitative research, they are used to interpret emotions, deeply hidden motives of actions and choices. They allow the identification of specific behaviours, show the patterns of thinking, conduct, habits and rules of action.

Integration of many complementary methods of decision-making in the information system requires, first of all, the development of such a model of data organisation which will be more adjusted to the theory of decision-making. This issue can be formulated in a form of a question. What notation in the organisation of factual resources should be used so that the decision-making situations can be fully described? Secondly, the integration requires arming of the decision-making analysis process on its each step with computer algorithms of transformation of various data forms in such a way that in the context of the problem there is used one common set of input data (numeric, linguistic or mixed). In order to increase the information potential of the obtained results and a better representation of reality one should connect the information, which is the effect of measurement with the expert interpretation.

10.2 The General Architecture of the Computerized Decision Support System (Dss 2.0)

The core of the architecture of the computerized decision support system (DSS 2.0) is the platform designed for the formulation of decision tasks based on the notation of the MLP method. Its main advantages are: the possibility to recognise in the information system the complex decision situations, evolution and creation of the model base, and in a wide range the use of linguistic data in mapping of the reality. In the system there should be described the decision situation in the form of the MLP model form. On its basis there are collected data about objects (e.g. offers, conclusions and other decision variants). Then, there are constructed the regulatory models and the desired calculations are made, which are the part of the scope of the multi-methodical decision analysis.

The functional scope of supporting the decisions was determined as the solving of decisive tasks connected with multi-criteria selection, grouping (sorting) and organising (ranking) of any decision variants, understood as objects of the analysis representing the given category of events or things. These objects must have a uniform information structure. The additional functionality of the system is the analysis and the evaluation *ex post* of the obtained results of the decision-making process. It should be noted that the studies carried out in the system can have the formal nature (official), taking on the form of the legally sanctioned procedure (e.g.

public tender, where the offers are evaluated) or less official, cognitive, where the decision maker is repeatedly supported through simulations (e.g. evaluation of employees, products, services, variants of planning, etc.). The fact that the theory of decisions creates methodological foundations for the analysis and generating best solutions is not about the utility of the information system in practice. In fact, the needs of management translate into the essential factors that should be taken into account in the design of system supporting decision-making, namely:

- multi-stage nature of the decision-making process,
- multi-criteria nature, in which the structure of criteria is simple (criteria vector) or complex (hierarchical or network dependencies),
- number of decision-makers and experts,
- scale of the decision problem (few or mass problems),
- flexibility of decision variants (customising the parameter values),
- linguistics of data (statements of experts or respondents).

The complexity of the description of the decisive situation causes that it is difficult to emerge the method that would be universal, to which we could attribute the possibility to obtain the best solution of many different decision-making problems.

The discussed system of supporting decision-making is a hybrid solution, which using the engineering techniques of the computer processing of data connects and shares in a simple useful form algorithms of various supplementary and implementing the paradigm of the methods supporting the decisions. The research procedure included in it is performed in three stages, it includes: (1) organization of data, (2) calculations of the decision analysis and (3) presentation of results (Fig. 10.1). The intention of the proposed scheme of thought comes from the understanding of the support of decisions as a process, in which based on the fact base (data) we analyse and conclude, and then we make decisions. This takes into account the knowledge of users and most of all of experts, who analyse facts, express their opinions using the ordinal scale of linguistic assessments and use the mapping methods proposed in the system.

Organizing data (Fig. 10.1, stage 1) as the base of integration of methods there was accepted the coherent and flexible information structure of the system, which was subordinated to the construction of MLP models (Multi-criteria Linear Programming). It allows you to define the template for the decision-making task (standard mathematical model, Fig. 10.1). This construction takes into account the requirements of the decision maker, which relate to the potentially analysed set of objects and they are expressed through: decision variables, limiting conditions, one- or two-level structure of criteria of assessment and the corresponding preferences (Becker 2008). According to the template to the system there are introduced data of objects (decision variants: W_1, W_2, …, W_n). Technical and economic parameters of each variant can be expressed in the form of numerical values and linguistic assessments (fuzzy values) from the ordinal scale defined by experts or respondents. For the optimization calculations all linguistic forms of data must get transformed into numerical values. The basis for the conversion of verbal expressions into

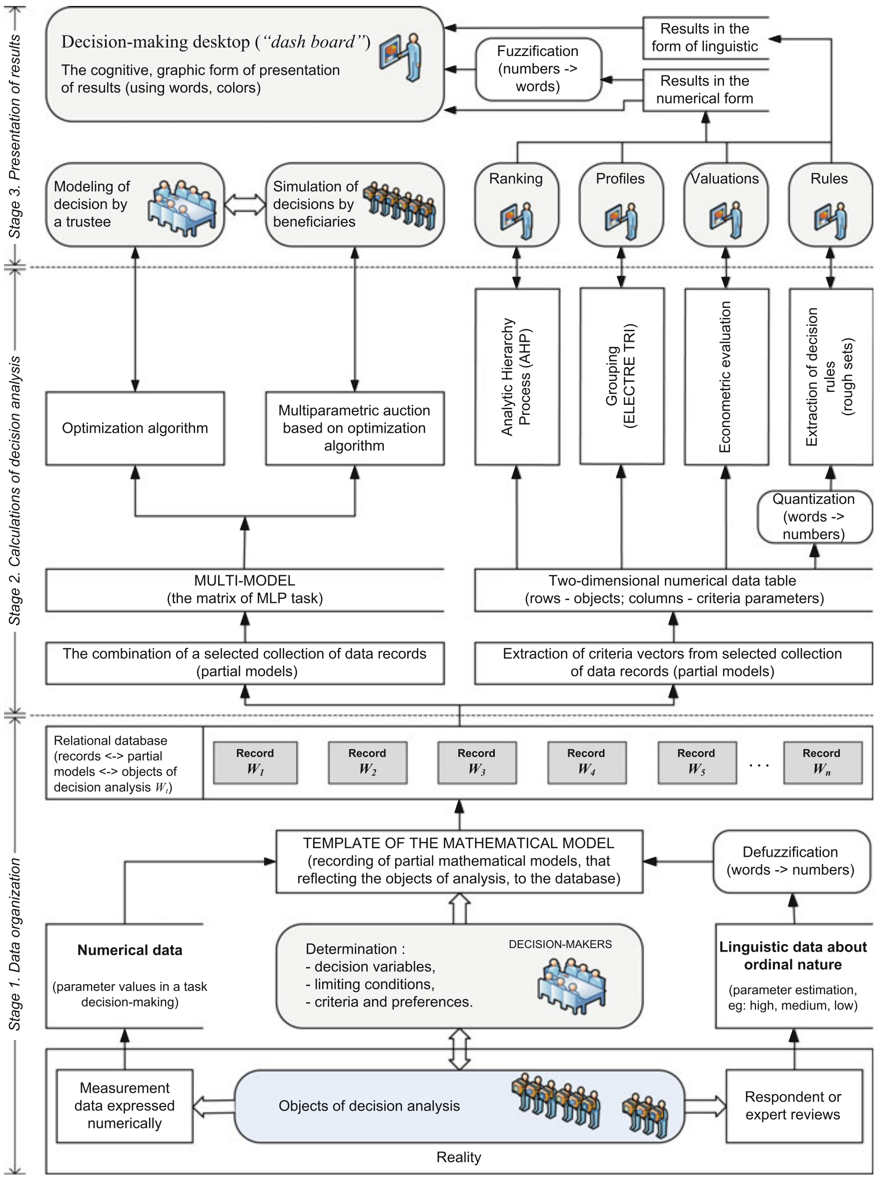


Fig. 10.1 General architecture of the computerized decision support system—DSS 2.0 (*Source* Becker and Budziński 2014)

numerical (defuzzification) and vice versa (fuzzification) is the methodology of the construction of linguistic quantifiers based on the theory of fuzzy sets. After the introduction and confirmation of data, each variant becomes the record (writing) in the relational database and at the same time is the autonomous, partial mathematical model. The object takes the form of the formalised task of the linear programming, which after obtaining the positive optimization result (where it is not the contrary system) is saved in the database with the admission status to the stage of decision analysis calculations.

The second stage (Fig. 10.1) includes the issues of combining data records—partial mathematical models identical to objects of the decision-making analysis—to the form of a multi-model (MLP task matrix) for the needs of the multi-criteria optimization and transformation to the simple, tabular structure of data required on other inputs of the multi-methodical analysis. Integration of methods in the system of supporting decisions consists of the use of their functionality on a common set of data (objects) within a coherent, logical and comprehensive information-decisive process consisting of:

- *optimization of decisions*—considered from the point of view of interests of the trustee's resources and from the perspective of beneficiaries competing for the resources,
- *multi-criteria analysis,* in which there were used the approaches: connected with the achievements of the American school [AHP method (Saaty 1980)], European [ELECTRE TRI (Roy 1991)] and Polish school [Rough Set Theory—(Pawlak 1982)],
- *identification* in terms of quantitative methods of the econometric analysis.

The third stage (Fig. 10.1) includes the presentation of detailed results for each method separately and together, in the form of the decision-making desktop ("*dash board*"), within which the applied methods (points B and C) function on the basis of a consultation of experts diagnosing the state of the tested objects. The desktop integrates the results of methods supporting decisions in the utility aspect. It is an interactive system enabling the multi-dimensional (multi-methodical) diagnostics of the selected object W_t (or a new one W_{n+1}) against the results of the whole set (W_1, W_2, …, W_n). It has the cognitive, graphic form of presentation of results of the applied methods. It is a kind of machine graphics, which consolidates the graphic visualization with cognitive processes taking place in the man's mind at the moment of making the decision. The structure of the desktop is based on the premise that knowledge about the object (its rating) expressed by shape and colour is absorbed faster than information in the form of numbers and text.

10.3 Standardized Information Structures Based on the Notation of the MLP Method

In the studies over the system supporting the decision-making a great attention was paid to the description (formalization) of information conditions of the considered decision situation, on which one can invest many methods of mapping reality and mainly describe almost all components of the decision-making process. The original solution is the construction of the platform of data organization based on the information notation of the MLP method. Defining decision problems (tasks) in the system is inseparable with the determination of the structure of the mathematical model template in the specially developed for this purpose module of the MLP model generator. Its service was divided into thematic groups (blocks) concerning the variables, balances and equations of partial goals and changes of labels (names, units of measurement and character relationships). Adding or removing any element is seen in all blocks. In detail in these groups there were distinguished (Fig. 10.2):

A. A.DECISION BLOCK—where we can add or remove decision variables and determine their type: floating point, integer and binary,
B. B.TASK BLOCK (individual constraints)—in which one can add or remove constraints and balances constituting the internal information structure of all objects W_t,
C. C.SHARED LIMITATIONS BLOCK—the area, in which one can add or remove constraints and balances conditioning the selection of objects W_t considered together in the multi-model matrix,
D. D.CRITERIA BLOCK (partial goals)—the area of adding or removal of equations of partial goals. In each record there are determined the *min/max* relations (Becker 2008).

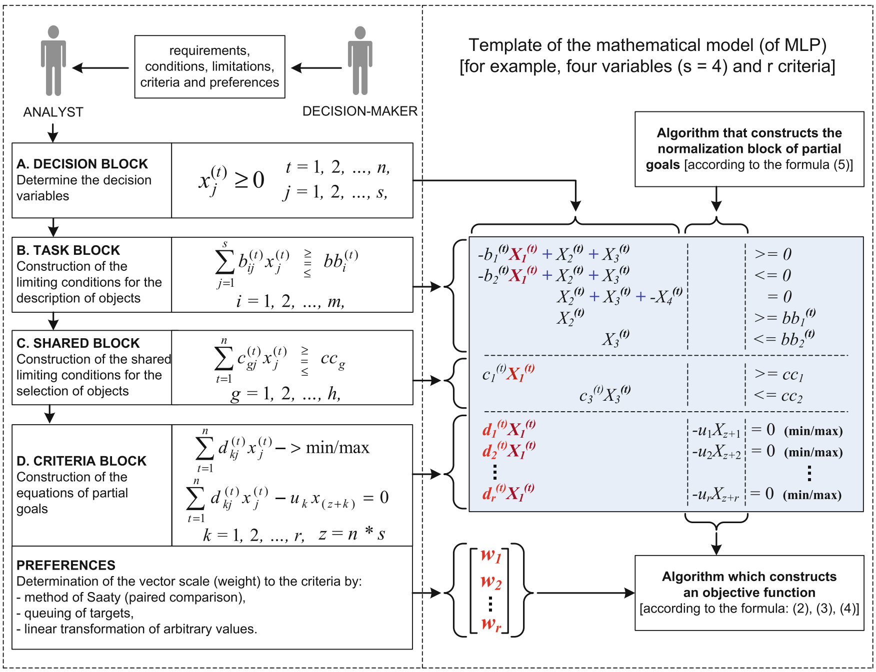


Fig. 10.2 The idea of constructing a pattern (template) of the mathematical model (*Source* Becker 2015)

Parameters $b_{ij}^{(t)}$, $bb_i^{(t)}$ $c_{gj}^{(t)}$, $d_{kj}^{(t)}$ and cc_g, presented in Fig. 10.2, can take, in the template of the model, the form of constant values or symbols (programming variables), which values are introduced by the proper data forms (index t means that separately for each object W_t).

In the system there was used the approach proposed by Budziński (1988), not requiring the determination a priori of the values of goals for implementation, based on the axiom of a "goal game", difference of non-negative quality indicators $\left(q_k = x_{(z+k)}\right)$ beneficial features and undesirable features $\left(q_k = -x_{(z+k)}\right)$ for $k = 1,2, \ldots, r$ and $z = n \times s$. In this method the partial goals (from block D, Fig. 10.2)

$$\forall W_t \exists x_j^{(t)} \left\{ f_k\left(\mathbf{x}_j\right) = \sum_{t=1}^{n} d_{kj}^{(t)} x_j^{(t)} \rightarrow (\min \ \vee \max) \right\}, \tag{10.1}$$

where $\mathbf{x}_j = \{x_j^{(1)}, x_j^{(2)}, \ldots, x_j^{(n)}\}$, are recorded in the form of balances

$$\forall W_t \exists x_j^{(t)} \left\{ \left(\sum_{t=1}^{n} d_{kj}^{(t)} x_j^{(t)} \right) - u_k x_{(z+k)} = 0 \right\}, \tag{10.2}$$

then their synthesis is performed to the form of the goal function

$$F(q_1, \ldots, q_r) = \sum_{k=1}^{r} f(q_k) = \sum_{k=1}^{r} w_k q_k \rightarrow \max, \tag{10.3}$$

where

$$q_k = \begin{cases} x_{(z+k)} & \text{for} \quad f_k\left(\mathbf{x}_j\right) \rightarrow \max \\ -x_{(z+k)} & \text{for} \quad f_k\left(\mathbf{x}_j\right) \rightarrow \min \end{cases}. \tag{10.4}$$

While $w_1, w_2, \ldots, w_r$ are the ranks of validity, preferences of reaching different goals. While u_k are the technical parameters of normalization bringing k partial goals to their equal rank in optimization calculations:

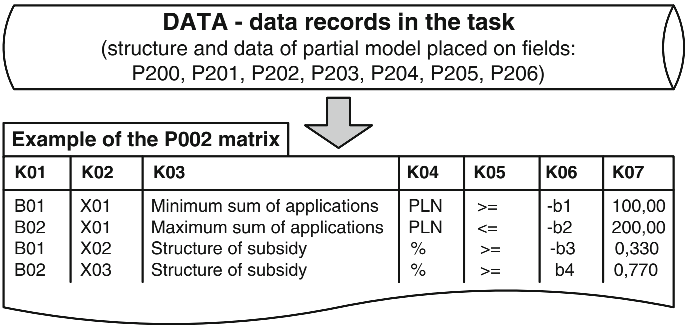
$$u_k = \frac{100 l_k}{\sum_{t=1}^{n} \left| d_{kj}^{(t)} \right|}, \tag{10.5}$$

where: $\left| d_{kj}^{(t)} \right|$ are the absolute values of technical and economic parameters. They stand in equations of partial goals with j decisive variables, and l_k is the accepted for calculations number of non-zero elements in the k row of partial goals (Budziński 2001).

