Modelling and Optimization of Strictly Hierarchical Manpower System

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Abstract: This paper addresses the problem of the hierarchical manpower system control in the restructuring process. The restructuring case study is described where eight topmost ranks are considered. The desired and actual structure of the system is given by the actual numbers of men in a particular rank. The system was modelled in the dicrete state space with state elements and flows representing the recruitment, wastages and retirements. The key issues were identified in the process as the stating of the criteria function, which are time variant boundaries on the parameter values, the chain stucture of the system and the tendency for the system to oscilate at given initial conditions. The oscillatory case is presented and the dynamic programming approach was considered in the optimization as unsuitable, examining the oscillations. The boundary space and optimal solution space were considered by indicating the small area where the solution could be optimal. The augmented finite automaton was defined which was used in the optimization with the adaptive genetic algorithm. The developed optimization method enabled us to successfully determine proper restructuring strategy for the defined manpower system.

1 INTRODUCTION

Strictly hierarchical manpower systems can be found in many places in production, industry, the public sector and the army, for example. As a case study we will consider the Slovenian Army, which has recenty been under the restructuring process, where the number of officers in the eight topmost ranks, from Second Lieutenant to Major General had to be changed according to NATO standards (Škulj et al., 2008; Škraba et al., 2011; Škraba et al., 2015). This mean that, for example, the nuber of men in the rank of Second Leutenant had to be reduced from 256 down to 148; for the case of Lieutenant, the number of men should be increased from 258 to 289 etc. The restructuring process for the eight topmost ranks is best described by the Figure 1. On the x-axis of Figure 1, the eight ranks are marked as $x_1 \ldots x_8$ while the number of men is shown on the x-axis. The desired values are shown by the dashed rectangles while the actual values are shown by solid lines. The optimal control of a large manpower system is a challenging task (Škraba et al., 2011; Škraba et al., 2015) due to the time variant boundaries of key parameters, that determine the system (Smith, 1998; Huang et al., 2009; Kofjač et al., 2009). There have been many atempts to provide the optimal solution of the descibed problem such as discrete minimization of quadratic performance index (Mehlman, 1980) however, there is no proper solution provided (Tarantilis, 2008), which would consider the fact, that the boundaries on the particular parameters might change in time. For example, the recruitment policy might be changed during the years of restructuring and the boundaries for the recruitment parameters change accordingly. Main goal is to formulate the mathematical model of manpower system and to develop algorithms, that will provide consistent, nonoscilatory control strategies to bring the strict hierarchical manpower system from initial states to desired end states (Mehlman, 1980; Škraba et al., 2011; Škraba et al., 2015). Since the addressed problem resembles the supply chain, similar approaches could be applied in e.g. inventory control, where oscillations are not desired or in processing industry control where the stability of the levels in chained tanks is important (Schwartz et al., 2006).

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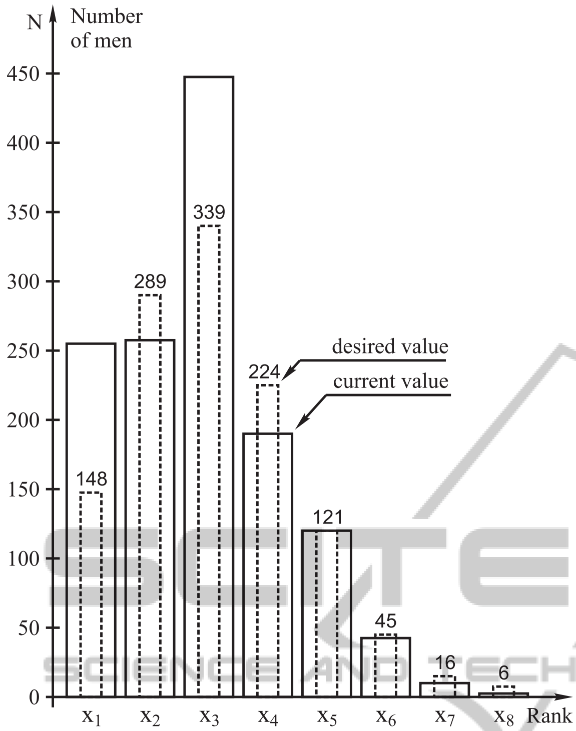

