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Fundamentals of the Model Behind the COSMOS Methodology Used for Team Assessment in Simulator Training

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Team working is the basic way of working in the control rooms of hazardous technologies and therefore its quality is a safety-relevant issue. In addition to the technological competence it is also crucial for the crews to have the necessary communicational skills. During simulator training these skills can only be improved if the simulator use is embedded in an appropriate setting. To support this skill acquisition a computer-supported methodology called COSMOS (COmputer Supported Method for Operators' Self-assessment) has been developed. With its help more effective communication and more complete shared mental models can be fostered. This paper is a report on the psychological fundamentals and the mathematical model of the COSMOS methodology.

team working   control room operators   nuclear power plant
simulator training   communication   social skills

1. INTRODUCTION

Urged by the experiences of major nuclear accidents—refer, for example, to Collier and Davis (1986), Reason (1987), USSR State Committee on the Utilization of Atomic Energy (1986)—great efforts have been invested to better utilise these experiences to avoid similar occurrences of such events in the future (Brown, 1990; Wilpert et al., 1994; etc.).

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As part of the aforementioned approaches aiming at learning the necessary lessons in time, recently a very explicit demand has been formulated that—in accordance with the Systematic Approach to Training (SAT) philosophy introduced by the International Atomic Energy Agency (IAEA)—a training simulator has to have an effective learning and evaluating environment. This supporting environment has to be capable of promoting the development of technical, communicational, and co-operation skills, and the evaluation of both individual and crew performance with the greatest possible objectivity (IAEA, 1989, 1990, 1991a, 1991b, 1994; Institute of Nuclear Power Operations, 1998). To meet these requirements, trainees have to be provided with carefully designed informative feedback for technical and social learning and, in addition to the usual evaluation by instructors, the possibilities of operators' self-assessment have also to be utilised. If conducted properly, self-assessment could be a powerful tool, among others, to increase objectivity, to enhance operators' self-knowledge and understanding of their fellow operators, and to improve communication skills within the group.

Our previous experiences—Antalovits and Izsó (1994)—have shown that the short evaluating sessions immediately after simulation training can be unique and psychologically extremely valuable situations that, with properly designed methods, can be used effectively to increase the preparedness of crews and, hence, the safety of operation.

A situation immediately after a cognitively demanding simulator session can be characterised by the following:

1. The experiences and memories that the crew members have of the details of simulated malfunctions, their own behaviour, and the activities of fellow operators are still quite vivid and fresh.
2. In addition to facts, the emotional flavour of a largely successful or unsuccessful situation is still remembered by the crew members as tensions, which need to be acted out.
3. The crew members still have quite definite opinions, whether correct or incorrect, about the expected roles and the actual effectivity of individual operators.
4. Video recordings and computer protocols are still available as objective sources to be drawn upon for discussion and debate.

Such a very intense learning process can begin involving not only technological knowledge and experience about their own and the others' task, but also concerning group norms, communicational skills, co-operation, and leadership effectivity. Opinions and knowledge about situations and problems to be solved, about risks, about roles expected of crew members during emergencies, and about optimal group behaviour are more realistic and more uniform as a result of this accelerated learning than they otherwise would have been.

The basic problem so far, however, has been the lack of methods with which to make use of these characteristics.

2. THE FUNDAMENTALS OF THE COSMOS METHODOLOGY

2.1. Steps of the Methodology

Based on the experiences described in the previous section, a new method called COSMOS (COmputer Supported Method for Operators' Self-assessment) has been developed (Antalovits, Izsó, & Jenei, 1995; Antalovits, Izsó, & Takács, 1995). COSMOS is a carefully designed special-purpose computer groupware that takes into consideration the mechanisms of both human errors and group dynamics. For group dynamics please refer to the relevant classic literature; for groupware design principles to Ellis, Gibbs, and Rein (1991); Grudin (1993); Newman and Lamming (1996); Shneiderman (1987, 1992); and so forth; for human errors and decision making under stress, for example, to Woods (1982); Reason (1994, 1997); Flin, Salas, Strub, and Martin (1997); Hale and Glendon (1987); Hale and Hale (1972); and so forth.

The main steps of the methodology will now be discussed.

