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On chaos control in hierarchical multi-agent systems

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Abstract. The paper is focused on the problems of chaos control in multi-agent hierarchical systems similar to the environment of the realization of automated factory projects. The research is based on a unique database of empirical studies of human faults and mistakes at the design and commissioning of factory automation systems. It is shown that for primary chaos control it is appropriate to use Design Structure Matrix (DSM) technology tools, enabling to describe synergistic relations between all teams' members on the basis of the frequency and amount of information interchange. For further chaos control an effective system is proposed to track and hinder different human shortcomings spreading in the hierarchical teamwork system. As a basis for it an advanced simulation technique, discrete event modelling, is used. The proposed methodology of suppressing the influence of human shortcomings allows us to increase the synergy in teamwork and to substantially reduce the losses of resources at starting up new factories.

Key words: chaos control, factory automation, control systems design, control systems commissioning, teamwork management, synergy deployment, Design Structure Matrix, discrete event modelling.

1. INTRODUCTION

The losses of resources at the start-up of new automated factories caused by human shortcomings reach up to 5–10% of the total labour costs and tend to increase with the growing complexity of control systems. That is without any doubt too much, thus the reasons for misspending resources should be cleared up.

It is a reality that from the engineering side automation systems have become more and more complex. Simultaneously the amount of data and number of variables circulating in these systems have enormously increased. Therefore, owing to a steady increase in systems complexity, the need for systems engineering is growing [1–3]. The above-described technical background has paved the way for a substantial increase in the role of engineering competence and human shortcomings [4]. This situation initiated a new wave of research into human shortcomings at the beginning of the present century [5].

A firm basis of any research in the field of the effectiveness of human cooperation is a realistic database of empirical studies of human shortcomings. The existence of such a unique database gives confidence about "bad" engineering and authenticity of the results attained by theoretical research, developed on this basis.

During the last 20 years, the authors' research activities have been focused on the empirical research into human shortcomings in the field of the quality of engineering design activities. First, a service database for non-safety-critical mechatronic office equipment was completed, and on the basis of it the concept of negative and positive synergy was developed [6]. Next a human shortcomings database was developed for factory automation design and commissioning, for the design of pneumatic and hydraulic control systems for industrial equipment, and for the design and production of serial light fittings. All these efforts were integrated into a fifth database, that of human shortcomings in

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quality management [7]. This database served as the starting platform for the present research, which began with compiling a new, advanced database of human shortcomings in the design and commissioning of factory automation systems. This database covers 26 automated factories on three continents, including pulp and paper mills, chemical and petrochemical plants, and power stations [8].

The experience of the research group has shown that human shortcomings can be treated as a result of negative synergy in mutual or inner communication of team members and due to the lack of competence or inability in managing the teamwork in the highly competitive environment [4]. In this context it is appropriate to define the concept of synergy used in the present paper. The word *synergy* refers to the interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects (http://www.oxforddictionaries.com/definition/english/synergy). However, synergy has a qualitative and a quantitative side. Changing the input parameters of the system may result in dramatic changes in the system's behaviour [9]. Qualitative changes in synergy have enabled using it in lattice dynamics, laser technology, superconductivity, etc. Quantitative synergy effects have been used successfully also in business and engineering. Despite the wide existence of synergy effects in nature and artefacts, in engineering the real deployment of synergy is often hidden behind the terms of optimization, rationalization, effectiveness, etc.

For a better integration of the above-mentioned matters the synergy-based approach is used in the present research, which aims to mutually compensate for teamwork weaknesses and to boost the beneficial features at joining technologies and human activities. The synergy-based approach to the start-up difficulties of factory automation systems is comparatively new, providing a real opportunity to analyse the reasons of human-based start-up impediments and to plan the measures to avoid them [10].

2. CHAOTIC BEHAVIOUR IN HIERARCHICAL MULTI-AGENT DECISION-MAKING SYSTEMS

In the calendar plan the process of automated factory design covers the drafting of the general description of the system, detailed task description for the system configuration, and a factory acceptance test, followed by commissioning. First of all, the owner names responsible persons in their team to keep watch on the progress of building a new production plant and to transfer their own requirements and necessary competence from the already existing production. Next, to run the project, a consultant company is hired to integrate all efforts of project and commissioning groups. The task of the consultancy group is to forward the owner's requirements to the process supplier(s). After that, it is necessary to collect the corresponding data from the process supplier(s), convert them into the required format, get approval from the owner, and give this input information to the automation supplier. Then the automation supplier starts system configuration, including application software programming and human–machine interface and process interface configuration. After the configuration is complete and the automation system is tested in the workshop of the automation supplier (Factory Acceptance Test), it is delivered to the factory and integrated with the process supplier's equipment. The activities continue with commissioning, where a lot of additional specialists are involved in the project team. A separate commissioning team, which includes members from project teams, is formed. Also, the end users are part of commissioning, getting trained to run the plant at the same time.