Figure 1: The desired (dashed rectangle) and actual (solid rectangle) values in a particular rank. It can be observed, that in the first rank x_1, the numbers should be reduced, in x_2 increased, in x_3 reduced etc. This makes the control of the chain more challenging. The initial transition process is prone to oscillations.

2 MODELLING OF THE MANPOWER SYSTEM

The system described could be modelled as the cascaded exponential delay structure with the ouflow in each compartment as shown in Figure 2. Our approach differs from the well applied Markov chain methodology (Guerry, 2014; Dimitriou and Tsantasb, 2010; Lanzarone et al., 2010) in modelling approach, where System Dynamics (Forrester, 1973) has been applied. In this manner, the model could be easily understood, which is important for the end users. If the end user does not understand the model behind the solution it is difficult to expect, that the system will be properly applied. The input to the system in Figure 2 is represented by $u(k)$ where k represents the discrete time step $k = 0, 1, \ldots$. In our case, this is the recruitment and it is the only possible input since one could reach the topmost rank only in strict hierarchical order, from the bottom up. It is not possible, for example, to enter the rank of Major not being the Captain first. The modelling of the system is similar to the

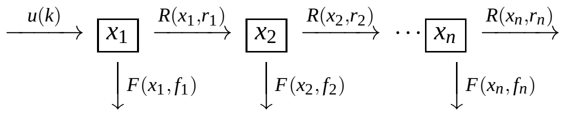

Figure 2: Cascaded Exponential Delay Structure of Manpower System.

modelling of supply chains (Kok et al., 2005; Pastor and Olivella, 2008; Huang et al., 2009; Chattopadhyay and Gupta, 2007; Feyter, 2007; Guo et al., 1999; Kanduč and Rodič, 2015) where similar undesired effects occur, such as bullwhip (Kok et al., 2005). Here we consider eight ranks $x_1, \ldots, x_8$, which are shown in Figure 2. The promotions are marked with R and are dependant on the value of the state element x_n as well as on the promotion parameter value r_n. The wastages are marked with F_n and are also dependent on the value of the state element x_n and the value of the fluctuation coefficient f_n. The presented structure is a delay chain where the change in the first element propagates through the whole chain. This represents a certain difficulty in providing proper system control (Aickelin et al., 2004; Bard et al., 2007; Albores and Duncan, 2008). The system shown in Figure 2 could be expressed by the principles of System Dynamics (Forrester, 1973) as a the set of difference equations in discrete form:

$$x(k) = x(k_0) + \sum_{i=k_0}^{k-1} \left(R_{in}(i) - R_{out}(i)\right) \Delta t \quad (1)$$

$$\frac{\Delta x(i)}{\Delta t} = R_{in}(i) - R_{out}(i) \quad (2)$$

where Eq. 2 represents *net change* of state x. Stock variables $x_1, x_2, \ldots, x_n$ (Levels) represent the state of the system, in our case the number of officers in a particular rank $x_1, x_2, \ldots, x_n$, while the Rate variables R and F (both are rates) represent the change in stocks such as transition rates R and fluctuation rates F defined as:

- R_0 rate element which represents the input to the system, i.e. recruiting, determined by value u.
- R_1 rate element which represents transitions from rank x_1 to rank x_2. R_1 is determined by the value of x_1 and coefficient r_1.
- R_2 rate element which represents transitions from rank x_2 to rank x_3. R_2 is determined by the value of x_2 and coefficient r_2, etc.
- F_1 rate element which represents the fluctuation from rank x_1. F_1 is determined by the value of x_1 and coefficient f_1.
- F_2 rate element which represents the fluctuation from rank x_2. F_2 is determined by the value of x_2 and coefficient f_2, etc.

