52. IWK

Internationales Wissenschaftliches Kolloquium

International Scientific Colloquium

PROCCEDINGS | **10 - 13 September 2007**

FACULTY OF
COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

TECHNISCHE UNIVERSITÄT
ILMENAU

Bibliografische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der deutschen Nationalbiografie; detaillierte bibliografische Daten sind im Internet über **http://dnb.ddb.de** abrufbar.

ISBN 978-3-939473-17-6

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
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Redaktionsschluss: Juli 2007

Verlag:
Technische Universität Ilmenau/Universitätsbibliothek
Universitätsverlag Ilmenau
Postfach 10 05 65
98684 Ilmenau
www.tu-ilmenau.de/universitaetsverlag

Herstellung und Auslieferung: Verlagshaus Monsenstein und Vannerdat OHG
Am Hawerkamp 31
48155 Münster
www.mv-verlag.de

Layout Cover: www.cey-x.de

Bezugsmöglichkeiten: Universitätsbibliothek der TU Ilmenau
Tel.: +49 3677 69-4615
Fax: +49 3677 69-4602

Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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Pham Thieu Nga / B. Wutke

Modifying Bellman's dynamic programming to the solution of discrete multi-criteria optimization problems under fuzziness in long – term planning

ABSTRACT

For optimal planning of the long-term development of large scale, complex systems we need suitable methods regarding the dynamic, multi-criteria and uncertain characters of optimization problems. In this paper we propose a method for solving multi-objective discrete optimization problems under fuzziness in long-term planning based on the Discrete Dynamic Programming (DDP) of Bellman. This modified method has been called **F**uzzy **D**iscrete **D**ynamic **P**areto-**P**rogramming (FDDPP).

INTRODUCTION

Long-term planning problems always have dynamic character. They require the optimization of a developing system over a finite period time horizon. Nevertheless, with respect to large scale, complex systems they usually have multiple criteria and their data are often uncertain. The planning processes can be represented by multistage models (graph models) and optimized by the method of dynamic programming of Bellman. But the multi-objective optimization problem under fuzziness requires modifications of this method.

In this paper, we present briefly the method of dynamic programming of Bellman first. Then, we discuss the modifications to apply the method of Bellman for multi-criteria optimization problems under fuzziness.

THE DYNAMIC PROGRAMMING OF BELLMAN

(1) Basic model of the multistage decision process

The whole process can be represented in a multistage model *(Fig. 1)*. The order of the stages is determined at the beginning. The outgoing state of a stage t is the entry state of the next stage $t+1$. Thereby the system state can be controlled through the transformation of a state into another. Within a stage the system state is considered unchanged. The optimization problem of the multistage decision process can be described as follows:

t - Stage, $t=1(1)T$

$\boldsymbol{x}^t$	-	State vector of the system in stage t, $\boldsymbol{x}^t \in X^t$
$\boldsymbol{u}^t$	-	Decision/Control vector in stage t, $\boldsymbol{u}^t \in U^t$
q^t	-	The cost for stage t, $q^t = q^t(\boldsymbol{x}^t, \boldsymbol{u}^t)$
$\boldsymbol{x}^t = \boldsymbol{x}^t(\boldsymbol{x}^{t-1}, \boldsymbol{u}^t)$	-	The transformation between stages.

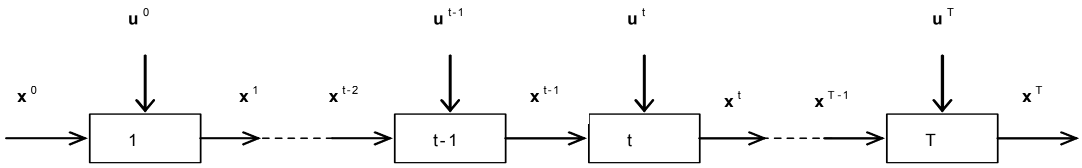

Figure 1. Multistage model

The problem is now to find a sequence of decisions/controls ($\boldsymbol{u}^{1*}$, $\boldsymbol{u}^{2*}$,..., $\boldsymbol{u}^{T*}$) that optimizes the criterion/return function $q = \sum_{t=1}^{T} q^t$ subject to the constraints $\boldsymbol{x}^t \in X$ and $\boldsymbol{u}^t \in U^t$. The sequence of controls is called the *optimal policy*.