2.1.1. Carefully designing in advance training scenarios that include identification of the key situations of a simulated emergency

Those elements of simulated malfunctions (operating conditions) that presumably will play a determining role in the decision to be made by the

TABLE 1. An Example Set of Key Situations for an Emergency Simulation Scenario

Code of key situations	Required actions from the crew for solving problems that emerged in corresponding key situations
K_1	Realising trip of Main Circulating Pump; stabilising power.
K_2	Realising Steam Generator rupture; identifying leakage.
K_3	Keeping Feed-Water Pumps in operation, keeping water level.
K_4	Realising that the loop can not be isolated; decreasing primary circuit pressure.
K_5	Adjusting appropriate cooling speed, avoiding reactor shut down.
K_6	Avoiding spreading radioactivity; isolating Steam Generator.

trainees occupying the various operator positions must be identified in advance. These elements define the key situations for which the trainees later—immediately after the training session—perform a retrospective group and individual self-assessment of their performance. An example set of key situations can be seen in Table 1.

2.1.2. Defining the key situations of the scenario and the trainees for the different operator posts to the computer right before the actual session

As part of the preparation for the simulation training the instructor puts the key situations of the scenario and the names of the trainees in different operator posts into the COSMOS software.

2.1.3. Conducting the simulation training session, recording and observing crew behaviour

All relevant information that characterises operators' activity, including interventions, behaviour, communication within the crew and between the crew and the instructor, behaviour of the team leader, and group climate is recorded by means of audio- and videotape, computer log, observation, and other methods.

2.1.4. A short discussion of the main events that actually occurred during the current exercise and redefining the key situations if necessary

Immediately after the training session the trainees and the instructor briefly discuss the main events of the session, redefining the key situations if necessary.

2.1.5. Determining and assessing perceived relative difficulties in key situations, with operators comparing pairs of situations and examining concordance within the crew

They then identify and compare the perceived difficulties in pairs of key situations, comparing in such a way only two at a time. The computer calculates the coefficients of intra-individual consistency, and group concordance data that is then projected on a large viewing screen. The consistency coefficients are defined as

$$K = 100 - \frac{2400\,a}{k_{\max}^3 - k_{\max}} \qquad \text{if } k_{\max} \text{ is odd, and}$$

$$K = 100 - \frac{2400\,a}{k_{\max}^3 - 4\,k_{\max}} \qquad \text{if } k_{\max} \text{ is even.}$$

It can happen, however, that assessments of the key situations are inconsistent. For example, if an operator judged key situation 1 to be more difficult than key situation 2, key situation 2 more difficult than key situation 3, and then key situation 3 more difficult than key situation 1, the last assessment in this three-part chain, or triad, contradicted the initial assessment. That contradiction is what we refer to hereafter as a decision loop, or inconsistent triad. In the formulas a is the actual number of decision loops (inconsistent triads) characterising individual decision contradictions, and $k_{\max}$ is the maximal number of key situations considered (actually 6 or 7).

Following this procedure the degree of group concordance is tested on the basis of the classic Kendall U statistics (Kendall, 1948). The formula adapted to our case is

$$U = \frac{\sum_{k_r, k_c}^{aggr, matr} c_{k_r, k_c}^2}{\binom{n}{2}\binom{k_{\max}}{2}} - \frac{n+1}{n-1},$$

where k_r, and k_c are the row and column indices of the aggregated difficulty matrix, respectively, n is the number of operators (in our case $n = 5$) and c is the element of aggregated difficulty matrix in the corresponding row and column. More details of the mathematical model can be found in the next section.

If all coefficients of individual consistency and group concordance are acceptable—high enough—the overall rank order is computed on the basis of a mathematical model. If this is not the case, the assessment is repeated to increase either individual consistency or group concordance.

2.1.6. Assessing fellow trainees and their own expected roles (in short also called involvement) and actual performances (in short also called effectivity) in each key situation

Having compared perceived difficulties of key situations, trainees conduct individual situation-by-situation or operator-by-operator evaluation and

Figure 1. Arrangement of the assessment session of a simulated emergency situation using the COSMOS methodology. The instructor is sitting in front of the screen and directing the session. Five crew members perform the evaluation using infrared input devices.

Figure 2. Hardware elements of COSMOS. Both the personal computer display and the large projector screen show the summarised result of the team evaluation in a graphical form.

self-assessment of expected roles (on a 3-point scale: *small*, *medium*, *large*) and performance (on a 5-point scale: *unacceptable*, *poor*, *medium*, *good*, *excellent*). Summary characteristics (and when necessary and justified also individual characteristics) are presented to the crew in graphic form on a large projector screen. If warranted by the results of discussion, assessment is repeated to increase objectivity and the degree of agreement within the group. The setting of the group self-assessment of performance and the individual self-assessment of performance is presented in Figure 1, whereas the hardware elements of COSMOS are presented in Figure 2.