In matrix form the system shown in Fig. 2 in discrete space where $\Delta t = 1$, takes the form of:

$$\begin{cases} \mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k) \\ \mathbf{y}(k) &= \mathbf{C}\mathbf{x}(k) + \mathbf{D}\mathbf{u}(k) \end{cases} \tag{3}$$

where matrix **A** is the matrix of coefficients. The input $u(k)$ to the considered system is provided by matrix **B** to x_1 such that

$$x_1(k+1) = [1 - r_1(k) - f_1(k)]\, x_1(k) + u(k) \tag{4}$$

In our case $u(k)$ represents the new recruitment to rank x_1 which is the input of the system. The dynamics of the model depends on recruitment, promotions and the fluctuation coefficients. Coefficient values $r(k), f(k)$ and the input $u(k)$ are determined with regard to the historical data, approximately for the past decade. The model was developed with `MATLAB/Simulink` (Škraba et al., 2011; Škraba et al., 2015). The task to achieve the desired number of men in particular rank is expressed as the distance to the target function which is predefined as the function with exponential term (Škraba et al., 2011); this distance should be minimized:

$$J = \sum_{n=1}^{r} \sum_{i=0}^{t_k} \Big(z_n(i) - x_n(i)\Big)^2 = \sum_{i=0}^{t_k} \Big(\mathbf{z}(i) - \mathbf{x}(i)\Big)^2, \tag{5}$$

$z_n(i)$ is the target function value for rank n at step i. One should compute $\min_{u \in U, r \in R, f \in F} J$ where U, R and F are input parameters with predefined value boundaries. The deviation from the desired values is only one part of the problem definition. As we will see this is not sufficient since there is a possibility that oscillations in the gained strategy might occur. Let us consider the example of three ranks, x_1, x_2, x_3 with initial conditions $x_1(0)$, $x_2(0)$, $x_3(0)$ and target values $z(k)$ with boundaries:

$$\begin{array}{ccccc} LB_u & \leq & \mathbf{u}(k) & \leq & UB_u \\ LB_r & \leq & \mathbf{r}(k) & \leq & UB_r \\ LB_f & \leq & \mathbf{f}(k) & \leq & UB_f \end{array} \tag{6}$$

At each time-step the optimization problem is solved for $\psi(k+1)$:

$$\min_{u,r,f} \quad \Big([z_1(k) - x_1(k) + f_1(k)x_1(k) - u(k) + x_1(k)r_1(k)]^2 + [z_2(k) - x_2(k) + f_2(k)x_2(k) - x_1(k)r_1(k) + x_2(k)r_2(k)]^2 + [z_3(k) - x_3(k) + f_3(k)x_3(k) - x_2(k)r_2(k) + x_3(k)r_3(k)]^2 \Big)$$

If we perform the optimization by the proposed equation the solutions might exercise undesired oscillations. Since there is no weight put on the oscillations in the rate elements, this is possible however undesired. For example, if the recruitment oscillated, it would mean that one should adjust the capacity of the training facilities accordingly which would not be desired. Here one strives to get the solution in the form of a moderate policy for all variables in question. An example of such a solution, which is optimal if only the distance from the desired trajectory is considered, is shown in Figure 3. In the Figure 3 the oscillations for the promotion from the Second Lieutenant to Lieutenant is shown. An important limitation that should be considered when stating the optimization problem is sensitivity to upper and lower boundaries. If one considers only one state element with a constant input for the recruitment and variable output rate coefficient, the feasability of achieving the target values is illustrated in Figure 4. On the x-axis the Lower Boundary (LB) value is shown going from 0 to 1, similarly for the x-axis where the Upper Boundary (UB) is shown. On the z axis the Difference between the desired and actual value is shown. Although this is only an example, the real numbers are much higher and such a strategy would not be acceptable. One could observe the unfeasible region in the x-y plane due to the lower and upper boundaries. It is interesting that for the simplest case the optimal region in the upper part of Figure 4 is relatively small. In this case we actually examine the lower and upper boundary space and observe the optimality region. As can be observed the volume is not symmetrical leading to the possibility of searching in the direction of the lowest deviation from the desired trajectory. Therefore, in order to prevent the system from this oscillating behaviour, the automaton A_2 has been constructed which considers strategies with one extremum point where:

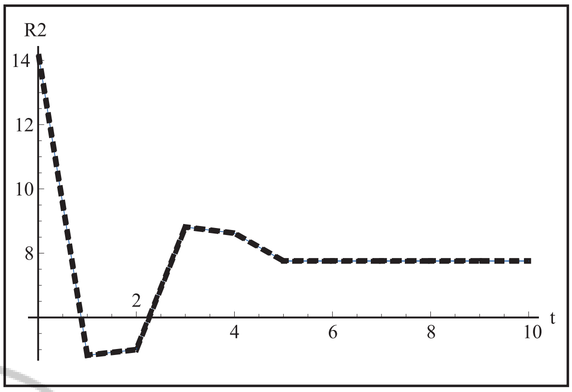

Figure 3: Example of the oscillating promotions on the Rate element R_2.

- The set of states is $S = \{S_0, S_1, S_2, S_3, S_4, S_5\}$
- The comparison alphabet is $A = \{l, e, g\}$
- The initial state is $i = S_0$
- The set of terminal states is $T = \{S_0, S_1, S_2, S_3, S_4\}$

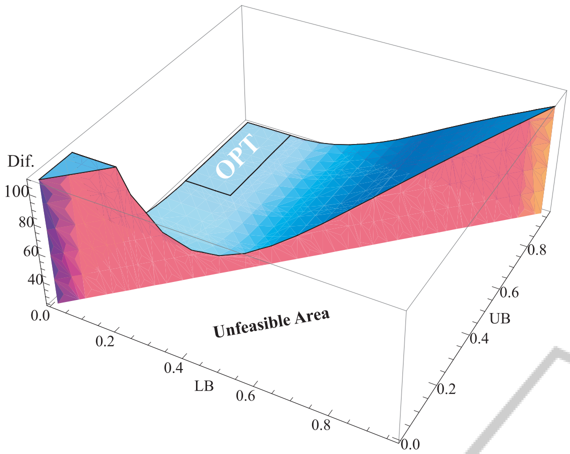

Figure 4: Feasibility region for the system with one state. Here only the variation of the output rate element is considered. Half of the x-y plane is not feasible. The optimal region is shown only as a small part of the parameter boundary space.

- The set of probabilities in the optimization penalty function $P = \{p_0, p_1, p_2, p_3, p_4\}$

The transition function of A_2, $\delta : S \times A \to S$ is defined by the rules A:

	p	l	e	g
$\leftrightarrow S_0$	p_0	S_2	S_0	S_1
$\leftarrow S_1$	p_0	S_3	S_1	S_1
$\leftarrow S_2$	p_0	S_2	S_2	S_4
$\leftarrow S_3$	p_1	S_3	S_3	S_5
$\leftarrow S_4$	p_2	S_5	S_4	S_4
$\leftarrow S_5$	p_3	S_5	S_5	S_5

(7)