The explanation of the idea of constructing templates in the *generator of MLP models* is difficult without approximation of its information structures. *The task* in the system supporting decision-making is created by three sets: *dictionary*—description of the logical sentence structure), *data* (data records representing objects in the task) and *validation*—allowed conditions to process data. There was accepted the principle that every object is the partial model and at the same time the data record (with variable lengths from the point of view of various decision tasks), and the whole task formally fulfils the condition of the relational database with its all attributes (*object = data record = partial mathematical model*). Records of the set of *dictionary, data and archives of templates* have identical structures of fields, what greatly simplifies the communication between them. Recalling the task one creates through the inheriting of *template from the archives its dictionary.* All starting model structures MLP come from this place. From the introduced records of the set *data* (that is partial models) we can construct a comprehensive model (multi-model), solve it and obtain the decisive interpretation, in the form of which there can function any objects—variants of the decision-making analysis—e.g.: offers, requests, scenarios and others. In the information system this is performed by an extensive procedure (Fig. 10.4).

The designed template is subject to feedback verification (*feasibility test*). The algorithm of the system checks its completeness and after substituting testing data it examines its solutions. Then it is transferred in the form of separate blocks to notepad fields (MEMO) of the *archives* set and *dictionary*. *Archives* constitutes the assurance for repositories describing various decision tasks considered in the system. In the design phase of a new template you can inherit from the previously proven solutions and develop (adjust) it to own needs. While the set of a *dictionary* (repository) is identified with the specific decision task. It constitutes the main set of meta data of the task, on which operates the information system after its opening.

Based on the information structure of the *template* algorithms of the system generate forms to introduce data about objects and block structures of partial models with the obtained data, so-called *matrices* (according to Fig. 10.2, block: A, B, C, D). These structures are registered in the form of records in the table *data* in the fields P200–P206. In Fig. 10.3 there is illustrated the example of a matrix for



K01	K02	K03	K04	K05	K06	K07
B01	X01	Minimum sum of applications	PLN	>=	-b1	100,00
B02	X01	Maximum sum of applications	PLN	<=	-b2	200,00
B01	X02	Structure of subsidy	%	>=	-b3	0,330
B02	X03	Structure of subsidy	%	>=	b4	0,770

Fig. 10.3 An example of the information structure of a matrix for parameters of block B (*Source* Own study)

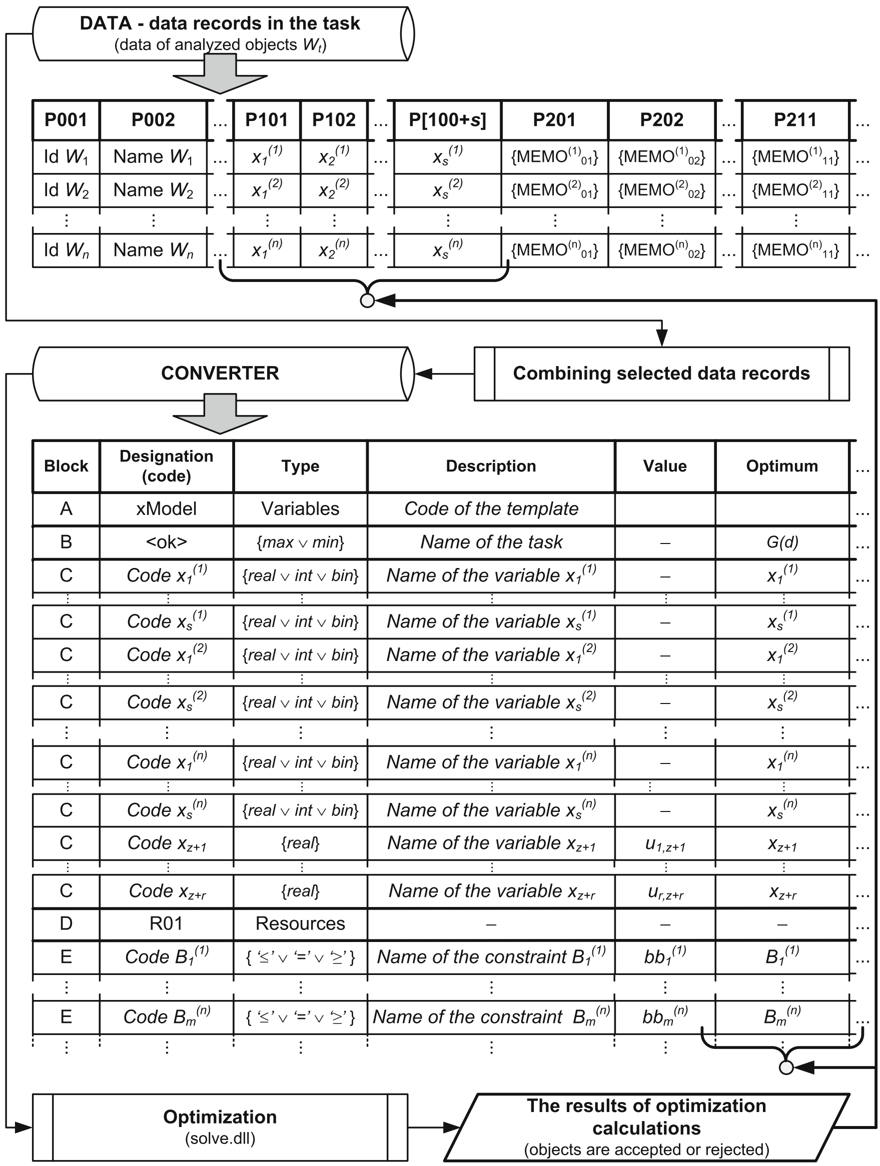


Fig. 10.4 The procedure of transformation of data records to the matrices of a multi-model (so-called *converter*) in the system supporting decision-making (*Source* Becker 2015)

parameters of block 'B' (record in the field 'P202'). It is worth mentioning that while adding objects to the system base in records of the table *data* there are only fixed values for parameters included in the template in the form of symbols—programming variables (constant values of parameters are recorded with the template in the set of a *dictionary*).

The next step after the introduction of information about the objects and the generation of matrices, is the use of records of data for optimization calculations. In theory, the transformation of structures of the generator is reduced to the connection of the selected records and construction of a multi-model from them. Then the performance of optimization calculations on it. However, in practice, from the point of view of the algorithmization, using the structures of connected partial models is very complicated. The multi-model is a multiple of variables of the partial model multiplied by the number of objects. A task with hundreds of objects may create a matrix of extremely large dimensions, measured in several thousand variables. In case of the mass data processing (the large number of analysed objects in the task) the algorithmic complexity of calculations may show up in the form of performance problems. Development of the effective solution for processing flexible data structures (models) has become a necessity in this situation.

In the engineering approach there was proposed an original method based on a special structure of meta data, called the *converter,* which is used to connect homogenous in the given task partial mathematical models. Its algorithms build the matrix of the multi-model for the indicated group of objects, regardless of the defined structure of a *template* in the given task, always based on the query of records from the table of *data* and the mentioned file of the *converter*. A thorough explanation is required by the structure of a set of the *converter*, which on one side is the basis for sending the matrix of a multi-model to the module of *solver* (optimising program). While on the other, it accepts the results of calculations and transports them to the proper records of the *data* table.

Converter is identical to the multi-model. It is a table of the relational database, which in its structure contains the full description of the combined records from the *data* table, that is partial models (Fig. 10.4). In the relation between the sets there is a specified system string. Equivalents of the fields of optimization results are found in the structures of records of both tables. The record fields in the file *data,* marked *P101, P102, …, P199,* are the places, in which there is performed the record of result data transported from the *converter*, from appropriate rows and fields in the column of *optimum*.

Marking the attributes in the *converter* (column layout) have the general nature, are used to represent various components of the block structure of the *template*. These are attributes common for each element of the model: *type, code name, type, description, parameter value, optimum* (and not included in Fig. 10.4: *evaluation, measurement units*). The column *optimum* is used for storing results from the last optimization. While the *evaluation* depending on the type of the element specified in the row represents: estimation value *ex poste* of partial goal functions, dual prices or unused resources shown by the optimising algorithm.

The main markings of the converter in the row system result from the category of elements found in the multi-model, there are: (1) decision variables *'x'*, (2) limiting conditions and balances '*B*' and the values of limitations *'bb'*, (3) parameters: '*b'*, '*c'*, *'d'* and goal function (10.3). In Fig. 10.4 there is shown a fragment of the row structure of a *converter,* keeping the compatibility of labelling of particular elements with previously accepted formulas in Fig. 10.2 and: (10.1)–(10.5).

As a result of optimization of a multi-model there is obtained the division of the considered set of objects into the *accepted and rejected* (Fig. 10.4). In the first winning group there are variants for which the value of utility functions reaches maximum and at the same time satisfies all limiting conditions determined in the task. The procedure of searching the best set of objects (optimal from the point of view of values of criteria and preferences included in the goal function) begins from the determination by the user of a set of data records for the study. Then the system starts the process of *combining data records* (transposition of result fields, decomposition of matrices) in the set of a *converter*. Thus obtained structure of record of the contents of a *multi-model* allows in a simple and quick way to prepare data in the LPS format for simplex calculations. In return, it accepts the results of optimising results from the *solver* module. Then, the system transfers them to data records, from which this structure was formed.

10.4 Profiles of Ordinal Scales Based on Linguistic Quantifiers

In the computer decision support system there are distinguished three areas of the use of linguistic quantifiers. The first one involves the transformation of linguistic data (e.g. assessment of experts) to the numerical form (defuzzification) required in the MLP mathematical model. It may relate to all values or only some parameters (defined in the template of the decision task, Fig. 10.1), which characterise the W_t objects considered in the decision task. In the second area there is the quantification of data (also referred to as discretisation, Fig. 10.1), which is carried out for the purpose of induction of decision rules. The basic quantification stage, connected with the division of the scope of attribute values into separate sections, can be implemented in an automated manner using the selected scoring and linguistic scale or arbitrarily determined by the user. The third area of the use of linguistic quantifiers is the decision display (Fig. 10.1). Data transformations are used in order to unify, consolidate and cognitively visualise the analysis results, obtained with different methods.

The ideal, to which we aspire, are the lossless transformations of numerical data to the linguistic forms, and vice versa. Tools, which relatively well allow for this type of conversions, are provided by the fuzzy logic. It is based on the term of *fuzzy sets*, meaning those, which do not have strictly defined boundaries. In 1965, Zadeh provided an idea and the first concept of a theory, enabling the fuzzy description of real systems. The fuzzy set is an object including the elements of some area of considerations, wherein each of these elements can fully belong to the fuzzy set, do not belong to it at all or belong to it to some degree (Łachwa 2001). The fuzzy set

A in the space (area of considerations) $X = \{x\}$, what can be written as $A \subset X$, is a set of pairs

$$A = \{(f_A(x), x)\},\ \forall x \in X, \tag{10.6}$$

where f_A: $X \rightarrow [0, 1]$ is the membership function, which assigns each element of the X space with the grade of membership to the given fuzzy set: from membership $f_A(x) = 0$ through partial membership $0 < f_A(x) < 1$ to complete membership $f_A(x) = 1$ (Kacprzyk 1986).

In fuzzy sets, the transition from membership to non-membership is gradual, and not abrupt, as in the conventional set. The concept of a fuzzy set is used for the formal recognition and quantitative expression of blurry, imprecise, ambiguous terms. They are commonly used for the qualitative assessment of physical quantities, conditions of objects and systems, and their comparison (Piegat 1999).

The concept of the scoring and linguistic scale profile ($scale^{(\tau)}$) in the computerised decision support system means the user-determined configuration of the adjustable elements of the ordinal scale, i.e.:

- *number of degrees* $\tau = 2, 3, \ldots, 11$—the system distinguishes 9 variants of the span of $scale^{(\tau)}$ (they were given Latin names: 'duo', 'tria', 'quatuor', 'quinque', etc., in which the next degrees were given the absolute, non-negative ordinance values $\alpha = 0, 1, 2, \ldots, \tau - 1$, always starting from zero,
- *linguistic values* (names of degrees) $a^{(\alpha)}$—for example, for $scale^{(\tau=3)}$ these may include: $a^{(\alpha=0)}$ = *'low'*, $a^{(\alpha=1)}$ = *'average'*, $a^{(\alpha=2)}$ = *'high'*,
- *type of characteristics of the linguistic quantifier*—this is a non-linear dependency ($y = ax^2 + bx$) or linear ($y = x$) applied to generate, for any span of $scale^{(\tau)}$, triangular or pentagonal membership functions for individual linguistic values $a^{(\alpha)}$ (Becker 2014).

Linguistic quantifier consists of the membership functions, which number corresponds to the number of degrees τ on the given scale. These functions are created based on linear or non-linear function transformations. For each scale there can be determined many different linguistic quantifiers. In the computer system there are prepared five basic variants of the linguistic quantifier with: (a) proportional, (b1) strongly growing, (b2) moderately growing, (c1) strongly decreasing and (c2) moderately decreasing distances between linguistic values $a^{(\alpha)}$. Disproportionate versions (b1, b2, c1, c2) can consist of triangles or pentagons, what in total gives nine proposals. For advanced users there is predicted the possibility of adjusting the shape of the characteristics of the linguistic quantifier according to the relationship

$$\mathrm{f}_\eta(\mathrm{x}) = \mathrm{y} = (\eta - 1)\mathrm{x}^2 + (2 - \eta)\mathrm{x}, \tag{10.7}$$

in which the η parameter adopts the values from the range of $\langle 0; 2 \rangle$, and $x = \alpha/(\tau - 1)$ If $\eta = 1$, the characteristics (10.7) is linear, distanced obtained on its basis between $a^{(\alpha)}$ are identical, and membership functions for each $a^{(\alpha)}$ have the form of equilateral triangles (except for extreme values $a^{(0)}$ and $a^{(\tau-1)}$, for which the half-figures are always taken into account). In other cases (when $\eta \neq 1$) the inscription

(10.7) determines non-linear relationships, and membership functions obtain the selected shape, of a triangle or pentagon. When $\eta \in \langle 0;\ 1)$, the system generates quantifiers of decreasing distances between successive $a^{(\alpha)}(\alpha = 0,\ 1,\ 2,\ \ldots,\ \tau - 1)$, while for $\eta \in \langle 0;\ 2)$ proportions of these distances move in the opposite direction.