2.1.7. Playing back a 2- to 5-minute video recording of the most critical key situation as a basis for making self-assessment about their own behaviour

Having the crew members view the recording of what they have judged to be the most difficult situation helps them recall the situation and refresh their memories. After watching the video clip, the crew members evaluate their effectivity in this critical situation along three dimensions: (a) information-gathering, (b) decision-making, and (c) co-operation. In addition to that they also assess their satisfaction with themselves on a 5-point scale. Operators receive global graphic feedback from these assessments in addition to summarised opinions formulated by their fellow operators. An example of global feedback is presented in Figure 3.

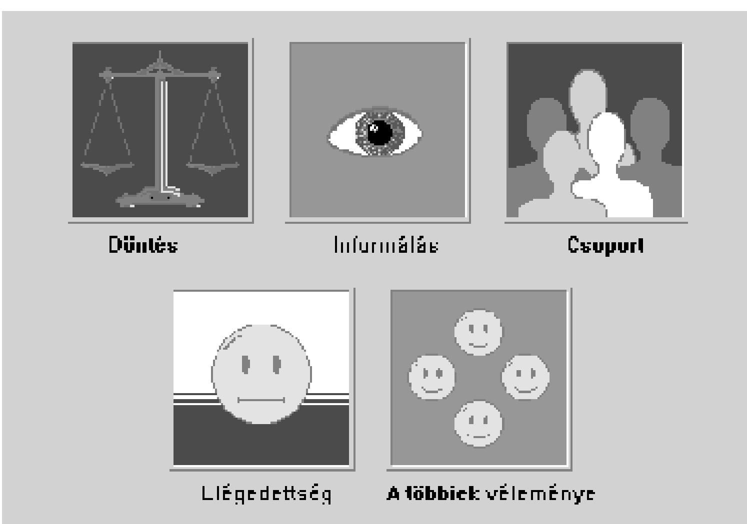

Figure 3. Global feedback of the result of an operator's self-assessment.

In Figure 3 the colour of the icon (red = poor; green = good) corresponds the qualitative aspects of the evaluation, however the proportion of filling of the icon’s frame reflects the quantitative aspects of the evaluation.

Icons represent the following self-assessing categories:

Döntés[1] = Correctness/effectivity in decision making;
Informálás = Gathering/providing information within the team;
Csoport = Personal impact/influence on team behaviour;
Elégedettség = Self-satisfaction with recent performance;