An important addition is the augmenting of the automaton with the probability operator p which is applied at the optimization as the penalty coefficient. In our case we can restate the criteria function as:

$$\Psi_J = \min_{u,r,f} \left(\mathcal{A}\,(p) \left[\mathbf{r}, \mathbf{f}, \sum_{k=1}^{t_k} \left(\mathbf{z}(k) - \mathbf{x}(k) \right)^T \mathbf{W} \left(\mathbf{z}(k) - \mathbf{x}(k) \right) \right] \right) \quad (8)$$

subject to:

$$\begin{array}{ccccc} \mathbf{u}_{min}(k) & \leq & \mathbf{u}(k) & \leq & \mathbf{u}_{max}(k) \\ \mathbf{r}_{min}(k) & \leq & \mathbf{r}(k) & \leq & \mathbf{r}_{max}(k) \\ \mathbf{f}_{min}(k) & \leq & \mathbf{f}(k) & \leq & \mathbf{f}_{max}(k) \end{array} \quad (9)$$

where $\mathcal{A}\,(p)$ represents the applied automaton with the augmented penalty probability, which alters the optimization function when the terminal state is not acceptable by appropriate weight, eliminating improper strategies. This is applied to the evolutionary algorithm and alters the value of the minimization function when the terminal state is not acceptable according to the appropriate weight. The automaton is also defined by the penalty coefficients p_0, p_1, p_2 and p_3 according to the number of alternating steps that were exercised by a particular strategy.

3 ADAPTIVE EVOLUTIONARY ALGORITHM WITH CONSTRAINT HANDLING METHODS

A penalty method was developed in order to reject the infeasible solutions which exercise oscillations of input parameters, such as *r(k)* and *f(k)*. Here, oscillations on the rate elements are also not desired. The idea behind the developed penalty method is that the discrete derivative of each r and f can be used to see if this function changed its orientation, i.e. the function is non-monotonic. After evaluating the error in the genetic algorithm, the feasibility is checked at each step of the algorithm. In order to calculate the penalty function, we have calculated the number of times when the derivative was more than or equal to zero, and the number of times when it was less than zero. For each case we have also calculated the sum of the derivative values for positive and negative points separately. The derivative value for the input to the system **u** was normalized to the interval [0,1], as its value is much bigger than for the rest of variables since recruitment is an absolute value and all other parameters are considered as coefficients between 0 and 1. In the next step, the two conditions were checked. Firstly, we have checked if all of the derivative values are positive or negative. In this case, the penalty value for this time series is zero. If there were several positive and several negative values, than the penalty size was set to the smallest module value between the two sums of positive and negative derivatives respectively. The penalty calculation can be formalized as (Škraba et al., 2015):

$$penalty = \begin{cases} 0, & if \quad (N_p = T-1 \, or \, N_n = T-1), \\ |S_n|, & if \quad S_p < S_n, \\ |S_p|, & if \quad S_n < S_p, \end{cases} \quad (10)$$

where N_p and N_n are the numbers of positive and negative derivative values, and S_p and S_n are the sums of the positive and negative derivative values respectively. These heuristic penalty values are calculated based on the idea that if most of the time the derivative was higher than zero, than the negative values should be changed to positive ones, so that these time series would become feasible. The oposite action is needed if the derivative is negative. The overall modified penalty value for all the time series was Total

Penalty (TP) and used in the genetic algorithm as:

$$TP = C \cdot \left(\sum_{i=0}^{k-1} pnlty_r + \sum_{i=0}^{k} pnlty_f + pnlty_u \right) \cdot \sqrt{G}, \tag{11}$$

where C is a penalty weight constant and G is the current generation number. In this case the penalty size increases at each generation. We also used a modification of the finite automaton defined as the set of rules (7) as a constraint handling method, and its main idea was that if the system ends up in states S_3, S_4 or S_5, it means that the corresponding coefficient made at least one oscillation, which is not desirable. In this case the finite automaton returned penalty value showing that this time series is not desirable and formed the penalty function. The return value is shown as the p_i value, defined by the equation:

$$pnlty = \begin{cases} 0, & if \quad p_0, \\ c_{i+1} - c_i, & if \quad p_1, \\ c_i - c_{i+1}, & if \quad p_3, \\ |c_{i+1} - c_i| + penalty_{i-1}, & if \quad p_3, \end{cases} \tag{12}$$

where c_i is the coefficient value for the state element i, and $penalty_{i-1}$ is the penalty value for the previous state. The return value is zero in states S_0, S_1 and S_3. For states S_3 and S_4 the return value depends on the size of the oscillation tracked, and for the final state S_5 the return value was the sum of the current and previous penalty during the oscillations of the time series.