In order to simplify the notation of the function determining the degree of variable membership $x' \in \langle 0; 1\rangle$ to linguistic values $a^{(\alpha)}$, determined for particular degrees $\alpha = 0, 1, 2, \ldots, \tau - 1$, the functional relationship has been transformed (10.7) to the following form

$$f_\eta(\alpha) = \frac{(\eta - 1)\alpha^2}{(\tau - 1)^2} + \frac{(2 - \eta)\alpha}{\tau - 1}. \tag{10.8}$$

Triangular membership functions are constructed for any span of *scale* $^{(\tau)}$—assuming that the variable $x' \in \langle 0; 1\rangle$ and represents the numerical value subject to conversion into the linguistic form—can be expressed in the form of the following entries (Fig. 10.5, an example for the five-point scale):

- for the first linguistic value $a^{(\alpha)}$ ($\alpha = 0$)

$$f_{a^{(0)}}(x') = \begin{cases} \dfrac{f_\eta(1) - x'}{f_\eta(1)} & for\, f_\eta(1) \geq x' \geq 0 \\ 0 & for\ other\ x' \end{cases}, \tag{10.9}$$

- when $\tau > 2$, then for every $a^{(\alpha)}$ satisfying the condition $0 < \alpha < \tau - 1$ particular membership functions can be generalised to the form of

$$f_{a^{(\alpha)}}(x') = \begin{cases} \dfrac{x' - f_\eta(\alpha - 1)}{f_\eta(\alpha) - f_\eta(\alpha - 1)} & for\, f_\eta(\alpha - 1) \leq x' < f_\eta(\alpha) \\ \dfrac{f_\eta(\alpha + 1) - x'}{f_\eta(\alpha + 1) - f_\eta(\alpha)} & for\, f_\eta(\alpha) \leq x' \leq f_\eta(\alpha + 1) \\ 0 & for\ other\ x' \end{cases}, \tag{10.10}$$

- for the last linguistic value $a^{(\alpha)}$ ($\alpha = \tau - 1$)

$$f_{a^{(\tau-1)}}(x') = \begin{cases} \dfrac{x' - f_\eta(\tau - 2)}{1 - f_\eta(\tau - 2)} & for\, f_\eta(\tau - 2) \leq x' \leq 1 \\ 0 & for\ other x' \end{cases}. \tag{10.11}$$

In a similar manner are constructed the linguistic quantifiers equipped with the membership functions shaped as a pentagon. Pentagonal functions in relation to triangular ones are more approximate to the shape of the non-linear characteristics (10.7). This is due to the fact that apart from the values $x'_\alpha = f_\eta(\alpha)$ calculated for each $\alpha = 0, 1, 2, \ldots, \tau - 1$, for which $f_{a^{(\alpha)}}\left(x'_\alpha\right) = 1$ and reaches the extreme, with

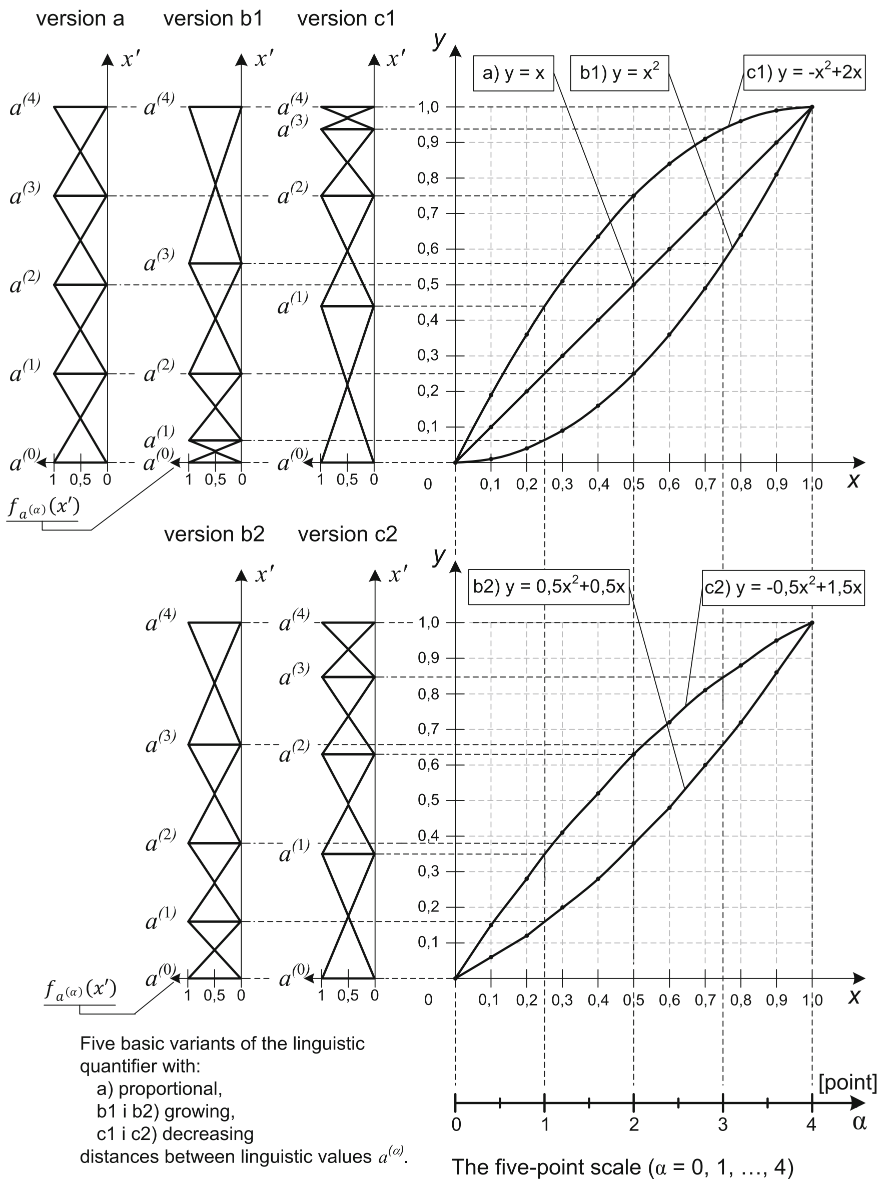


Fig. 10.5 Constructing linguistic quantifiers based on triangular membership functions (example for the five-point scale; *Source* Becker 2015)

the same rule there were also determined the intersecting points $x'_{\alpha+} = f_\eta(\alpha + 0,5)$ i $x'_{\alpha-} = f_\eta(\alpha - 0,5)$ of the adjacent membership functions, where $f_{a^{(\alpha)}}\left(x'_{\alpha-}\right) = 0,5$ i $f_{a^{(\alpha)}}\left(x'_{\alpha-}\right) = 0,5$ (Becker 2015).

According to Łachwa (2001) the issue of assigning the parameters describing the specific objects with the right membership degrees to linguistic expressions of the ordinal nature, it should be stated that doing this in a good way is difficult. This procedure is usually of the subjective nature and depends on the situational context. Clarifying this issue, membership degrees which are individual and depend on the circumstances indicate a kind of trend, which reflects on the set of studied objects from the given area of considerations some arrangement, created by association with the set of specific features. To determine the membership degrees there is used, for example, the questionnaire method common in statistics. The membership value is calculated as the relation of the number of affirmative answers to the number of all answers provided by responders. Another, popular method is determination of membership degrees by the expert. However, the expert often determines only the general shape of the membership function, and the accurate parameter values are selected experimentally.

In the decision support system there was proposed a tool for creating individual profiles of scoring and linguistic scales, which act as ready-to-use models of the linguistic quantifiers with the selected membership functions. These may include the equilateral triangles (type a—proportional scales, Fig. 10.6), irregular triangles or pentagons (variants of the b and c type) of varying proportions on the ordinal scale, what is understood as different distances between degrees and focal points (the point of intersection of two functions), additionally they can have the growing or decreasing trend. A multitude of parameters configuring the profile of scoring and linguistic scale allows to define in the given decision task (z) the individual, required for each p^* parameter in the template of the mathematical model, linguistic quantifier.

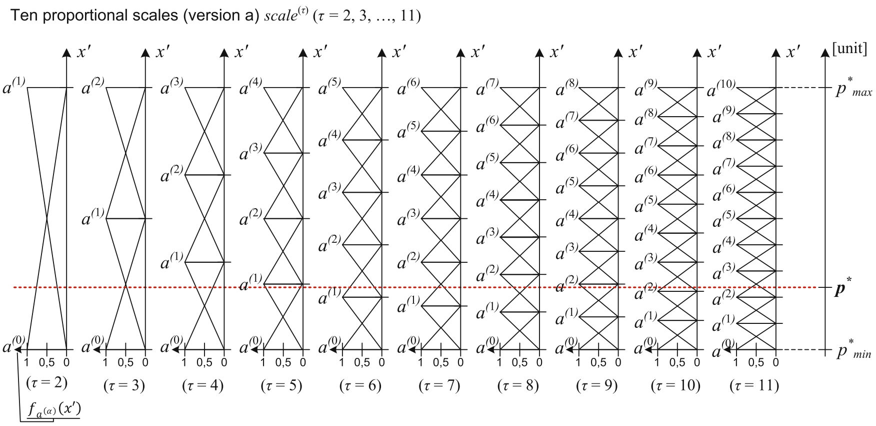


Fig. 10.6 The use of the linguistic quantifiers in the DSS system (projection of values of the p^* parameter on the axis of the proportional scales; *Source* Becker 2015)

The choice of the quantifier characteristics can be the result of the expert's suggestion, discussion of a group of several people (e.g. decision-makers and experts) or the survey, which van be performed in the phase of obtaining data (e.g. in the form of additional questions in the offer proposals submitted by beneficiaries representing the objects).

After determining the character of the membership function for the quantifier and for the given scale profile, there should be determined the number of its degrees (τ). In the system there are two kinds of allocation of this size to the given p^* parameter. The group variant, in which τ is determined for all experts assessing p^* and the individual one, where τ is selected by each expert giving opinion on p^* according to his preferred (intuitive, best perceived) structure of the assessment value system. In the computer system there were made available 9 scale models ($scale^{\tau}$), which have from $\tau = 2$ to $\tau = 11°$ (Fig. 10.6). It should be noted that the greater number of degrees on the scale may influence the extension of the process of parameter assessment, but instead there is obtained the higher precision of transformation of linguistic notes onto the numerical values, and in a large group of assessing people this may also result in their greater diversity.

The use of linguistic quantifiers in the decision support system is related to the bi-directional conversion of numerical and linguistic data. Defuzzification means the conversion of signals from the qualitative field to the quantitative one. In the system it relates to the parameter assessment (p^*) expressed with imprecise measures $a^{(\alpha)}$ within the determined profile of the scoring and linguistic scale. For the given $a^{(\alpha)}$, according to (10.8), the value $x'_{\alpha} = f_{\eta}(\alpha)$, is calculated, for which $f_{a^{(\alpha)}}\left(x'_{\alpha}\right) = 1$. Then, the value $x'_{\alpha} \in \langle 0; 1\rangle$ is proportionally converted into the acceptable parameter scope $p^* \in \langle p^*_{min}; p^*_{max}\rangle$ (Fig. 10.6). The conversion process taking place in the opposite direction, where quantitative data (precise) are converted to qualitative is called fuzzification or dissolving. The numerical value of the parameter $p^* \in \langle p^*_{min}; p^*_{max}\rangle$ is transformed proportionally to $x' \in \langle 0; 1\rangle$, then for each scale process (with the selected model $scale^{\tau}$ and quantifier characteristics—type *a, b* or *c*) there are calculated the values of membership functions for every $a^{(\alpha)}(\alpha = 0, 1, 2, \ldots, \tau - 1)$ according to the entries (10.9, 10.10 and 10.11) for triangular functions (or similarly for the pentagon-shaped functions—more in the paper (Becker 2015)). The highest value $f_{a^{(\alpha)}}(x')$ from the calculated ones determines the linguistic category $a^{(\alpha)}$. It should be noted that the applied data transformation based on the theory of fuzzy sets—in which based on the linear characteristics and different non-linear ones the scopes of membership functions are determined (equal, increasing or decreasing)—is adequate to the process of determining the quantization intervals (discretisation) of the attribute values in the induction studies of decision rules. The generated data scopes can be clarified by the system user.

10.5 Conclusion

The elaboration presented the issues of the linguistic and numerical transformation of data used within the uses of the computer decision support system (DSS 2.0). They most often concern the problems solved with experts, who express their opinions using imprecise terms, for example, assessment: of employees or recruits, grant or loan applications, tenders including the specialised services or devices, etc. The place of experts may be occupied by respondents, e.g., the representative group of students assessing individual departments, directions of teaching.

Linguistic quantifiers, included in the form of fuzzy and ordinal scale profiles, on one hand, are used in order to bring data to the specific form and provide them to the input of the appropriate decision support method. On the other hand, numerical method results are converted to the linguistic form and integrated with others on the decision desktop. The aim of this operation is the synthesis of results obtained with different methods based on the cognitive presentation and interpretation (using words and spectrum of colours).

What is interesting is the use of scale profiles of a different number of degrees describing the conditional attributes and the decision attribute to the search of such quantization, due to which there will be generated the most valuable rules. Generalising the description of attributes (reducing the number of categories), we admittedly influence the structure and consistency of the data set, but we are moving towards the deep knowledge, expecting the rules of a more general content and greater coverage. This rule can be reversed and the shallower knowledge may be sought, that is more precisely formulated rules in the description of reality.

The original information platform, developed within the construction of the system supporting decision-making (modelled on the MLP modelling) provides a comprehensive description of decision-making problems. The prototype technology of the transformation of database records to matrices of partial models allows the automated connection of any collection to the form of a multi-model of the MLP task. The adopted formalization of data also allows the automatic formulation of structures deviating from MLP models and recalling solutions of other methods of interpretation. As a result, one can attempt on this base to connect methods as new mapping hybrids.

The wider context for the presented issues of the transformation of the data forms and the transformation of structures of the MLP decision models is the integration of the knowledge sources—measurement data, expert opinions, unified structures of mathematical models and collections of selected methods—in the information system, in an important moment for the information and decision-making process, which is the decision-making game. The goal of each game is the selection of the solutions from the best available ones.

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Chapter 11
New Frontiers and Possibility in the Construction of Learning Systems with Using of the Educational Program Complex "Labyrinth of Knowledge"

A.A. Zapevalina, V.M. Troyanovskij and O.A. Serdyuk

Abstract Principles of technological processes management with cascade organization and distribution structure can be successfully used for a wide range of information systems. Increasing of competence based on knowledge—a point of contact and technical and learning systems. The process of building and knowledge development is the basis of the technological process used in the educational program complex "Labyrinth of knowledge". Organization of the process of learning requires the implementation of a set of operating modes: view mode and the transfer of knowledge, controlling regime, account of individual abilities of students, adaptation, development and updating of the knowledge base. Variety and branching of knowledge is leads to a network structure of their organization. Conversion of the network structure to the labyrinth with the objective function of motion and feedback leads the formulation of the problem of learning to the class of adaptive control of complex technological processes. Algorithms and software for "labyrinth of knowledge" allow implementing these processes technically. Automatic processing of current information on the education status of each student can personalize the learning process and implement operational tuning of the whole process on a certain stage with using formally controlled parameters without the teacher intervention. At the same time, logging and accumulation of current information of the progress of training provides additional information for a teacher about the effectiveness of the used methodology and didactic material. The use of modern information technology with their rich graphics, dynamics and the possibility of additional modeling makes the learning process efficient and enthralling. Some disturbing moments, associated with the walk through the maze, are discussed in the article end.

Keywords Training simulators · Intensification of leaning · Variety of knowledge · Probabilistic assessments · Simulation · Control problems · Statistical estimation · Sampling · Identification

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11.1 Introduction

Ideas of intelligent control of complex manufactures are used more and more widely (Bakhtadze et al. 2008). Identification methods and associative search play a significant role here (Bakhtadze et al. 2007, 2011; Natalia et al. 2012). Advances in microelectronics and computer technology make it possible to realize scientifically predictive capability of adaptation and learning in technical systems (Tsypkin 1968; Poznyak and Kaddour 1997). With this, increasing of competence based on knowledge—a point of contact and technical and learning systems.

Training systems and simulators (Zaynutdinova 1999) are used for efficient obtaining skills and experiences in various fields of technology related to the mass training of specialists to work on the same type of equipment or with similar actions of work, for military purposes, for hazardous industries, etc. The composition of the teaching material is due to the program subject area. The use of computer and information technologies in education meets the requirements of Russian Federal state educational standards of the third generation and also opens up opportunities individualization of students learning (Office of Educational Administration 2013).

The new possibilities of learning systems building using program complex "Labyrinth of knowledge" are discussed below (Zapevalina and Troyanovskiy 2012).