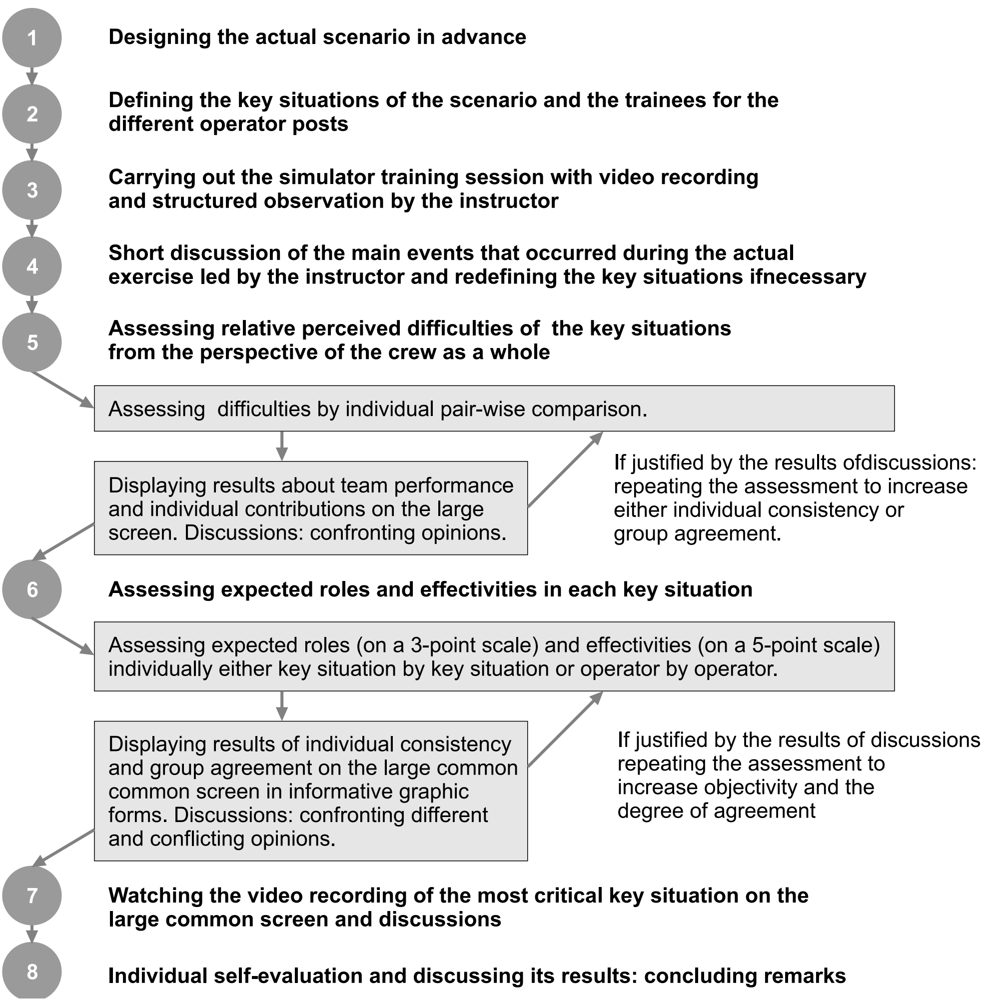

Figure 4. Flow chart of the use of the COSMOS method.

[1] Although COSMOS has an English version, it is the Hungarian version that is routinely used. That is why these screen feedback messages are in Hungarian.

Többiek véleménye = Summarised assessment of other team-members about the performance of the actual operator.

2.1.8. Reviewing results and giving detailed feedback to trainees in a discussion moderated by the instructor, concluding remarks

The instructor embeds the use of COSMOS into the process of evaluating performance. In other words, this method is never used in isolation. Rather, the instructor applies it as a flexible set of tools subordinated to pedagogical and didactic goals as a form of reinforcement. The instructor can also use the method to provoke debate by focusing on conflicting viewpoints and opinions, depending on the pedagogical context. In addition to the varied graphic feedback formats designed to inform operators, detailed and sophisticated numerical and tabular information about group and individual self-assessment is made available to the instructor by the mathematical model underlying the COSMOS method, the purpose being to deepen that person's understanding of, and insight into, group behaviour, dynamics, attitudes, and norms.

A summing up flow chart of the use of the COSMOS method can be seen in Figure 4.

2.2. A Summary of the Mathematical Model[2]

2.2.1. Testing individual consistency

Given K_1, K_2, K_3, K_4, K_5, K_6, K_7 key situations at the most (K_k, where $k = 1$, 2, 3, 4, 5, 6, or 7; that is $k_{max} = 6$ or 7), trainees are asked to compare these in pairs from the viewpoint of difficulty caused to the group as a whole (Guilford pair-wise comparison method). The pairs have to appear in random order, COSMOS uses the Ross quasi-random table for this purpose.

If $k_{max} = 6$, there are 15, if $k_{max} = 7$ there are 21 comparisons to be performed. The result of these comparisons are summarised in an individual difficulty matrix for each trainee. These matrices have k_{max} lines and k_{max} columns and contain only 0s and 1s. An individual difficulty matrix of a trainee is shown in Figure 5.

[2] A similar mathematical model for similar purposes was published earlier by Hajtman, Izsó, and Radinszky (1990).

K_1	K_2	K_3	K_4	K_5	K_6	K_7	Line total ok
K_1		1	0	0	0	0	1
K_2	0		0	0	0	0	0
K_3	1	1		1	1	0	4
K_4	1	1	0		1	1	4
K_5	1	1	0	0		1	3
K_6	1	1	1	0	0		3

Figure 5. Individual difficulty matrix of a trainee. The K_1, K_2, ... , K_6 key situations are the same as indicated in Table 1.

This trainee judged K_1 more difficult for the crew than K_2, therefore there is a 1 in the field determined by line K_1 and column K_2. Similarly, the trainee judged K_3 more difficult than K_1, therefore there is also a 1 in the field determined by line K_3 and column K_1. For reasons of symmetry it follows that there are 0s both in the field determined by line K_2 and column K_1, and in the field determined by line K_1 and column K_3.