4 RESULTS

Figure 5 shows the example of the nonoscilatory dynamics on the state element for Second Lieutenant (Level element L). On the x-axis the time in years is shown. Here we consider a six year period. On the y-axis the nunber of men in the rank of Second Leutainant is shown. In this case, we have considered the reduction of the number of men from 100 to 70. It can be observed that the state element does not cause oscillations due to the applied modified finite automaton at the optimization process. Advanced optimization approaches have been descibed in (Semenkin and Semenkina, 2012b; Semenkin and Semenkina, 2012c; Semenkin and Semenkina, 2012a; Semenkin and Semenkina, 2014) with modified finite automaton (FA) (Škraba et al., 2014). Figure 6 shows the example of the nonoscillatory dynamics of the promotions on the Rate element R. Again, on the x-axis the time for the period of six years is shown. This time, on the y-axis, the rate of promotions is shown. The unit on the y-axis can be noticed which is [men/year]. As one can observe, for the case of three flows, there are no oscillations in the strategy. The system stabilizes at time $k = 5$. Figure 7 shows the dynamics on the rate elements of Fluctuations. As before, the x-axis represents time in years while the y-axis shows the rates of fluctuations with the unit of men per year. The oscillations are not present which fulfils our goal of providing a nonoscillatory strategy to achieve the desired states. All three elements, state, promotion rates as well as fluctuation rates are nonoscillatory providing the moderate policy which would lead the sys-

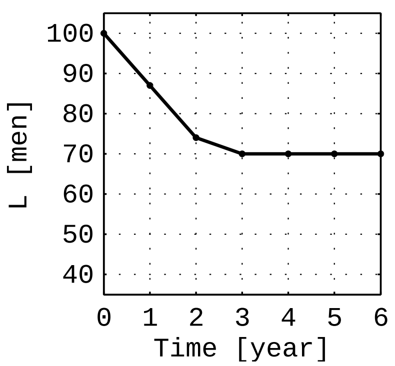

Figure 5: Example of the nonoscillatory dynamics on the state element for Second Lieutenant (Level element L).

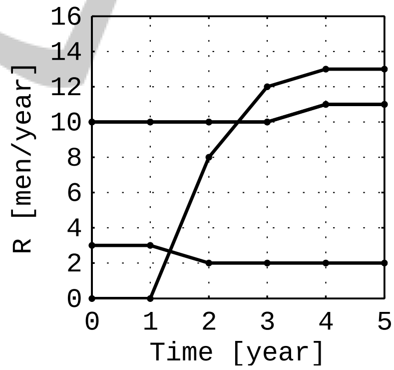

Figure 6: Example of the nonoscillatory dynamics of the promotions on the Rate element R.

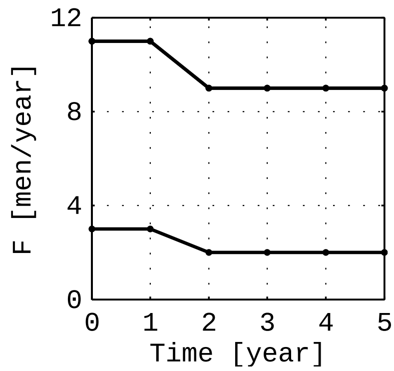

Figure 7: Example of the nonoscillatory dynamics of the fluctuations F.

tem from the initial states to the desired states in the prescribed time. Although the change might not appear to be significant, it is obvious that the strategy of the HQ could not examine oscillations since there are many activities bond to one another. Besides, that the undesired disturbances could propagate within the whole system.