11.2 Formulation of the Problem

Principles of technological processes management with cascade organization and distribution structure (electrical power engineering, pipelines, etc.) can be successfully used for a wide range of information systems, where the process of creation and development of knowledge is the basis of the entire technological process.

Organization of the process of learning requires the implementation of a set of operating modes: view mode and the transfer of knowledge, controlling regime, account of individual abilities of students, adaptation, development and updating of the knowledge base (Fig. 11.1). Variety and branching of knowledge produces network structure. Conversion of the network structure to the labyrinth with the objective function of motion and feedback leads the formulation of the problem of learning to the class of adaptive control of complex technological processes.

11.3 Methods for Solving (with Using Modern Information Technologies)

Control of knowledge is constantly used in the learning process and this process is similar to the stabilizing feedback in technical systems, provides the information necessary for the transition to adapt (Fig. 11.2). The program uses special methods

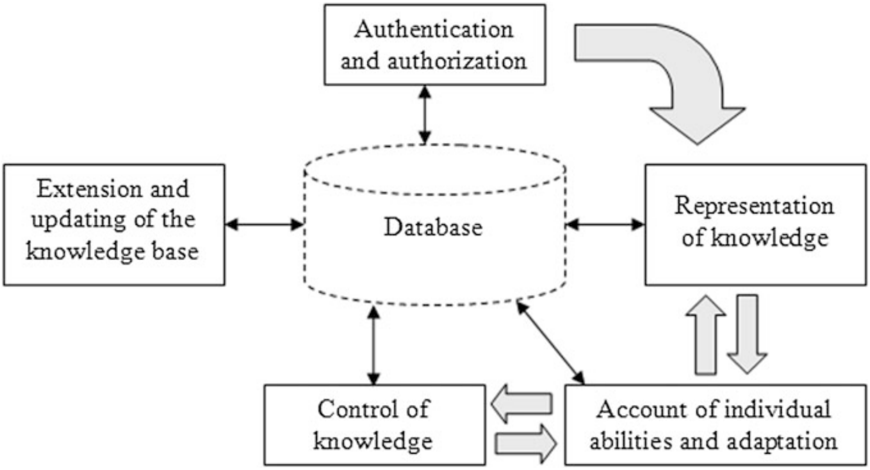

Fig. 11.1 Communication of operation modes in the training program complex "Labyrinth of knowledge"; *gray arrows* indicate the order of regimes change

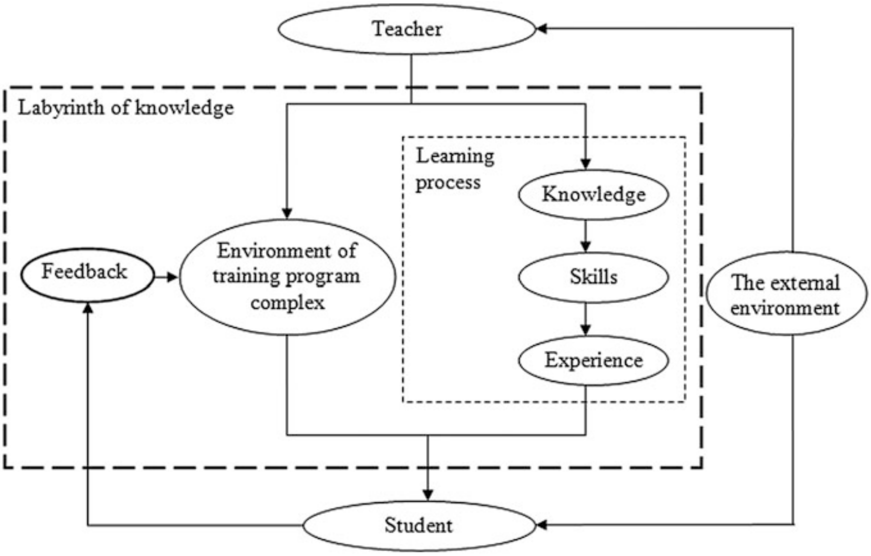

Fig. 11.2 Approximate scheme of the learning process

of control knowledge for maintain the interest of students (Zapevalina and Troyanovskiy 2012; Troyanovskiy 2002).

Algorithms and software for "Labyrinth of knowledge" allows this processes to be realize. Automatic processing of current information on the status of education

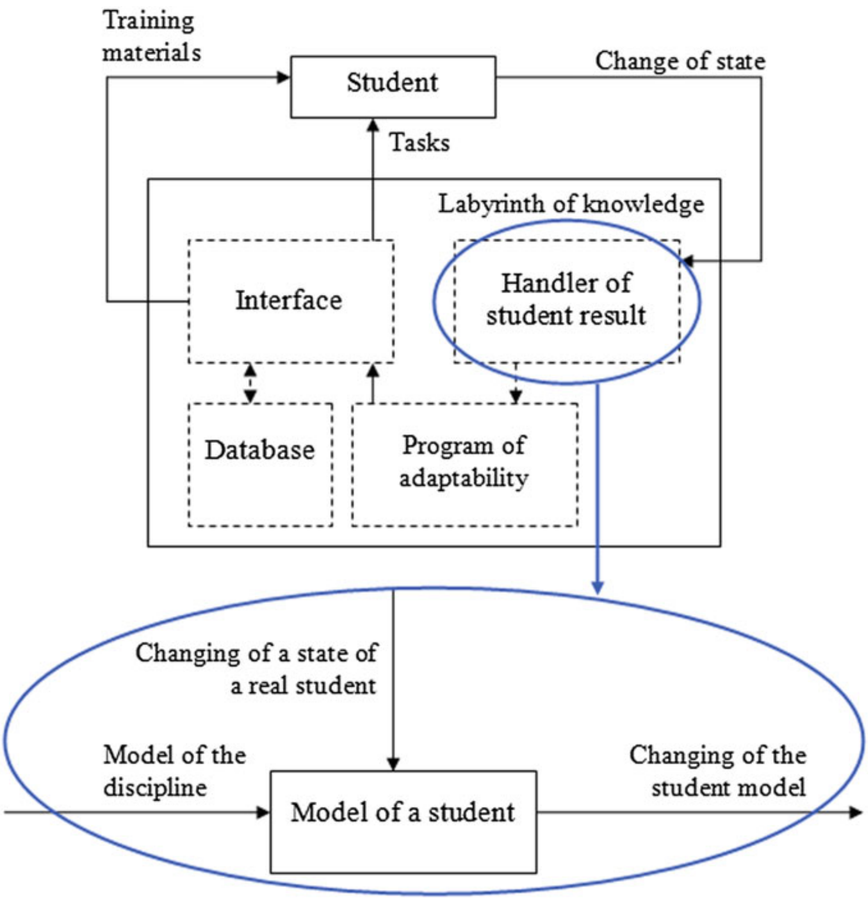

Fig. 11.3 Model of the learning process with using of the program complex "Labyrinth of knowledge"

of each student can personalize the learning process and implement operational tuning of a certain stage of the whole process by formally controlled parameters without the intervention of the teacher (Fig. 11.3).

At the same time, recording and the accumulation of current information of the progress of training provides additional information for the teacher about the effectiveness of the methodology followed and of a didactic material.

Algorithms and software of "Labyrinth of knowledge" allow to realize processes of interactive training with use modern gaming methods (Fig. 11.4).

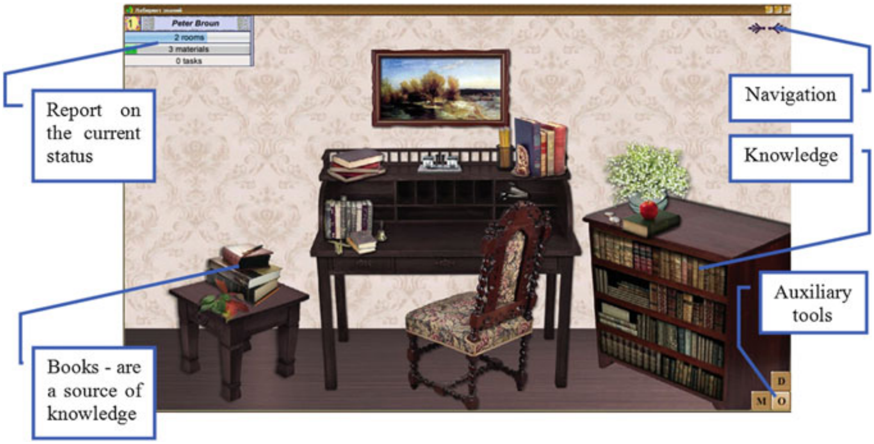

Fig. 11.4 The example of interface educational program "Labyrinth of knowledge"

11.4 What Is Alarming When Using the "Labyrinth of Knowledge"?

The process of knowledge acquisition (part 2) corresponds to the classical paradigm: "From living contemplation—to abstract thought and from him—to practice". Each stage has its own "pitfalls" that developers of learning systems attempt to circumvent or overcome. However, the effectiveness of their efforts is appears only at the final stage, in practice. All this reminds wandering in a maze, where can be objective deadlocks, failures due to poor accounting of constraints or methods of knowledge application.

Limitations which arise, for example, in problems of identifying, during the physical experiment, etc., can be represented in form (Fig. 11.5):

Using the data of normal operation of the object requires consideration of a wide range of related issues:

1. Work in real time.
2. Stochasticity of influences.
3. Dynamic properties of objects.
4. Limited observation intervals.
5. Discrete-continuous transformations.

Work in real time. Reaction of physically realized objects and operators cannot come earlier, than entrance influence has been enclosed. Unfortunately, as mark Middlton (1958), Tsypkin (1964) and other, many graceful mathematical constructions lead to physically unrealized operators and necessity to search for the subsequent approached decisions, when calculating information processing and management systems.

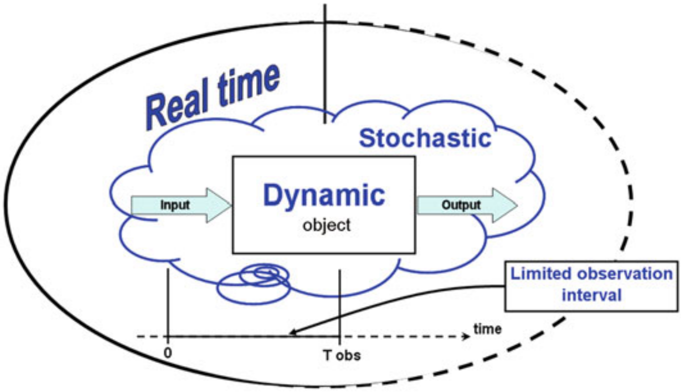

Fig. 11.5 Restrictions in total system

Stochasticity of influences—Dynamic properties of objects—Limited observation intervals. It is the central knot of problems. Stochasticity of influences requires use of statistical methods. The statistics initially considers casual events, probabilities, etc. on the basis of the theory of sets. Dynamic properties of the object and work with private realizations at the limited observation intervals create obstacles for use of classical statistical methods.

The problem of using discrete-continuous model of a continuous process arises as result of the discrete-continuous transformations of signals with digital computer aid for continuous processes. Possibility and legitimacy of consideration of all processes (and continuous and discrete) in uniform time are considered in Troyanovskyi (2009). However we would like to analyze especially: how the parity of the sampling period, time parameters of signal's properties and dynamic properties of object in common influence representation of the researcher about object?

Consider these problems in more detail.

11.5 Stochasticity of Influences—Dynamic Properties of Objects—Limited Observation Intervals

Classical probability theory and the theory of random processes presuppose the existence of a hypothetical ensemble (set) of independent realizations (Middlton 1958; Montgomery and Runger 2011). Any cross-section of this set gives independent random variables and number of such variables may be infinite hypothetically. In practice, analysis of a private realization may lead to appearance of correlated samples and their number is always limited.

As far as these differences may affect the results of statistical analysis (Fig. 11.6)?

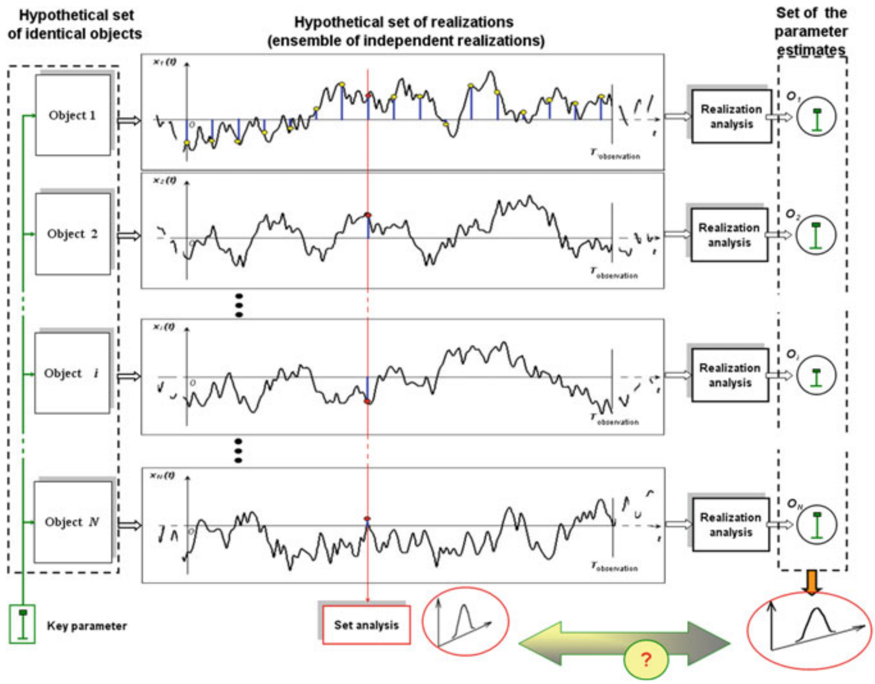

Fig. 11.6 Statistical estimations on set and along realization: how close they are?

Independent counts will be taken into consideration when the set is cut across statistically independent realizations. Besides, capacity of the hypothetical set can be infinite. At the same time the counts chosen from private realization may be correlated, and their number is always limited.

What differences in the estimates will this fact lead?

Here are two simple examples (Troyanovskyi 2004, 2009):

1. It is known that a good approximation to the normal distribution is given by the sum of five random values, each of which is evenly distributed on the interval [0,1] (Fig. 11.7).

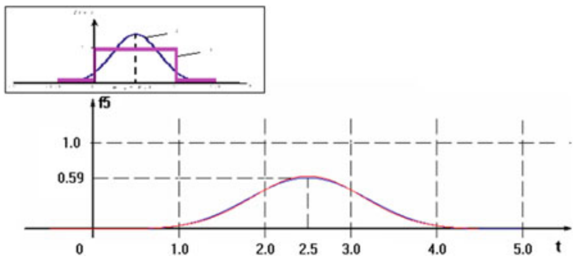

Fig. 11.7 Composition distribution approximation from initial even to normal distribution

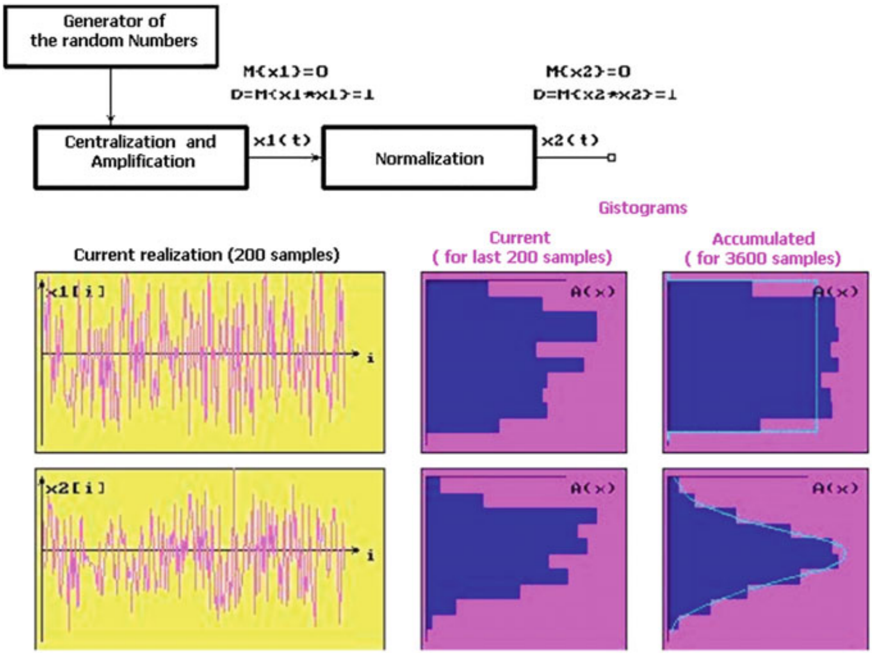

Fig. 11.8 As the amount of data affects on the fluctuation histograms

But it is the ideal representation. In practice, thousands of counts for distribution estimates that are similar to the ideal are required (Fig. 11.8).