The above-described system is a hierarchy where the information of completed tasks is transferred from one team to another within the scheduled time. Such a multi-agent distributed artificial intelligence system is very sensitive to tainted information transfer [11,12]. It is inevitable that an agent's decision also depends on the decisions made by another agent higher in the information flow. If agents use tainted or imperfect information, they tend to make poor decisions. Eventually this leads to a chaotic behaviour of downward agents and the downgrading of the performance of the whole system. In such a way human shortcomings may cause real chaos in the automated factory design and commissioning. This obstacle makes the whole system extremely complicated and nonlinear.

For the present research a detailed database of human shortcomings in the design and commissioning of factory automation systems for the years 2006–2013 was compiled. The newly introduced advanced classification of human shortcomings is shown in Fig. 1.

In this new database human shortcomings are divided into three main categories: faults, mistakes, and strategic miscalculations. The faults class **F1** includes all misunderstandings in communication between the client, consultant, and the design teams or between design team members. The faults class **F2** includes all shortcomings connected with negligence. All transfers of unsuitable or late information and documentation in the design process are classified into the faults class **F3**.

The nature of mistakes is far more complicated. To this category belong wrong decisions **M1**, caused by lack of core competence. Mistakes **M2** are conditional and are caused by the impossibility of predicting the characteristics of the production process at the moment of design. They may be resolved in the course of further project activities. The third class **M3** includes mistakes

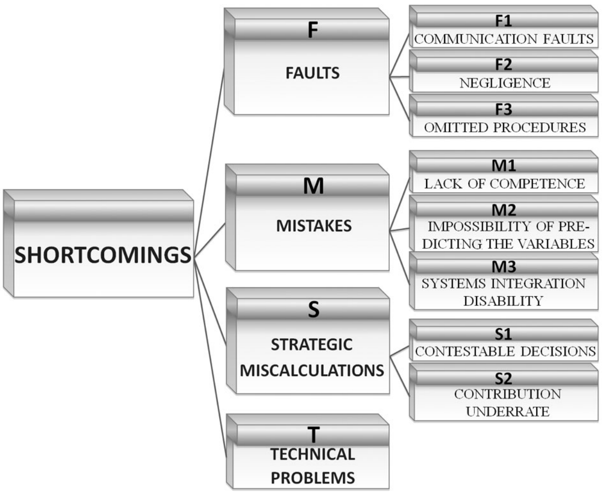

Fig. 1. Advanced classification of human shortcomings.

caused by system integration disability that leads to the situation where technologies cannot be integrated due to their different development levels.

A new, differentiated category of human shortcomings is strategic miscalculations **S**. Contestable decisions **S1** may be made due to the temptation to use cheaper or simpler technical solutions that are not able to grant the necessary operating ability and quality. Contribution underrate **S2** is a widespread phenomenon in a highly competitive society meaning that under market pressure unrealistic obligations are accepted. Technical problems **T**, which involve classical reliability problems, are a special category here.

Figure 2 presents statistics of shortcomings in the design and commissioning of factory automation systems. For obvious reasons the factories involved are confidential.

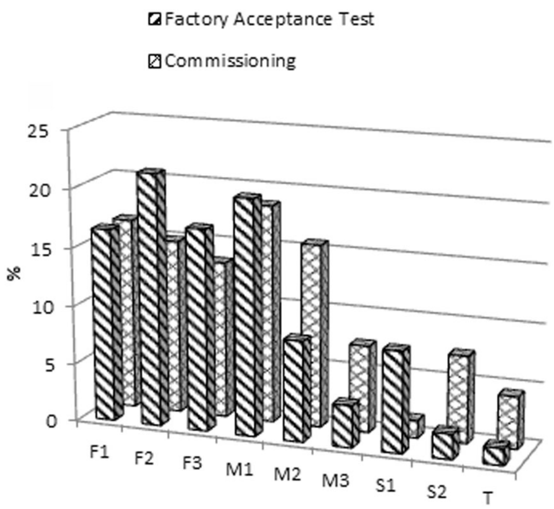

Fig. 2. Statistics of shortcomings in the design and commissioning of automated factories.