5 CONCLUSION

The determinatiion of the control strategy for the hierarchical manpower system is demanding task due to the chain structure of the considered system. The system was sucessfully described in the discrete state space. Another important difficulty is time variant boundaries on the parameter values. The boundaries are also dependant on the state elements and therefore also change in time. All the mentioned conditions put the described problem in the field of `hard problems`. An additional condition is that oscillations in any of the parameters or states are not desirable. The approach with the classical dynamical programming proved that oscillations are inevitable if one only seeks the shortest time to achieve the stated goals. By the consideration of the lower and upper boundaries for the one state example, we have shown that the optimal region for a particular parameter is limited and dependent on the values of the lower and upper boundaries. Oscillations were sucessfully terminated by the application of the modified finite automaton which also considers the penalty function for the parameter discrete derivatives. The applied adaptive genetic algorithm has been tested and provides promising results for solving such complex tasks. An important issue which was not addressed in the paper is the user interface since the user has to deal with approximately 100 variables for controlling only eight ranks in the period of 10 years. The develped methodology is applicable for controlling not only the manpower systems but also similar supply chain structures where one has to deal with the bullhip effect (Kok et al., 2005). A general observation of the literature review showed that there is no single method that would provide an optimum solution for the described problem. One reason lies in the weights that could be arbitrarily applied to a particular part of the optimization problem.

Initially it would seem reasonable to define the control problem only as minimization of the distance to the target function with consideration of parameter boundaries. Here the rationale is that the target trajectory should be reached without considering the costs when rate elements are within those prescribed, i.e. normal boundaries. This kind of problem formulation would actually yield the optimum solution if one would like to achieve target values in the shortest possible time. An important finding is however the statement of the problem, where only the minimization of the distance to the target function by considering the boundaries is insufficient, resulting in possible undesired oscillatory solutions.

An important reduction of the complexity of the problem addressed was achieved by introducing the Trajectory function.

In order to complete the definition of the control problem, the acceptable strategies were described and FA were developed accordingly. The differences between two differently stated control problems were shown in examples. The application of FA provided proper results where the gained strategies did not display undesired oscillation patterns. Certainly, there is a cost that is paid for providing the proper shape of the strategy, which was shown by the different values of quadratic performance index, meaning that more time is needed to achieve the desired goal.

With the application of the developed system decision-makers were faced with considerable gaps between desired and estimated states, which were indicated by the results of the described scenarios. Experts and decision-makers were certainly roughly aware of these discrepancies, but the results provided by the developed system offered much more explicit and elaborated evidence of the problems related to future trends.

The provided real world example and solution showed that the developed approach successfully provides the strategies which could be implemented in the real-world system. According to the stated scenarios an important question concerning the attainability of a particular rank has been answered.

An important consideration in the application of optimization techniques is user interaction. Optimization methods applied are advanced, yet the system should enable user-friendly manipulation of input variables. It has to be mentioned that the user interface has a major role in the addressed optimization problem. Users try to optimize the process regardless, of advanced analytical and numerical techniques with their knowledge about the system and previous experience. A useful user interface could solve a significant portion of the problem by a simple calculation which is usually carried out *ad hoc*. The entire system for manpower planning was developed as major changes in the military system were made which had not been previously faced. Drastic changes in rank numbers yielded a new dimension to the problem of the manpower planning of officers who had to be supported by the new approach described here. However, no sophisticated numerical procedure could be successful without: a) a user friendly interface, and b) an understanding of the problem by the user. In our case, the target functions as well as the parameter boundary values are stated as time vectors. In the worst case, the user has to determine *43* vectors; *1* vector of initial states, *34* boundary vectors and *8* vectors with target trajectories in order to perform a particular optimization run. The minimal set of input data when boundaries and initial states are set automatically on the basis of historical data is the vector of goal states with terminal time.

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