Applying the A.N. Kolmogorov's criterion for the analysis of likelihood of statistical hypothesis, it is easy to establish that in those conditions where the probability of similarity of the original even distribution and the normal one is only 0.003, for a sum of three numbers it increases to 0.711, and for a sum of five numbers it reaches 0.964.

2. Calculation of the average estimation. Corridors of convergence, in the case of independent counts and correlated counts, could be very different by use a sample of limited amount (Fig. 11.9).

11.6 The Rocks and Realities of Inertialless Object Identification (Troyanovskyi 2009)

11.6.1 The Rocks

Even more effect is found already at the task solution of identification (Fig. 11.10) for inertialless object with single input and output.

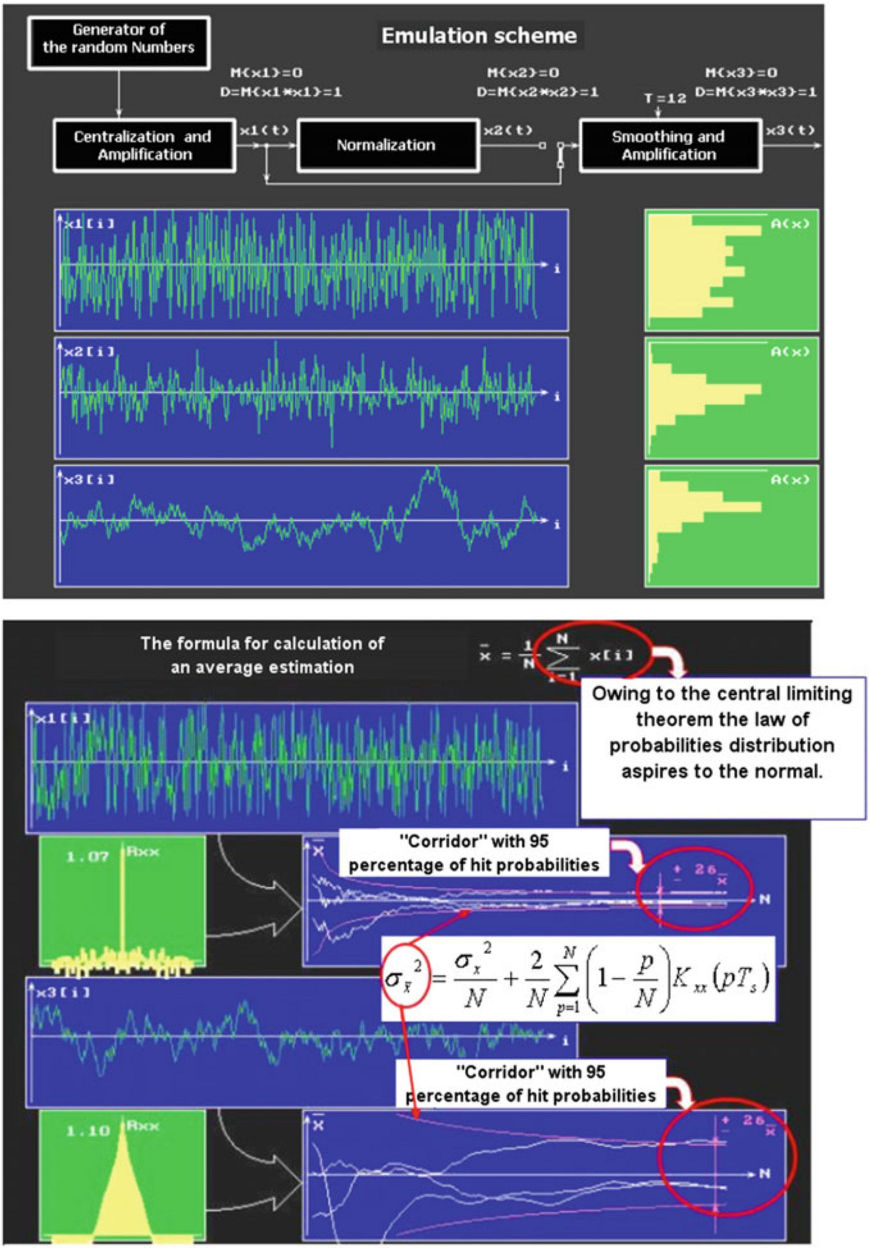

Fig. 11.9 Confidence intervals definition for the calculation of the average along realization of random process

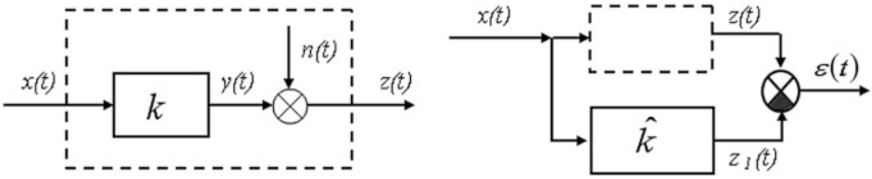

Fig. 11.10 Analysis scheme of an inertialless object identification precision; *k*—true gain factor of the object

For signals and their characteristics the next statements could be written:

$$z(t) = y(t) + n(t) = kx(t) + n(t). \tag{11.1}$$

$$\varepsilon(t) = z(t) - z_1(t) = z(t) - \hat{k}x(t). \tag{11.2}$$

$$\begin{aligned} M\{\varepsilon(t)\} &= M\{z(t) - z_1(t)\} \\ &= M\{kx(t) + n(t) - \hat{k}x(t)\} \\ &= M\{(k - \hat{k})x(t)\} + M\{n(t)\} \\ &= (k - \hat{k})M\{x(t)\} + M\{n(t)\} = 0. \end{aligned} \tag{11.3}$$

$$\begin{aligned} \sigma_\varepsilon^2 &= M\{\varepsilon^2(t)\} \\ &= \sigma_z^2 - 2\hat{k}M\{x(t)z(t)\} + \hat{k}^2 M\{x^2(t)\} \\ &= \sigma_z^2 - 2\hat{k}K_{xz}(0) + \hat{k}^2\sigma_x^2, \end{aligned} \tag{11.4}$$

where $M\{\}$—sign of the expectation.

Here, the best estimation, with usage of the set characteristics, is always exactly equal the true gain factor of the object, regardless of the noise level:

$$\begin{aligned} \hat{k} &= \frac{K_{xz}(0)}{\sigma_x^2} = \frac{\grave{I}\{x(t)(kx(t) + n(t))\}}{\sigma_x^2} \\ &= \frac{k\sigma_x^2 + M\{x(t)n(t)\}}{\sigma_x^2} = k. \end{aligned} \tag{11.5}$$

Formally, the expectation of independent signals multiplication is zero.

Physically, this can be interpreted as a limiting averaging case for an infinite set of particular multiplications of the signal samples and (independent) noise. It is an infinite power of hypothetical set that reduces the average of these particular products to zero.

11.6.2 The Realities

The average over a finite number of counts along the time axis leads to the appearance of fluctuating component in the evaluation

$$\tilde{k} = \frac{\sum_{i=1}^{N} x_i(kx_i + n_i)}{\sum_{j=1}^{N} x_j^2} = k + \frac{\sum_{i=1}^{N} x_i n_i}{\sum_{j=1}^{N} x_j^2}, \quad (11.6)$$

where $\tilde{k}$—estimation, determined by the least-squares method (Troyanovskyi 2009).

If signal and noise are independent then estimation $\tilde{k}$ is not displaced and consistent:

$$M\{\tilde{k}\} = k + M\left\{\frac{\sum_{i=1}^{N} x_i n_i}{\sum_{j=1}^{N} x_j^2}\right\} = k. \quad (11.7)$$

For the Gaussian input signal and δ—correlated noise:

$$\sigma_{\tilde{k}}^2 \approx \frac{\sigma_n^2}{\sigma_x^2 (N-2)}. \quad (11.8)$$

The conditions of majorant convergence of approximate mathematics series are gained by derivation of the above relation. Modeling results are shown at the Fig. 11.11.

11.7 The Problem of Using Discrete-Continuous Model of a Continuous Process

Let the test object or process has a linear structure (Fig. 11.12).

Here k—static transfer constant (gain factor);

$h(t)$—object weight function, reflected its dynamic properties. The function is normalized

$$\int_{\lambda=0}^{\infty} h(\lambda) d\lambda = 1 \quad (11.9)$$

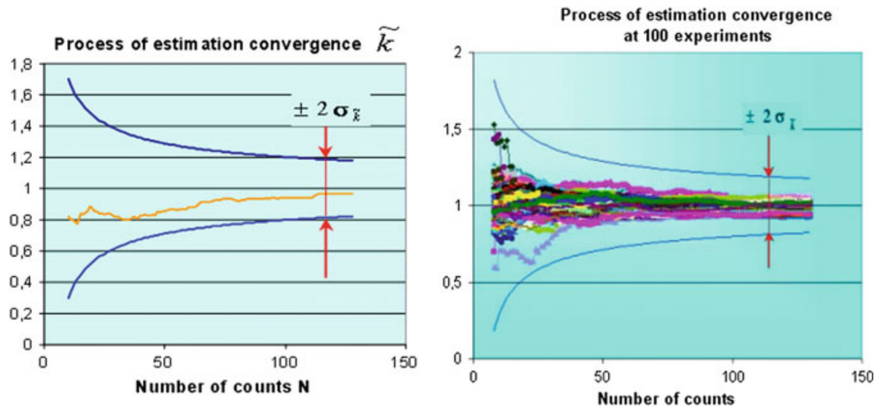

Fig. 11.11 Modeling the process of inertialless object's amplification factor estimation convergence

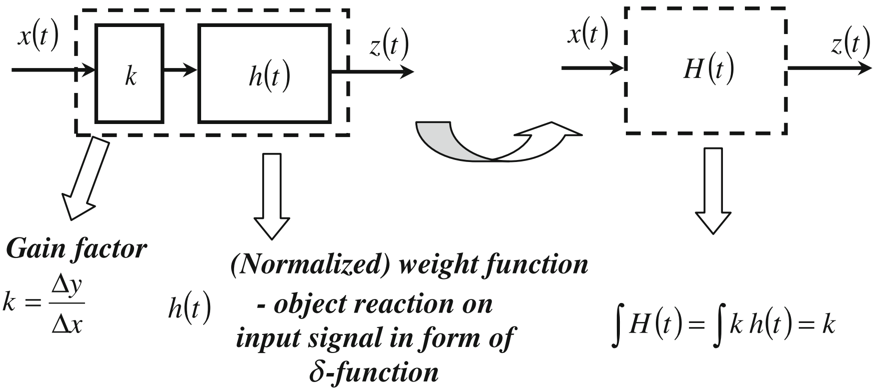

Fig. 11.12 An object with linear structure

Connection of signals at the input and output of a linear dynamic object is described by the convolution equation

$$z(t) = k \int_{\tau=-\infty}^{t} x(\tau)h(t-\tau)d\tau \tag{11.10}$$

Remarks

1. The last equation does not impose any restrictions on the type of signal, including the random signals.
2. Eq. (11.10) is invariant to the time reference point.

It is easy to show that the static transfer constant k has the physical meaning of the ratio of steady output signal to the input step signal (at the end of the transition process), and the weight function $h(t)$—an object reaction on input signal in form of δ-function at $k = 1$.

Note that if in the result of some experiment we can determine the generalized characteristic

$$H(t) = k\,h(t),$$

Then by ratio (11.9)

$$\int H(t) = \int k\,h(t) = k.$$

Let us now see what happens when you use of a discrete-continuous model instead of a real continuous object. To do this, from the original continuous signal discrete samples are selected and subjected to digital processing and subsequent recovery (Fig. 11.13).

The process of sampling is described by the procedure of multiplying the original continuous signal on sequence δ—functions:

$$x^*(t) = x(t)\sum_{i=-\infty}^{\infty}\delta(t - iT_s), \tag{11.11}$$

where $x^*(t)$—quantified in time signal $x(t)$, T_s—period of sampling.

For the linear case, the discrete output signal are determined with aid weighting factors of processing function and the sampled input signal as

$$y[i] = \sum_j h[j]\cdot x[i-j]. \tag{11.12}$$

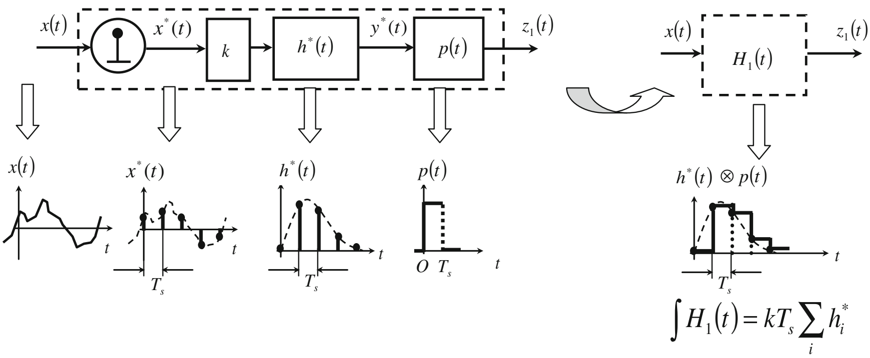

Fig. 11.13 The structure of a discrete-continuous model

If the discrete input and output signals are expressed as continuous functions of time, just as was done for the signal $x^*(t)$, the latter expression takes the form:

$$y^*(t) = \sum_j h[j]x(t) \sum_i \delta(t - iT_s - jT_s) \tag{11.13}$$

or

$$y^*(t) = \int_\lambda h(\lambda) \sum_j \delta(\lambda - jT_s)x(t) \sum_i \delta(t - iT_s - \lambda)d\lambda = \int_\lambda h^*(\lambda)x^*(t - \lambda)d\lambda, \tag{11.14}$$

where it is defined

$$h^*(\lambda) = h(\lambda) \sum_j \delta(\lambda - jT_s) \tag{11.15}$$

discrete weight function of a linear processing unit, obtained by discretization of the original continuous function—a prototype, or the multiplication of discrete ordinates $h[j]$ on the sequence of δ-functions.

Restoring a continuous waveform from its discrete samples is made by a variety of ways. In the case of a simple digital-to-analog converter or the zero-order clamp, the last signal value, converted to analog form, remains at all near term T_s. It can be described by a weight function

$$p(t) = \begin{cases} 1 & at\ 0 \le t < T_s \\ 0 & beyond\ this\ interval \end{cases} \tag{11.16}$$

The generalized weight function $H_1(t)$ and the reconstructed signal $z_1(t)$ are characterized by step functions (Fig. 11.13).

The difference between functions $H(t)$ and $H_1(t)$ determines the difference of static transfer constant of a real object, and discrete-continuous model.

Indeed, in the case of a continuous object $\int H(t) = \int k\,h(t) = k$, but for a model $k_1 = \int H_1(t) = kT_s \sum_i h[i]$ that demonstrates a shift in the transfer constant k_1 relative to the true quantity k.