As the statistics is based on data summarized from about 26 factories, the probability of any human shortcoming during the ongoing project can be presumed. The statistics of shortcomings in a project has been on average between 1500 and 3000 working hours for teams involved in automation design and commissioning. Additionally, there are losses of profit caused by the delayed start of production. The real number and impact of shortcomings depends on the competence of the project team and also on the complexity of the task.

As any of the shortcomings may lead to chaos, its control is extremely important. Classical solutions for chaos control [11] do not apply to the present specific hierarchical task and it is necessary to find a new strategic approach to solve the problem. In the present research a two-step approach is proposed. First an exhaustive synergistic information transfer system should be created to suppress the development of chaos from the very beginning. And finally inhibitive chaos control to suppress the spreading of human shortcomings has to be developed.

The search for a powerful tool for describing human relations and grouping them on the basis of their cooperation tasks resulted in proving the Design Structure Matrix (DSM) technology to be the most suitable [5]. It allows structuring project communication according to communication intensity and profundity (none, moderate, and strong) with the target of synergy allocation. The additional value of the DSM technology is the wide choice of mathematical tools to exploit the information concentrated in the DSM matrix. The mathematical treatment of DSM communication matrixes enables computing the most capable teams, scheduling and evaluating their activities, and creating an optimal communication and cooperation scheme where the competences and capabilities of the teams and their members can be entirely exploited in the synergy deployment manner [13].

3. BASIC CONCEPTS FOR INHIBITIVE CHAOS CONTROL

The above-described discussions have led to the understanding that the best way to cut losses of resources at automated factory design and commissioning caused by human shortcomings is to create an effective system to track the different human shortcomings and hinder their spreading in the hierarchical teamwork system.

The structure of the proposed system is presented in Fig. 3. The formation zones of shortcomings are shown as integrated ones taking into account that a human fault or mistake may originate at any moment on the time scale. The same applies to the blocking zones of shortcomings. Impacts of shortcomings behind the arrows are

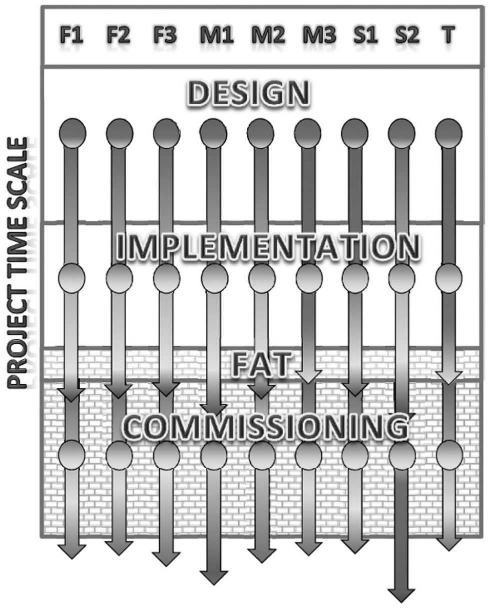

Fig. 3. Impact of shortcomings on the total project time shown by arrows as the real working hours spent on correcting specific shortcomings. FAT – Factory Acceptance Test. See Fig. 1 for designation of shortcomings.

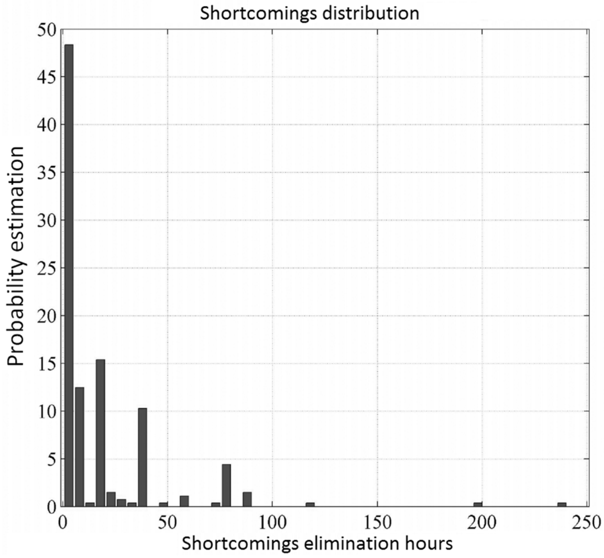

Fig. 4. Example of the probabilistic prediction of the time for the removal of shortcoming results.

the real working hours spent on the correction of a specific shortcoming impact. The overrun of the longest arrows on the time scale is conditional as it depends on how many human resources with necessary competence can be concentrated on eliminating the impact of shortcomings. As it is seen in Fig. 3, the most dramatic losses can be caused by lack of competence (M1) and contribution underrate (S2). The project time depends on the complexity and novelty of the designed factory. The simplest projects last about half a year and the more complicated ones up to 4 years; the average duration of projects is from 1 to 1.5 years.