(2) Bellman's principle of optimality

The Bellman's principle of optimality was formulated as follows [1]: *"An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision"*. Using Bellman's principle of optimality, a general solution schema can be indicated through recursive substitution. Dependently on the direction in which the system will run during the recursion the forward solution (from the first to the last stage) and backward solution (from the last to the first stage) are to be distinguished. The dynamic programming in this paper bases on the backward solution principle. The conditions of the dynamic optimization procedure are as follows: Sequence of stages, separable criteria and restrictions, monotony of the return function.

(3) Application of the Discrete Dynamic Programming (DDP) to the planning task

The DDP method of Bellman is special appropriate for discrete dynamic optimization problems if the space and the time are modeled in graph models. The planning processes for large scale and continuous developing systems are represented by discrete graph models with a finite number of the discrete time stages, nodes and edges. Each node is a variant. In every stage several variants (nodes) can exist. The edges connect nodes in each stage. With this graph model, where the states are nodes and the controls are edges, the DDP method of Bellman can be applied effectively: Starting with the first node, the principle of the recursive optimization is carried out until the entry node is reached in the first stage.

The special feature of this planning task is that the optimal decision function, the stage transformation and the stage cost are given as discrete values. As far as that is concerned, the tabular calculation for the determination of the optimal functions is applied [6].

MODIFYING BELLMAN'S DYNAMIC PROGRAMMING TO THE SOLUTION OF THE MULTI-CRITERIA OPTIMIZATION PROBLEM

The DDP method of Bellman is usually used for optimizing the problems of single-criterion; however the main characteristics of the real-world planning problems have multiple criteria. For solving the multistage multi-objective discrete optimization problem the method of DDP must be expanded. The Pareto-principle can be applied in this case. If each edge of the graph model is a vector of goal quantities, the method is carried out also in stages at which all goal quantities of the edges outgoing from a node are compared with each other according to the half order principle during the selection of an optimal alternative. Thus, all pareto-optimal trajectories of the compromise set are found in the solution field. The modifying method is called as **D**iscrete **D**ynamic **P**areto-**P**rogramming (DDPP). The following example demonstrates the procedure at the DDPP. Given is a graph model including 3 stages and 3 variants *(Fig. 2)*. The value of every edge corresponds to the state of the node to which this edge directs. Each node is a state vector including 2 components (Q1, Q2), which correspond to 2 different objective functions.

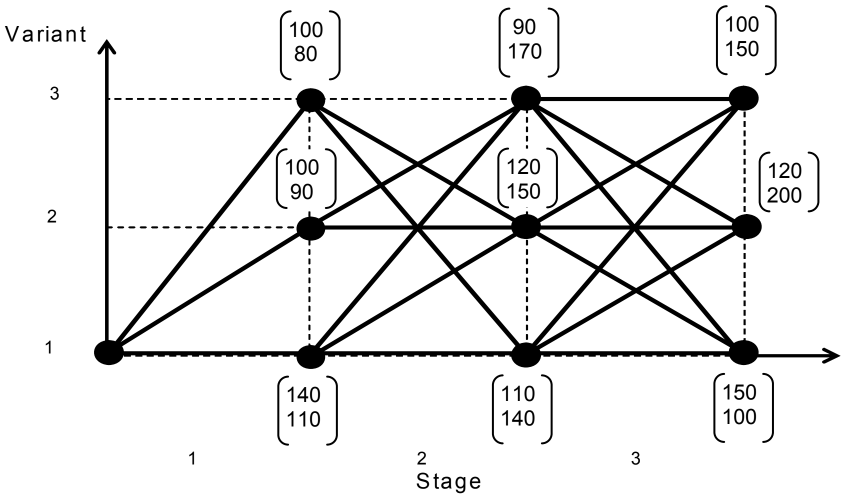

Figure 2. Example for Discrete Dynamic Pareto-Programming

Step 1: Starting at the last stage, the following edges are chosen:

- 1-1, 2-1 and 3-1 with Q1=150 and Q2=100
- 1-3, 2-3 and 3-3 with Q1=100 and Q2=150.

Step 2: In the next stage the following edges are chosen:

- 1-1-1 and 3-1-1 with Q1 = 110 + 150 = 260 and Q2 = 140 + 100 = 240
- 1-3-3 and 2-3-3 with Q1 = 90 + 100 = 190 and Q2 = 170 + 150 = 320
- 2-2-1 with Q1 = 120 + 150 = 270 and Q2 = 150 + 100 = 250
- 3-1-3 with Q1 = 110 + 100= 210 and Q2 = 140 + 150 = 290

Step 3: In the first stage the following optimal trajectories are determined:

- 1-2-3-3 with Q1 = 100 + 190= 290 and Q2 = 90 + 320 = 410
- 1-3-1-1 with Q1 = 100 + 260= 360 and Q2 = 80 + 240 = 320

Unlike the DDP, as result the DDPP in general supplies ***several*** optimal trajectories.