Simulation shows that the relative size of distortion is greater than 1 for aperiodic link of the first order and the relative size of distortion less than 1 for aperiodic link of the second and higher order.

The size of relative displacement can make 10 and 100 %. It depends on the weight function of the object and the ratio between period T_s and the weight function length of the object.

Thus, if the speed of digital computers begins to noticeably inferior temporal scales of the process, discrete-continuous model of the process causes significant distortion, even in a static transfer constant. The same words can be said about the dynamic characteristics of the model, but the corresponding analysis, some results of which are described in Troyanovskyi (2004, 2009), Serdyuk (2009), is beyond the scope of this article.

11.8 Conclusion

1. Ideas of the intelligent control of complex manufactures, the knowledge-based management practices—are the points of contact between the technical and training systems.
2. Connection of control methods, technical capabilities of computational tools and modern information technology allows to create an effective learning environment with functions of adaptive simulator.
3. Separating data from the program and transfer a functions, associated with the interaction, to single routines allows to create a flexible system of engineering and tuning of simulator.
4. The use of active and interactive lesson forms with maintenance of individual educational path of each student, additional modeling and visualizing information makes the learning process efficient and enthralling for a student. Fixing and accumulation of data on passage of training create a prerequisite for further analysis and improvement of the educational program.
5. Training with using "Labyrinth of knowledge" can give a guess about sources of discrepancies between theory and practice.

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Chapter 12
Scenario Analysis in the Management of Regional Security and Social Stability

V. Kulba, O. Zaikin, A. Shelkov and I. Chernov

Abstract Chapter represents the methodological and applied issues of development the management processes of regional security. It describes the methodology of diagnosis, structural analysis and evaluation of the major threats to regional security. The problems of countering the destructive information effects based on misinformation and manipulation technologies are examined. The results of the analysis of the main features of the management processes of regional security are presented. There are the mechanisms of the use of scenario analysis in the management of socio-economic development of the region and ensuring its protection against external and internal threats to social stability. A formalized methodology to assess the effectiveness and efficiency of management of regional security is considered. The results of the scenario study investigation of multi-graph management models of regional security are given.

Keywords Regional security · Social stability · Threats diagnostics · Management · Information impact · Scenario analysis · Simulation · Symbolic graphs · Management decisions · Extremism countering

12.1 Methods of Diagnosing Threats to Regional Security

In modern conditions the emergence of more and more new problems and challenges (geopolitical conflicts, globalization, international terrorism, the global financial and economic crisis, natural and socio-genic disasters, pandemias, etc.) the

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role of control systems of regional security considerably increases. To achieve these goals these systems must adapt to dynamic changes occuring in the external and internal environment and to be proactive emerging challenges and threats to the success of socio-economic development.

Effective management of regional security needs formal target forecast of the behavior of both the control object (in this case—the region) and its surroundings. This forecast allows to identify key risk factors that carry the various threats to the purposes and objectives of management of regional development. These factors can be grouped in a hierarchical series of generations: contradiction → sources of threats → threat → sources of vulnerability → risks → damages (Schultz et al. 2013).

The contradictions are one of the most important concepts of system analysis, which determines the ability of socio-economic systems to changes and development. In terms of challenges of sustainable regional development and regional security it seems appropriate to understand the contradictions as elements of system purposes mismatch between its subsystems and external environment, as well as the means to achieve them.

This type of contradiction in a stable socio-economic development can be latent, but in the pre-crisis and crisis period they become apparent in the social, economic, political and media spheres, international relations, etc.

Negative contradictions that appear both within the region and in the external environment, generate respectively external and internal sources of threats. These sources are in fact carriers of potential threats to effective regional development and can into be both external and internal threats to regional security similarly to contradictions generating them can be divided into external (depending on the source localization—the first and the second type) and internal relating to the control system (Fig. 12.1).

External threats of the first type are global ones and are related to the negative impact of global processes and trends, instability or crisis in the global economy (including opposition of geopolitical opponents to the country development and the imposed by Western countries different kind of economic sanctions for the sake of their political interests, the organization of "color" revolutions, etc.), fluctuations in the world market supply and demand, energy prices, currency exchange rates, etc.

Threats to regional security of the second type are related to the existing problems of social and economic development of the country, imperfect system of economic management, financial problems and inefficient systems of budgeting and inter-regional cooperation, natural and man-made disasters, etc.

Internal threats to regional security, emerging and localized within the administrative—territorial unit, reflect the characteristics of the social and economic development of the region and are very diverse.

Threats to regional security are based on a number of external and internal sources of vulnerability, the occurrence of which can be both objective and subjective. In fact, the source of vulnerability is the object or "target", to which can be directed process of the external or internal threats.

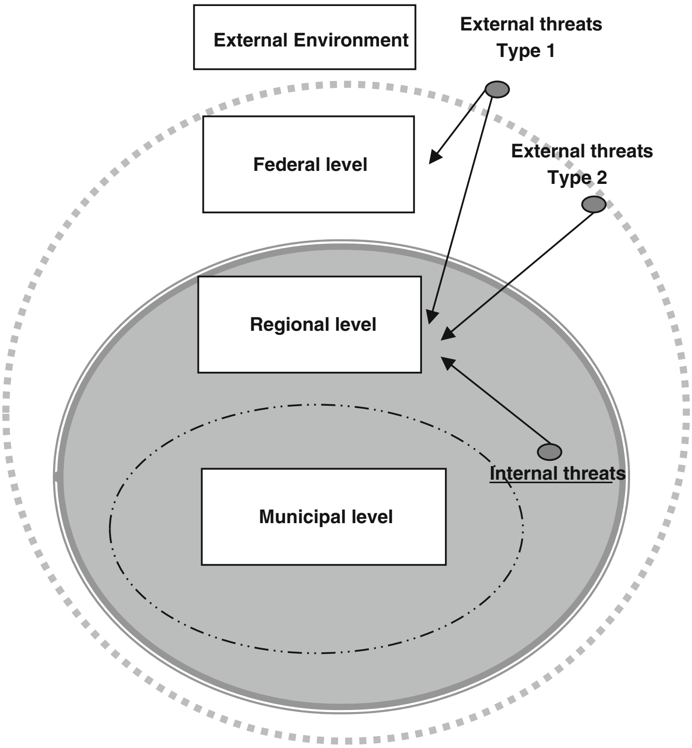

Fig. 12.1 The structure of regional security threats

At present one of the actual issues is the struggle against the various manifestations of extremist nature, as well as ethnic and religious conflicts.

Not aiming full disclosure and the nature of the emergence of extremist manifestations in social life (this is a topic for a separate and serious interdisciplinary research), we note that extremism in the most general form is characterized as a commitment to extreme views and actions, which radically negates the existing social norms and rules. The greatest threat to social stability at the regional level is religious—political extremism. In recent decades extremist phenomena are becoming more widespread. On the one hand, they have a strong relationship with the pseudo-religious postulates, on the other hand, they take place in the political life of society and in many cases are related with attempts to create a different kind of quasi-state agencies (Matveev 2009; Timofeev 2012).

In these conditions the central problem of regional security management is the development of formal methods and models for detection of threats and research of the processes of internal and external destructive information impact (EDII) on civil society, as well as diagnosing the information flows impact on the regional and social security.

Practically, the most significant factor is the lack of reasonable criteria, methods and techniques of assessing the effectiveness of the decisions made to repulse EDII, and methodology of the active information campaigns (AIC), aimed to ensure social stability. This in turn not always allows to predict possible outcomes and choose the most acceptable way to counter EDII.

12.2 Analysis of the Features of the Regional Security Control Processes in the Context of Globalization

Modern global processes of human development led to significant increase in the openness of Russian society, which, as recent experience shows, creates a number of social processes conflicting in their goals and manifestations. On the one hand, the development of democracy promotes the harmonization of the interests and aspirations of different communities and social groups, and thus—the preservation of social stability. On the other hand, the society becomes more vulnerable to destructive information influence from outside, aimed to destabilization of the social life of the country and its regions. In recent years this is one of the goals of geo-political opponents of the Russian Federation, striving for global dominance. Thus the greatest danger is the negative impact on the consciousness and worldview of people, giving this consciousness qualities and properties desirable from the standpoint of the goals.

At present basic threats to regional security in the information sphere in general, and social stability in particular are (Vozzhenikov 2006; Kulba et al. 2009):

- changes and/or formation of beliefs, opinions, interests, attitudes, perspectives, vital purposes, which are necessary to opposite side and related with criteria and orientation of people;
- imposition of pseudo-values, promotion of western and the American lifestyle and the so-called "European values";
- promotion of views on international and domestic events and processes favorable to Western countries;
- attempts to compromise the governments at the federal and regional levels in order to reduce public trust in it;
- distortion of historical facts in the life-country, attempts to dilute the national identity of its citizens;
- provoking processes of imbalance and conflict of interests of different generations of Russian citizens, and social communities;
- promotion of extremist pseudo-doctrines;
- support for nationalist and separatist sentiments;
- distortion of historical facts in the life-country and attempts to dilute the national identity of its citizens;
- provoking of processes of imbalance and conflict of interests of different generations of Russian citizens and social communities;

- support of processes of youth marginalization;
- promotion of extremist pseudo-religious doctrines;
- support of nationalist and separatist sentiments;
- lack of respect for spirituality, traditional religion and elements of the national culture of the Russian peoples;
- forming effect of action (direct or delayed, inertial) related to a wide range of practical actions (voting, a manifestation of social activity through participation in meetings, demonstrations, or, conversely, lack of participation, etc.);
- formation and/or change of psychological norms and characteristics of human activity, the total emotional and psychological background of their existence;
- formation of normative characteristics of human communication in a given period of time.

In practice of the organization of informational countering the destructive external information campaigns the geopolitical rivals can use considerable arsenal of various methods to manipulate public consciousness. This is a complex of coordinated and distributed in time information impacts on the chosen target audience and intended to get the anticipated results (Qalandarov 1998; Kara-Murza 2006).

Information impacts of this type apply in a certain way structured information, as well as specialized information schemes providing a certain influence on human consciousness and its orientation to reach specific goal, or to induce the desired action. It is possible to allocate three levels of manipulation of public consciousness according to the depth of the impact on the target audience audience (Saltykov 2011):

- enhancing of destructive information actions, ideas, attitudes, motives, values, moral and behavioral norms that already exist in the people's minds and relevant setting goals,
- local (partial) changes of mood, views, emotional perception or attitude to a certain events, facts and processes;
- radical change in system of views, vital values, behavioral norms of the target audience.

Manipulation of public consciousness is closely connected with focused distortion of the information supplied in the framework of the campaign. One of the direct forms of distortion is misinformation—intentional dissemination of false news under the guise of objective information in order to impact on the target audience.

The most important task of regional security management system is to ensure social stability in the region and, in particular, to prevent any form of social conflict.

It is known that the conflicts in the social sphere, on the one hand, can discreetly develop for a long time, on the other—arise unexpectedly, suddenly, e.g. as a spontaneous reaction of the citizens on the "negative" event (in the public mind), and/or as a result of internal or external destructive information impacts provoking social conflict.

According to the logic of the conflict situation in the social sphere, the regional security management process should cover the whole range of regional development problems while security management system should operate in three main modes:

1. stationary—mode of social stability;
2. emergency—resolution of developing conflict;
3. post-emergency—liquidation of consequences of social conflict.

The first mode—stationary is characterized by a lack of information about clear evidence of the conflict threat.

The main objectives of the management system in the steady-state are the following:

- advanced analysis of the state and trends of development of the situation in the region and environment;
- the development and improvement of the criteria, as well as qualitative and quantitative indicators to assess the level of regional security;
- diagnosis, identification, analysis, classification and ranking of sources of threats to sustainable regional development and social security;
- scenario analysis and assessment of the potential danger of sources of threats;
- developing of the strategy and long—and medium-term pre-emptive plans to counter the threats of regional security and preventing of social conflicts.
- definition of qualitative and quantitative indicators to assess the level of regional security.

A crucial role in this mode plays the monitoring of regional security, providing the systematic, targeted and comprehensive measurements of parameters of the situation in the region and their following analysis.

The information, incoming the regional security management system, must be handled in four main areas. Within the first area the processing of the current operational information should be continuously carried out. The second area is the problem-functional, the third one is a segment—regional and fourth area is generalizing, where not only the incoming information is integrated, but also the results of its analysis with respect to problem-functional and territorial aspects for strategic generalizations are considered.

One of the most important areas of information work is to assess, analyse, summarize the total volume of available information related to certain events as well as the forecast of the situation. After a rather complex analytical research the operational, tactical and strategic assessments can be defined. As practice shows lack of necessary information is often a major obstacle to the organization of early diagnosis of threats to social stability and prevention of social conflict. In many cases, this is due to insufficient active search for identifying and use of relevant data.

Unlike the management system in emergency situations as well as the natural and technological disasters, the stationary mode actually combines the modes of everyday activities and alert (Arkhipova and Kulba 1998). The reason is that the main and high priority task of regional security management system is prevention the social conflicts. Therefore even the appearance of the signs of the potential threat of conflict requires the immediate and adequate reaction to the existing situation. By what was said, the emphasis in the regional security management process should be made on pre-emptive methods to identify the sources of threats and signs of the social conflict.

The second mode—(emergency) is characterized by circumstances, the set of which is defined as the emergency of social conflict. The main objectives of this mode are to find ways to resolve the conflict as soon as possible, to prevent its escalation, to ensure law and order, to protect the civil and industrial facilities and infrastructure of life, as well as to conduct other emergency measures. Solution of the given set of tasks should be based on (1) scenario analysis of basic displays of the potential threat of conflict escalation, (2) development of operational scenarios of the dynamics of conflict, scenario analysis of the effectiveness of various political, economic, social, informational, legal, etc. means of resolving conflict, (3) analysis of the effectiveness of solutions to de-escalate social conflict, (4) realization of control and management procedures countering the sources of the conflict escalation, (5) assessment of resource requirements for different types of conflict solution. The most difficult from all points of view is the initial stage of origin and development of the conflict. The lack of reliable information on the situation often is nutrient medium for the emergence and spread of the various rumours, tend to be very wide range and often polar assessments, equally competing for authenticity. Evaluation formed in this period is very hard to correct, the reliable information is not always competent to perceive. Change of opinions and attitudes prevailing in the initial stage of the shortage of reliable information, is achieved only by systematic targeted efforts.

The third mode—post-emergency (liquidation of the social conflict consequences) relates to the need of the set of activities directed at restoring of social stability. Tasks of management system in this mode are the following: (1) complex assessment of the consequences of a conflict situation, (2) development and scenario analysis of the solutions to remove consequences of the conflict, as well as to eliminate the causes that led to the conflict, (3) development of the adjustment strategy to counter threats to regional security.

Analysis of the dynamics of the processes of regional development under the actions of different nature is an important part of formal procedures for solving control problems of regional security, arising in the study of semi-structured and unstructured problems. Such problems are characterized by low accuracy of the input data and qualitative description of the postulated relationships. This leads to low efficiency of traditional analytical models.

12.3 Mechanisms of Using Scenario Analysis in the Management of Regional Security

Attempts to develop accurate methods for solving problems of this class are facing significant challenges that, on the one hand, are due to the necessity of forming a limited set of generalized regional indicators of (social and economic) security, determined by a large number of raw data that must be taken into account in the formulation and evaluation of management solutions to reduce social tensions.

On the other hand, the procedures of generalizations, convolution, aggregation, etc. for significant number of dynamically changing sets of diverse factors are very complex and in the general case it is a fairly complex hierarchical (multilevel) system of statistical indicators and expert estimates.