The o_k line total is already a difficulty measure: the higher is o_k, the higher is the difficulty in the trainee's opinion. On the other hand, it can be proved that if there are some numbers repeated among o_ks, the operator is not perfectly consistent, and the number of loops can be calculated from o_k by the following formula:

$$a = \frac{k_{\max}(k_{\max} - 1)(2k_{\max} - 1)}{12} - \frac{1}{2}\sum_{k=1}^{k_{\max}} o_k^2 .$$

For example, from the data in Figure 5 the number of loops made by this trainee is as follows:

$$a = \frac{6(6 - 1)(12 - 1)}{12} - \frac{1}{2}(1^2 + 2.4^2 + 2.3^2) = 2 .$$

The question if this (or any other number of loops) is still tolerable or not is tested statistically in COSMOS by the following x^2 approximation:

$$x^2 = \frac{8}{k_{\max} - 4}\left[\frac{1}{4}\binom{k_{\max}}{3} - a - \frac{1}{2}\right] + f,$$

$$\text{where } f = \frac{k_{\max}(k_{\max} - 1)(k_{\max} - 2)}{(k_{\max} - 4)^2}.$$

2.2.2. Filtering key situations

As ambiguous formulation of key situations could also be the reason for inconsistent judgements, it is necessary to test if certain key situations are involved in loops more frequently than expected from chance distribution. For this purpose the COSMOS software finds all the loops in the five individual difficulty matrices and produces statistics about their occurrences.

If A is the total number of loops and the k-th key situation is involved in loops g_k times, the following can be written:

$$A = \sum_{i=1}^{5} a_i \text{ and } \sum_{k=1}^{k_{\max}} g_k = 3A.$$

The first formula summarises the loops by operators, whereas the second does it by key situations. With the help of the following binomial formula the model checks if the number of key situations involved in loops can still be explained by mere chance (accidental inattention of operator) or not (definite misunderstanding by the operator).

$$P_j = \binom{A}{j}\left(\frac{3}{k_{\max}}\right)^j \left(\frac{k_{\max} - 3}{k_{\max}}\right)^{A-j}, \text{ where } j = 0, 1, 2, \ldots, A.$$

These probabilities are summed up until the sum exceeds .95 thus providing a 95% level of confidence. The j index of this last P_j probability gives the g thresholds beyond which we have a good reason to believe that this particular key situation is involved in loops so often that it can not be explained by chance alone.

2.2.3. Testing the degree of relative perceived difficulties of key situations and the concordance of operators

The weights characterising relative perceived difficulties of key situations and the coefficient of concordance of operators are calculated from the aggregated difficulty matrix, the elements of which are simply the sums of the corresponding elements of the five individual difficulty matrices. An aggregated difficulty matrix of a crew is shown in Figure 6.

	K_1	K_2	K_3	K_4	K_5	K_6	Line total ck	Difficulty weight wk
K_1		0	4	5	4	3	16	0.213
K_2	5		5	5	5	4	24	0.320
K_3	1	0		1	1	0	3	0.040
K_4	0	0	4		2	0	6	0.080
K_5	1	0	4	3		0	8	0.107
K_6	2	1	5	5	5		18	0.228

$U = 0.5733$	$\chi^2 = 90.67$	$f = 33.33$	$z = 5.36 \quad (z_{5\%} = 1.645)$

Figure 6. Aggregated difficulty matrix of a crew. The K_1, K_2, ... , K_6 key situations are the same as indicated in Table 1.

The definition of w_k difficulty weight is

$$w_k = \frac{c_k}{\sum_{k=1}^{k_{\max}} c_k}, \text{ from which it follows that } \sum_{k=1}^{k_{\max}} w_k = 1.$$

From Figure 6 it can be seen that in comparing K_2 with K_1, K_3, K_4, and K_5 the crew had perfect agreement: all five operators judged K_2 more difficult. It is also seen that comparing K_5 with K_4 resulted the highest disagreement: three operators considered K_5, the other two operators K_4 more difficult.

The exact statistical testing of group concordance—as mentioned earlier—is done on the basis of Kendall U statistics, the formula of which was also presented earlier. It can be proved that the significance of Kendall U statistics can be checked by the following χ^2 approximation:

$$\chi^2 = \frac{2}{n-2}\left(\sum_{k_S,k_O}^{aggr,matr} c^2_{k_S,k_O} - n\left(\frac{k_{\max}}{3}\right)\frac{(n-1^2-2}{2(n-2)}\right), \quad f = \frac{k_{\max}(k_{\max}-1)\,n\,(n-1)}{2\,(n-2)^2}.$$

Although χ^2 and f would already be enough for testing the significance of U, for technical reasons COSMOS transforms χ^2 into a standard normal distribution by the following formula and the level of one-tailed significance is calculated from it:

$$z = \sqrt{2\chi^2} - \sqrt{2f-1}.$$

2.2.4. A summary of the main parameters of the COSMOS model

Table 2 gives a concise summary of the main parameters of the COSMOS model.