MODIFYING BELLMAN'S DYNAMIC PROGRAMMING TO THE SOLUTION OF OPTIMIZATION PROBLEMS IN A FUZZY ENVIRONMENT

In the planning, the data will play an important role. Nevertheless, the data in the real world are often uncertain. In most cases, necessary data must be estimated in part or be approximated, or it is required to forecast future values. In order to give an optimal solution for the practical problems, this uncertainty of the data must be considered. Suppose the values of the states are not merely exact real numbers but fuzzy numbers, the use of the conventional Bellman's principle for the DDPP with fuzzy model requires a modification of the procedure.

(1) The stage transformation

For the stage transformation the extension principle of Zadeh [2] was applied. The extension principle may be used for the arithmetic operations, making it possible to handle fuzzy numbers. Let $A_i \in X_i$ be some fuzzy sets and $f : X_1 \times ... \times X_n \to Y$ be some (nonfuzzy) function, $y = f(x_1,...,x_n)$. Then, due to the extension principle, the fuzzy set $B \in Y$ induced by the fuzzy set A_1, ,,,, A_n through f is

$$\mu_B(y) = \begin{cases} \sup\limits_{y=f(x_1...,x_n)} \min(\mu_{A_1}(x_1),...,\mu_{A_n}(x_n)), & \text{if } \exists y = f(x_1,...,x_n) \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

(2) Selection the better edge

For the definition of the *"better"* edge in the graph model the ranking procedure of Chen [3] was used.

The common concept of almost all ranking procedures consists in calculation a membership value for every alternative. It is valid for 2 alternatives a_i and $a_j \in A$:

$$a_i \succ a_j \quad \Leftrightarrow \quad \mu_C(i) > \mu_C(j) \tag{2}$$

The method of Chen is to find the total utility or ordering value of each fuzzy number A_i using the concept of maximizing set and minimizing set:

$$\mu_C^T(i) = \frac{1}{2}\left[\mu_C^M(i) + (1 - \mu_C^G(i))\right] \tag{3a}$$

where $\mu_C^M(i) = \sup\limits_{u\in U} \min(\mu_i(u), \mu_M(u))$ $\qquad \mu_M(u) = \left[\dfrac{u - \operatorname{Inf} U}{\operatorname{Sup} U - \operatorname{Inf} U}\right]^k$ (3b)

and $\mu_C^G(i) = \sup\limits_{u\in U} \min(\mu_i(u), \mu_G(u))$ $\qquad \mu_G(u) = \left[\dfrac{\operatorname{Sup} U - u}{\operatorname{Sup} U - \operatorname{Inf} U}\right]^k$ (3c)

The value of k can be varied to suit the application. For example: The case $k=2$ is risk-prone, the case $k=1/2$ is risk-averse.

Fuzzy numbers with triangular, trapezoidal shaped membership functions are often used in the practice. Suppose the values of states are fuzzy numbers A_i with triangular membership functions, each having three vertices, with coordinates $(c_i, 0), (a_i, h_i), (d_i, 0)$ as in *Figure 3*. In details, if the fuzzy number A_i has the membership function:

$$\mu_{Ai}(u) = \begin{cases} \dfrac{h_i(u - c_i)}{(a_i - c_i)}, c_i \le u \le a_i\ , \\ \dfrac{h_i(u - d_i)}{(a_i - d_i)}, a_i \le u \le d_i\ , \\ 0, \quad otherwise \end{cases} \tag{4}$$