In these conditions, the role of scenario analysis methodology, based on the process of development and research of simulation models considerably increases. These models, created on the basis of the iconic digraphs, allows use as input data both of qualitative and quantitative type. Main advantage of proposed methodology is the ability to assess the vulnerability of regional socio—economic systems (SES) under external and internal threats. Moreover it provides a comprehensive analysis of the current situation in the region at a given time horizon; the formation of short-term and long-term forecasts of its development; assess the effectiveness and coherence of strategic and tactical decisions, distributed in time and space to achieve set goals in the conditions of uncertainty.

The considered approach also allows to draw conclusions about the most likely and appropriate directions of dynamic processes in SES, their stability, and other significant characteristics on the basis of information on the structural features of the system.

Content of object behavior scenario is a model of circumstances changing related with the emergence and development of a certain situation and determined in discrete temporary space with a given time step. The scenario is developed and investigated in condition of unresolved problems. It is an obstacle to a stable and crisis-free development of the socio-economic system.

The most important tasks of scenario analysis in framework of regional security management processes are shown in Fig. 12.2.

In general, the process of organizational management of regional security based on a set of scenarios, one of which is selected to perform this task. Efficiency of solving the problem in this case in general is characterized by index:

$$W \Rightarrow \max.$$

All factors used in the process of scenario analysis can be divided into three groups:

1. a priori known factors (e.g. conditions to achieve the goal or to solve the problem) which let denote α;
2. elements of the solution depending on the subject of management, forming the set X;
3. unknown factors which let denote ξ.

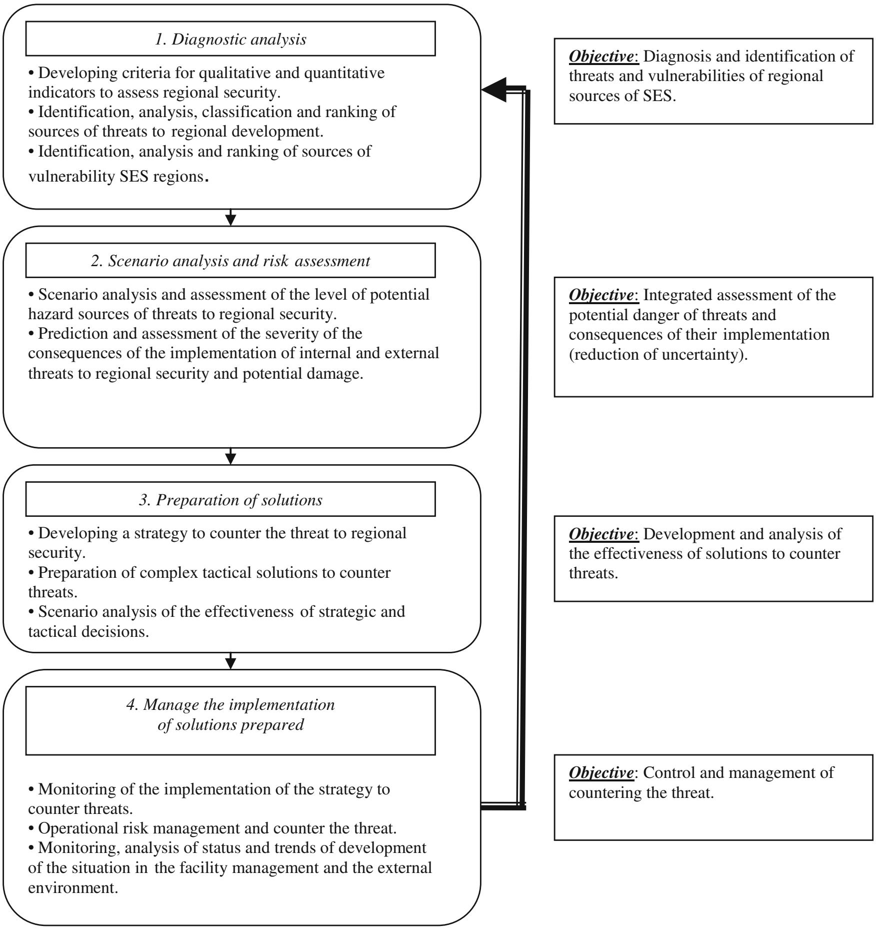

Fig. 12.2 Scenario analysis of management processes counter threats to regional security

Efficiency index W depends on all above mentioned groups of factors: $W = W(\alpha, X, \xi)$.

Since the value W depends on unknown factors ξ, it cannot be computed and is uncertain. Therefore, strictly speaking the expression $W = \max W(\alpha, X, \xi)$ is not quite correct. In this case, the original problem can be formulated as follows: in given conditions α, taking into account the unknown factors ξ, to find a solution $x \in X$, which provide maximum of efficiency index W. This methodological approach allows us to define the problem structure of constructing scenarios as the problem of a certain set of alternatives representation, using its subsets and components.

12.4 Simulation and Scenario Analysis of Efficiency Management of Countering Extremist Manifestations

Before to discuss the results of the scenario analysis of the management process of social security is necessary to briefly recall the main principles and approaches to development and research of the situation models in the social sphere. They are presented in a set of previous works (Schulz and Kulba 2012; Schultz et al. 2011).

The process of modeling and synthesis of alternative development scenarios is carried out using the apparatus of functional iconic graphs.

A mathematical model of the iconic, weighted iconic, iconic functional digraphs, i.e. oriented graphs is an extension of classical graph model. Besides the digraph *G (X, E),* where *X*—a finite set of vertices and *E*—set of arcs, the additional components are included in the model, e.g. a set of vertices' parameters, $V = \{ v_i, i \leq N = \|X\| \}$ i.e. each vertex x_i has its parameters $v_i \in V$. We also introduce the functional transformation of arcs *F (V, E),* i.e. to each arc correspond a sign, or weight or function.

If the functional has the form

$$F\left(v_i, v_j, e_{ij}\right) = \begin{cases} +1, & \text{if the growth (decrease) of } v_i \text{ causes a rise (fall) of } v_j, \\ -1, & \text{if the growth (decrease) of } v_i \text{ causes a fall (rise) of } v_j, \end{cases}$$

then a model is called sign-digraph.

If the functional has the form

$$F\left(v_i, v_j, e_{ij}\right) = \begin{cases} +W_{ij}, & \text{if the growth (decrease) of } v_i \text{ causes a rise (fall) of } v_j \\ -W_{ij}, & \text{if the growth (decrease) of } v_i \text{ causes a fall (rise) of } v_j \end{cases}$$

then a model is called weighted sign-digraph.

Here W_{ij} is the weight of the corresponding arc.

If the function is $F\left(v_i, v_j, e_{ij}\right) = f_{ij}\left(v_i, v_j\right)$, then such a model is called a functional sign-digraph.

Let's introduce the concepts of the impulse-process in discrete-time space on extended digraphs.

The impulse $P_i(n)$ in the vertex x_i at time $n \in N$ is defined as the changing of the parameter in the vertex of digraph at time *n:*

$$P_i(n) = v_i(n) - v_i(n-1).$$

The value of the parameter v_i at the vertex x is defined by the relation:

$$v_i(n) = v_i(n-1) + \sum_{j=1, j \neq i}^{N} F\left(v_i, v_j, e_{ij}\right) P_j(n-1) + P_i^0(n).$$

Here $P_i^0(n)$—the external impulse introduced into vertex e_i at the time n.

From these two difference equations the equation for impulse in the studied process can be easily obtained

$$P_i(n) = \sum_{j=1, j \neq i}^{N} F\left(v_i, v_j, e_{ij}\right)\ \left(P_j(n-1) + P_i^0(n)\right).$$

Impulse-process is called autonomous, if

$$\left(P_k^0(m) = 0 \quad \forall\, m \geq 1,\ \ \forall\, x_k \geq X\right)$$

and simple one, if

$$\left(\sum\nolimits_{k=1}^{N} P_k^0(0) = 1\right) \& \left(P_k^0(m) = 0 \quad \forall\, m \geq 1,\ \ \forall\, x_k \in X\right).$$

The concepts of even and odd cycles are used in the analysis of impulse processes on the sign-graphs. The even cycle has positive product of signs of all its incoming arcs while the odd cycle has negative product. The even cycle is the simplest model of structural instability, since any initial change of parameter in any vertex leads to unlimited growth of parameters module, while any initial change of any vertex parameter of an odd cycle will only lead to the oscillation of vertices parameters.

The vertex of the sign, weighted sign, functional-sign digraph is an absolutely stable for a given impulse process, if the sequence of the absolute values of the impulse in this vertex is limited. Further it is obvious the transition to the stability definition of all sign-digraph. Sign-digraph is called impulse (absolutely) stable for a given impulse process, if every vertex is absolutely impulse stable.

Parameters of vertices of the graph are the key indicators that describe the state and dynamics of the situation (factors), the structure of the graph reflects the cause—effect relationship between them. Set of parameter values of vertices in the graph model describes a specific state of investigated situation at a given time. Changing the parameter values of the vertices generates impulse and is interpreted as the transition from one state to another. Management of system development is simulated by change of the structure and by impulses at certain vertices.

Structural base model of the information counter extremist manifestations includes the models of external destructive information impacts (EDII) on the socio-economic, political, legal, socio-cultural and political-military aspects of regional security, the models of the information impacts of attacks and counter-attacks from each side, as well as models of EDII and active information campaigns (AIC) (Fig. 12.3).

In the first stage of modeling there were analyzed alternative scenarios of situation development, which are a result of exposure to EDII aimed at inciting religious-political extremism. Modeling of EDII complex is realized by means of specialized tools, which introduce corresponding perturbations. The formation of a

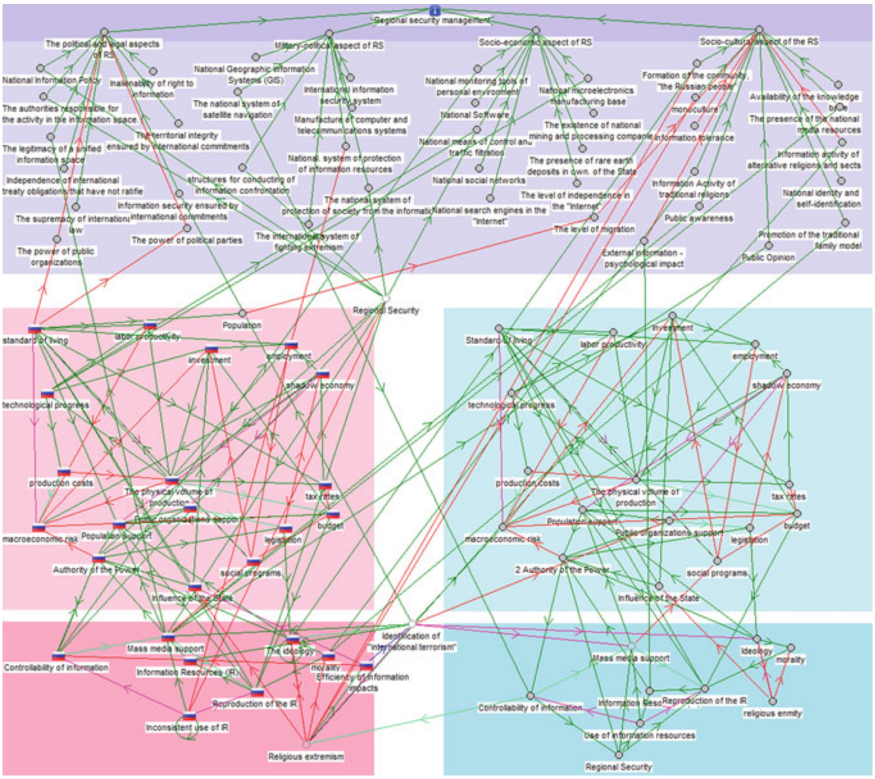

Fig. 12.3 The structure of the basic model to counter extremist manifestations

new event (stage) of the generated scenario is related with a change in the dynamics of at least one key factor. These factors are: macroeconomic risk, effectiveness of information impacts, the authority of the power, the available information resource and the coherency of its use, as well as the above mentioned basic aspects of regional and social security.

Scenario 1: "The lack of the destructive information impacts".

Modelling is carried out for the following initial conditions:

- factor "Religious extremism" is not active;
- factor "Management of regional security" is not active (countering EDII practically absent).

Obtained in such initial conditions scenario is shown in Fig. 12.4 (graphic form).

As may be seen from the represented plots positive dynamics of changes is observed for all key factors: authority of the government and its support by society are growing, macroeconomic and associated risks of a different nature are falling, social stability and the standard of living are growing, as well as social situation controllability.

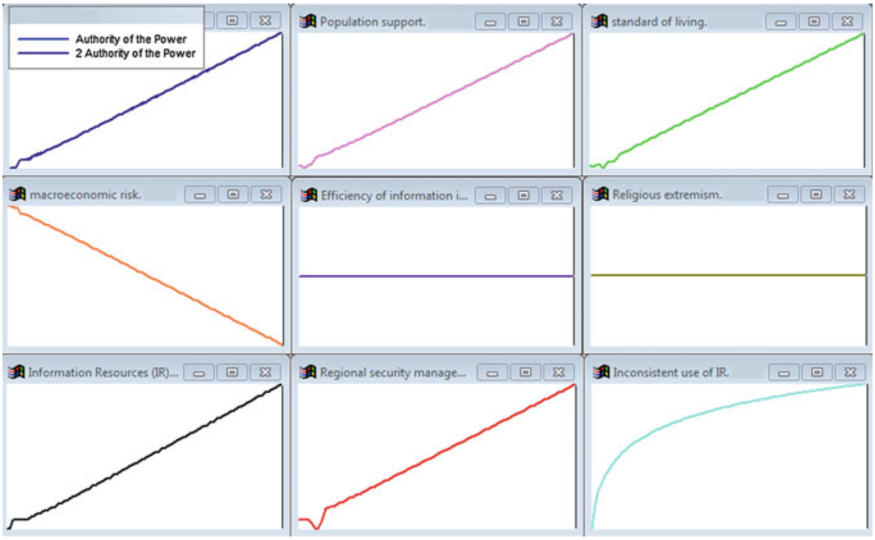

Fig. 12.4 Scenario 1 (graphic form)

Scenario 2: "The manifestation of EDII aimed at inciting extremism".

The influence of destructive information impacts in the model is presented by the following changes in the state of the structural elements:

- factor "Religious Extremism" is active;
- religious and political extremism covers 6 % of the population;
- the vertex "Management of regional security" is inactive (countering practically is absent or ineffective);
- manifestation of external destructive information impacts is modeled as enhancement of influence of the factor "Information resources of opposing side (SES2)" on a factor "Religious extremism".

The dynamics of changes of basic factors of model in the framework of scenario 2 is presented in Fig. 12.5.

Formation of a new event (stage) of the generated scenario is related with a change of the dynamics of at least one key factor. The following key factors are considered: macroeconomic risk, effectiveness of information impacts, the authority of power, the availability of information resource and the degree of coherence of its use, as well as economic, political, legal, cultural and military aspects of regional and social security.

It should be noted that, despite the fact that the indicators of military and political aspects of regional security begin to "fall" practically at once, the integrated safety assessment in the first stage of modeling does not inspire fear. In the next stage instability is observed in the two aspects of regional security: politically-legal and socio-economic. Nevertheless in the fourth stage they begin to show the trend to grow.