TABLE 2. A Concise Summary of the Main Parameters of the COSMOS Model

I_{ik}, Involvement of i-th operator in k-th key situation	judged by the operators on a 3-point scale
E_{ik}, Effectivity of i-th operator in k-th key situation	judged by the operators on a 5-point scale
I_k column total of the Involvement of crew for k-th key situation	$I_k = \frac{1}{5}\sum_{i=1}^{5} I_{ik}$
w_{ik} role importance of i-th operator in k-th key situation	$w_{ik} = \frac{I_{ik}}{\sum_{i=1}^{5} I_{ik}}$ (independently for each k)
H_{ik} contribution of i-th operator to group performance in k-th key situation taking into account w_{ik} role importance and w_k difficulty weight	$H_{ik} = w_{ik} \cdot w_k \cdot (E_{ik} - 1)$
H_k column total of H_{ik} (group performance in k-th key situation)	$H_k = \sum_{i=1}^{5} H_{ik}$
H_i line total of H_{ik} (total contribution of i-th operator to group performance)	$H_i = \sum_{k=1}^{k_{\max}} H_{ik}$ ($k_{\max} = 6$ or 7)
E_k column total of E_{ik} (a measure of average individual performance in k-th key situation without taking into account w_{ik} role importance and w_k difficulty weight)	$E_k = \frac{1}{5}\sum_{i=1}^{5} E_{ik}$
E_i line total of E_{ik} (a measure of the performance of i-th operator without taking into account w_{ik} role importance and w_k difficulty weights)	$E_i = \frac{1}{k_{\max}}\sum_{k=1}^{k_{\max}} E_{ik}$ ($k_{\max} = 6$ or 7)
GP group performance taking into account w_{ik} role importance and w_k difficulty weights	$GP = \sum_{i=1}^{5} H_i + 1 = \sum_{k=1}^{k_{\max}} H_k + 1$

3. RESULTS OF A CASE STUDY

As the aim of this paper, as indicated in the title, is only to present the fundamentals of the psychological and mathematical model behind the COSMOS methodology, discussing validation issues was not targeted here in more details. The main results of the validation study, however, have already been published elsewhere (Antalovits & Izsó, 1996, 1999; Izsó

& Antalovits, 1996, 1997) in a more comprehensive way. In the following therefore only a short summary of this case study is given.

After carrying out video-supported laboratory pilot studies with the COSMOS method involving members of the simulator training staff a series of validation studies was carried out in April–May 1996 at the Paks Nuclear Power Plant, Hungary, during which 10 operator crews performed their regular simulator sessions completed with the use of COSMOS by previously prepared instructors. These operator crews were made of the following five operator posts: BE = Block Electrician, SS = Shift Supervisor (head of crew), RO = Reactor Operator, TSFO = Turbine Senior Field Operator, and TO = Turbine Operator.

These sessions had the same scenario[3] to make the results comparable between crews. The results of this study are of course not the conclusions of this particular paper as its aim was only to describe the model. The interested reader can find statistical proofs in Antalovits and Izsó (1999), where, however, the description of the mathematical model is only broadly outlined. This and the present papers are therefore complementary to each other. The main results we found are listed here only for the sake of completeness.

It was found that

- careful and attentive operators are able to make consistent judgements concerning relative difficulties of six key situations within a scenario;
- shift supervisors—leaders of crews—are more consistent in their judgements than other crew members;
- the agreement in these judgements between the five crew members are generally satisfactory (if not, the reasons can easily be revealed and utilised in learning);
- the larger the numbers of inconsistencies—decision loops—concerning key situations the less those situations are understood by operators;
- (self)evaluation can effectively accelerate both technical and social learning.

Since this first trial application the COSMOS method has been routinely used, as a conclusion it can be stated that the method has been proved to be advantageously usable after simulator training sessions. It helped to identify sources of problems of misunderstandings as well as disagreements, and also provided operators with quick and meaningful feedback, accelerating the learning process both technologically and socially.

[3] This scenario was developed by the staff of the Simulator Centre and involved the six cognitively demanding key situations already presented in Table 1.

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