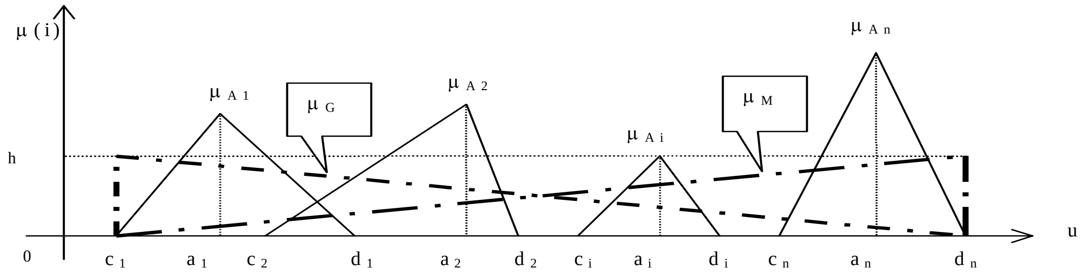

Figure 3. Ranking fuzzy numbers with triangular membership functions

When $k=1,\ i=1,2,...,n,\ \ h = Inf\ h_i,\ u_{min} = Inf\ S,\ u_{max} = Sup\ S,\ S = \bigcup_{i=1}^{n} S_i\ ,\ S_i = \{u \mid \mu_{Ai}(u) > 0\}$

we obtain the total utility of each fuzzy number A_i as follows:

$$\mu_C^T(i) = \frac{h.h_i}{2}\left[\frac{d_i - u_{min}}{h_i(u_{max} - u_{min}) - h(a_i - d_i)} + \frac{1}{h_i} - \frac{u_{max} - c_i}{h_i(u_{max} - u_{min}) + h(a_i - c_i)}\right] \tag{5}$$

If the values of states are fuzzy numbers A_i with trapezoidal membership functions, each having once vertex (b_i, h_i) more, $b_i > a_i$. When $k=1$, we obtain the total utility of each fuzzy number A_i as follows:

$$\mu_C^T(i) = \frac{h.h_i}{2}\left[\frac{d_i - u_{min}}{h_i(u_{max} - u_{min}) - h(b_i - d_i)} + \frac{1}{h_i} - \frac{u_{max} - c_i}{h_i(u_{max} - u_{min}) + h(a_i - c_i)}\right] \tag{6}$$

$\mu_C^T(i)$ is a measure to compare the fuzzy numbers, which describe the values of states in graph model.

So the dynamic discrete optimization problem under fuzziness is solved mathematical cleanly. With this modification the DDPP has been expanded once more and is called as **F**uzzy **D**iscrete **D**ynamic **P**areto-**P**rogramming (FDDPP).

APPLICATION OF FDDPP - METHOD

The above-mentioned FDDPP-method was applied to the decision support system DSPES (Decision Support System for Planning of Energy Supply) [4]. DSPES is a system for long-term energy supply planning in the commune/region. The planning problem is modeled as multi-criteria, multistage evolution problems in decomposed systems with global resource constraints. The hierarchical decision-making system consists of 2 layers. The subordinate layer consisting of several levels is responsible for the optimal resource distribution. It is supposed, the large scale system here a city or a region is decomposed into (indirect) coupled subsystems through the restriction of the global resources, available for the overall system in each (time) stage. Since the system

is considered unchanged within a stage, the problem of the resource distribution is a static optimization problem under fuzziness due to the approximation and the forecast of data. The solution method of this problem [5] is not a subject of this paper. The results of the static optimization problem are fuzzy numbers with triangular membership functions. The above layer (the strategic layer) determines the optimal developing trajectory of the chronological evolution of the energy support for the overall system about the long-term planning horizon consisting of several stages. Each subsystem is represented by a discrete graph model consisting of nodes and edges at which the state of every node was supplied from the subordinate layer, (in form of a triangular fuzzy number). From these local graph models of the subsystems, a global graph model for the overall system is formed. Using the FDDPP-method the optimal trajectory in the global graph model is determined. Through a mapping of the optimal trajectory in the global graph model the optimal trajectories of the local graph models are determined.
DSPES was tested with 2 projects successfully [4]. The first project was for a city with 16 thousand of people, 60 technologies to supply energy for 9 different demands. The second project was for a city with 186 thousand of people, 301 technologies to supply energy for 22 different demands. Both these projects have time horizon of 20 years consisting of 4 stages, 4 global resource constraints and 3 criteria (the consumption of primary energy, total costs and emission of pollutants) to optimize.

CONCLUSION

In the long-term planning of real large scale and continuous developing systems the consideration regarding different criteria is very necessary. Simultaneously, with these complex systems the appearance of uncertain data is not avoidable. This paper proposed the method of Fuzzy Discrete Dynamic Pareto-Programming (FDDPP) by modifying the Discrete Dynamic Programming (DDP) of Bellman for solving the multi-criteria discrete optimization problem under fuzziness. The proposed method has several improvements and was applied to a decision support system successfully.

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