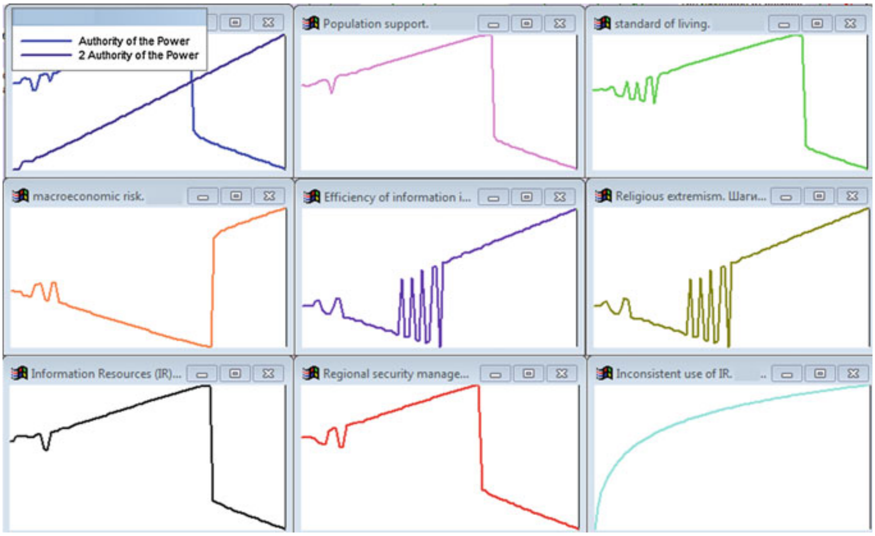

Fig. 12.5 Scenario 2 (graphic form)

The main characteristic of the next (fifth) stage is reduction of indicators of the socio-economic aspects of regional security, which this time is final.

The sixth stage is characterized by the growth of information impacts, which lead to an intensification of the manifestations of religious and political extremism. At the seventh stage there is a decline of the authority of the power, that affects in the reduction of the volume of used information resource. The level of public support for the authorities also reduces. At the last (eighth) stage the remaining two aspects of regional security: political-legal and socio-economic, go to the fall phase, although before they showed a positive trend.

Summarizing the results, we can make the following conclusions: there is a long stage, when even with inconsistent use of information resources it is possible effectively counteract EDII aimed to support extremist manifestations. Then there is a gradual deterioration of the key factors, which is replaced by a stable negative dynamics.

Scenario 3: "Intensification EDII aimed at inciting extremism".

The Influence of destructive information impacts on social stability is modeled as follows:

- factor "Religious extremism" is active;
- religious and political extremism covers 20 % of the population;
- vertex "Management of regional security" is inactive (practically there is no countering);
- intensification of external destructive information impacts is modeled as growth by 40 % of the influence of impact factor "Information resource (SES2)".

The dynamic of change of basic factors of model in the framework of scenario 3 is presented in Fig. 12.6.

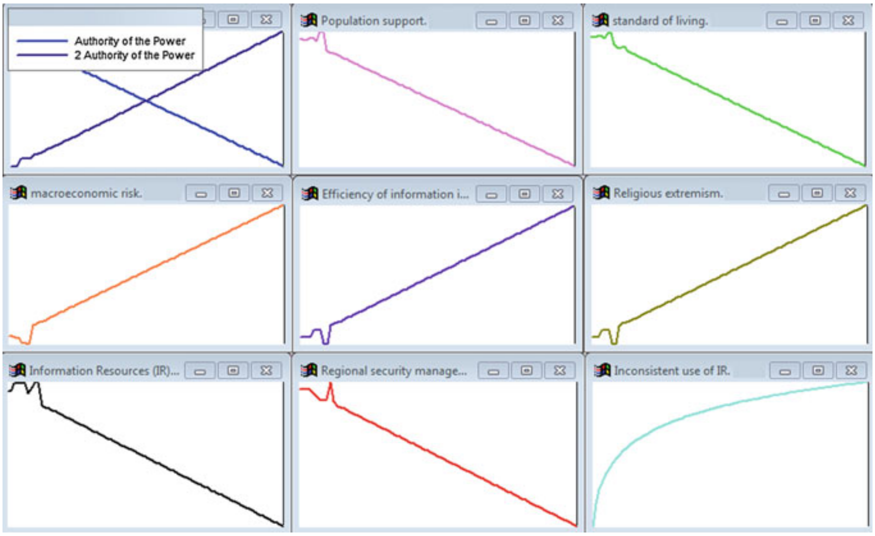

Fig. 12.6 Scenario 3 (graphic form)

As one may see from the represented graphics, in the given scenario the positive changes of the basic aspects of regional security are practically absent. Moreover, already in the first stage there is a negative dynamics ("fall") of all key factors, except the public support of acting power, which also shows "fall" at the last stage.

In fact, the given scenario reflects situation, when efficiency of countering EDII considerably reduced due to inconsistent management (low coordination of the various management objects in the realization of information campaigns) that leads to the destruction of the reproduction of the information resource, and ultimately—to its deficit. This situation leads to a decrease of basic and regional social security.

Scenario 4: "Countering EDII using additional information resources".

It is generated to analyze the effectiveness of information confrontation based on the use of additional resources without modifying the model structure, i.e. without involving new factors and relationships. In the study of this scenario the inverse management problem was formulated and solved. The goal of solution of the inverse task is to avoid reduction of the factor "Regional Security" by acting on the factors "Legislation" and "Ideology", which are the control subjects.

Simultaneously the following tasks were solved:

- search of principal possibility to achieve management goals,
- finding of the intensity and time of impact factors—the management subjects,
- analysis the effectiveness of such impacts to achieve goals and assess the strength of the impact.

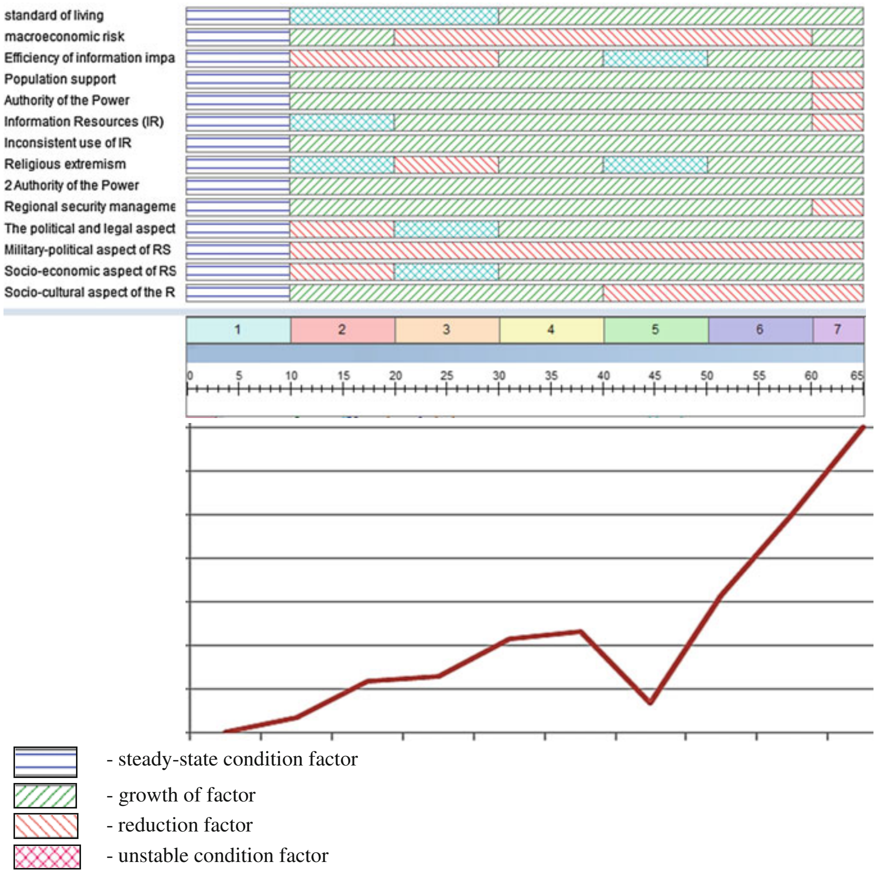

Fig. 12.7 Scenario 4 (the analytical form)

Figure 12.7 shows the results of the research. At the top part of the figure it is shown a scenario of the situation development as a result of the impact of EDII aimed at inciting religious and political extremism. Below it is a plot of resource costs to counter EDII required to achieve system goals. In the bottom part of the figure there is a range of event types.

Analysis of the gained results has shown that the more is the delay of countering EDII, the greater becomes the required amount of involved resources (including information), needed to stabilize the situation. Therefore, the main parameters for efficient information countering is reaction time of attacked system, which is required for the actions to counteract EDII, as well as the “window of instability” of EDII source, that may arise in the unfolding scenario and leads to changes in the nature and intensity of external EDII.

Scenario 5: “Evaluation of the effectiveness of coordinated counteraction EDII”.

The influence of external destructive information impacts on social stability is modeled as follows:

- factor “Religious extremism” is active;
- religious extremism covers 20 % of the population;
- intensification of external destructive information impacts is modeled as influence increase by 40 % the impact factor “Information resource (SES2)” (resource of opposite side) on a factor “Religious extremism”;
- the vertex “Management of regional security” is active and positively affect on the consistency and coordination of used information resources to counter EDII as well as on conducting own AIC aimed at maintaining of social stability;
- the factor “Identification of international terrorism” is active. It identifies the enhancing of process of the religious—political extremism as a kind of acts of international terrorism. This leads in turn to the necessity to delegate some political—legal control functions of regional security to the federal level in order to use the internationally—legal mechanisms of social stability in the region.

The dynamics of change of basic factors which are used to assess trends in the situation development in the scenario 5 is illustrated in Figs. 12.8 and 12.9 (graphics of different aspects of regional security).

As one can see from the graphics, in the given scenario there is observed a short period of instability of factor “Support of population” as well as a short-term fall in the main aspects of regional and social security.

In the next step the situation radically changes to a positive side due to intensification of efforts of regional security management system to coordinate actions to counter EDII. This leads to improvement of all aspects of regional and social

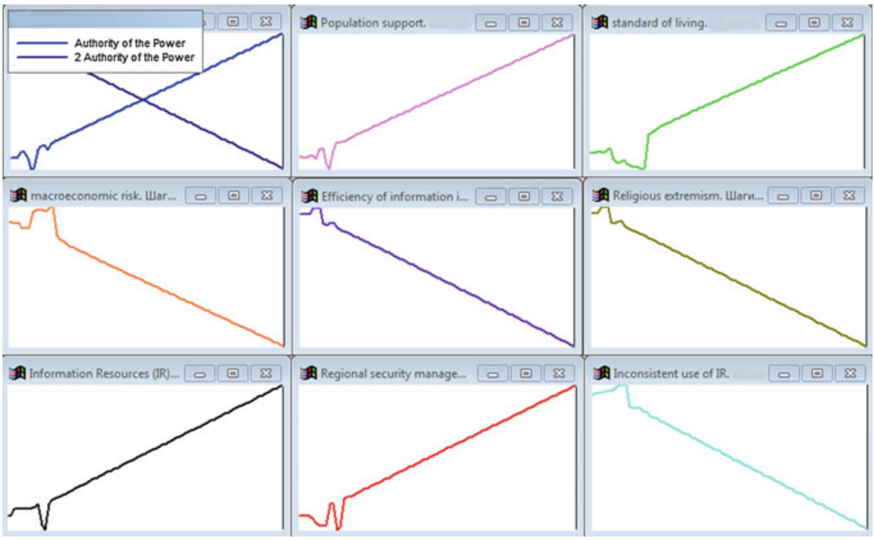

Fig. 12.8 Scenario 5 (graphic form)

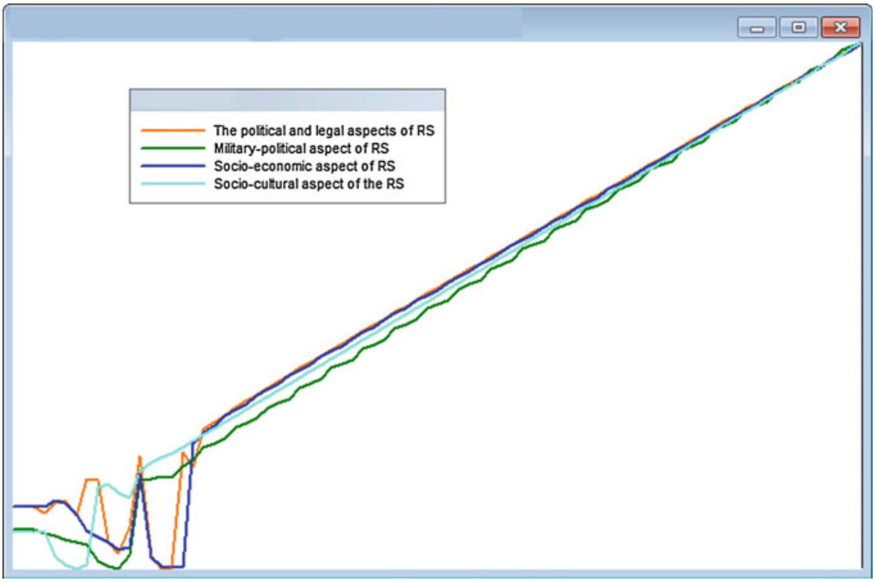

Fig. 12.9 Dynamics of the various aspects of regional security (scenario 5)

security and favorable dynamics of the behavior of key factors of the modeled system (SES).

The situation may be improved due to expansion of the range of information resources used to counteract EDII through the use of the information impact on the opposite side. It can be carried out within the international legal framework, based on the identified relationships between religious and political extremism and international terrorism, as well as the facts of collaboration of certain political circles abroad to extremist manifestations.

The given situation is characterized by sharp changes of direction and dynamics of the key (critical) factors and can be considered as a deliberate hostile external impact, aiming to harm the state in a whole (depending on the success of solving real social, political and economic problems of the country and its regions). The situation development under constant structural relations in the model can be identified by the monitoring system. In this case it becomes obvious a fact of artificial inciting of social conflict by direct foreign support of extremism, and the direction of the external destructive information impacts is one-factor and can be identified unequivocal.

In practice, defense from the external destructive information impacts of this kind can be made by different and well-known international legal means of influencing the geopolitical rival (public allegations of interference in the internal affairs of another state, the charges in violation of international agreements and support for extremism and international terrorism, public access to the international society with various tribunes, etc.).

It should be noted that the fact of the identified (or publicly declared) targeted external destructive information impact can be used as an own information resource. Thus, identified EDII under proper and judicious management can be important information resource for protection from them. For this purpose, for example, can be used such ways of countering as:

- discrediting in the international community opinion the actions of another state as an accomplice to terrorism;
- public addresses and appeals to the international non-governmental organizations;
- conducting complex AIC aimed at creating a world public opinion in support of their own national interests;
- promotion of the own position in the country—a geopolitical enemy and attracting the certain political and official circles;
- other methods of political and media pressure, etc.

One should be aware of the existence of the so-called “double standards” in a number of developed countries, according to which the assessment of the same actions committed by different actors (most states) is also different, and not only on the “value” of this assessment, but also “a sign”. In particular, a number of international events in recent years demonstrates the “double standards” in the understanding and interpretation of the various international legal acts on the part of Western countries, primarily the United States.

12.5 Conclusion

As was shown by the scenario study, now even the most successful (in terms of the level provided by the socio-economic development) regions cannot be fully insured against deliberately provoked or antisocial manifestations of extremism to destabilize society. Therefore, the regions should be prepared to effectively repel a wide range of external (and more broadly—internal) threat to social stability.

And vice versa—an inefficient solution of current and future social problems, even if information policy is effective, leads to additional sources of vulnerability, and as a consequence—to reduction of regional and social security.

Proposed in this paper approach to solve the complex of stated tasks is based on modeling and scenario analysis of processes of the situation development in the regional socio-economic systems and in the external environment. Its main advantage is the ability to predict the behavior of research objects by generating scenarios of their development in accordance with the set objectives and performance criteria. The considered approach allows to make conclusions about the most likely and appropriate directions of development of dynamic processes, their stability, and other significant characteristics based on information about the structural features of investigated system.

Identification and study of patterns of intra- and inter-system interactions, structural–functional relationships between system elements, description and prediction of their essential features, the formation on this basis effective strategic, tactical and operational decisions will certainly enhance the efficiency of controlled progressive development of regional socio-economic systems, and, as a consequence, regional security.

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