Figure 4 shows the typical result of the histogram estimating the probability density function. It gives an idea of the probabilistic nature of any fault type presented in Fig. 3.

The formation of human faults and mistakes is fully accidental and therefore project activities are more or less chaotic. However, the chaotic nature of designing and commissioning automated factory projects never results in a catastrophe where the project has to be stopped. During commissioning all the impacts of shortcomings will be removed and production will be launched with the loss of valuable time. The profitability and competitiveness of a new factory are another question.

Planning the duration of a project has presumably a probabilistic nature leading to the field of soft computing. It is a very complicated area as at iterations the new or corrected information can appear at any moment of the process of rework. At the same time the amount of repetitive work is decreasing according to the learning curve. On the basis of probabilistic analysis of the wrong actions of decision-making agents special tracking maps can be completed to enable us to evaluate the probabilistic dangerousness of the different types of faults and mistakes. These maps are completed by integrating the synergy-based approach into information management with the use of an advanced simulation technique – discrete event modelling [14].

As an example, probability analysis for the part of a project team's communication matrix is shown in Fig. 5. An incline to longer periods is clearly visible in the figure. This is typical for situations where the real duration of the project is close to the pessimistic presumption about the project time.

Discrete event modelling allows computing probability distribution of lead time in the project network where iterations take place among sequential, parallel, and overlapping tasks. So we reach a complete treatment of the evaluation of the time losses due to the

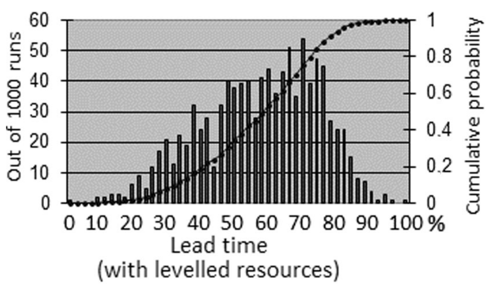

Fig. 5. Possible duration of the project as a discrete event modelling result.

faults and mistakes in information transfer taking into account the necessary iterations, reworks, and learning curves [14].

The findings of the present research allow us to aver that the full picture about the formation of human shortcomings, their impacts, and blocking activities has been attained. It was proved that the most powerful effect on the neutralization of human shortcomings could be achieved by increasing synergistic information transfer procedures between all project teams and their members. As a result, a concept for the probabilistic evaluation of project duration is proposed, which is of great importance in the project planning stage.

4. CONCLUSIONS

The research efforts in the area of automated factory design and commissioning have given sufficient evidence that most of the troubles with quality are caused by shortcomings in human activities. It is shown that the Design Structure Matrix (DSM) technology is a capable tool for suppressing human shortcomings. This technology enables us to visualize the synergy relations in information interchange between working groups of development projects as well as between the group members. The DSM technology allows us to form the most capable teams and to schedule their activities and predict the time necessary to complete the project. The proposed methodology of tracking and hindering human shortcomings at automated factory design and commissioning presents an opportunity to increase synergy in teamwork and so to substantially reduce the losses at starting up new factories.

REFERENCES

1. Seilonen, I., Pirtioja, I., and Koskinen, K. Extending process automation systems with multi-agent techniques. *Eng. Appl. Artif. Intel.*, 2009, **22**, 1056–1067.
2. Samad, T., McLaughlin, P., and Lu, J. System architecture for process automation: review and trends. *J. Proc. Contr.*, 2007, **17**, 191–201.
3. Jämsä-Jounela, S.-L. Future trends in process automation. *Annu. Rev. Control*, 2007, **31**, 211–220.
4. Kaljas, F., Källo, R., and Reedik, V. Human aspects at design of mechatronic systems. In *Proceedings of the 9th Mechatronics Forum International Conference, Ankara, 30 Aug – 1 Sept 2004*. Atilim University Publications, 2004, 147–157.
5. Eppinger, S. D. A planning method for integration of large-scale engineering systems. In *Proceedings of the International Conference on Engineering Design ICED'1997*. Tampere, 1997, 19–21.
6. Tähemaa, T. and Reedik, V. Positive and negative synergy at mechatronic systems design. In *Proceedings of International Conference Nord Design 2000*. DTU Publications, Copenhagen, Denmark, 2000, 35–44.
7. Hindreus, T. and Reedik, V. Synergy-based approach to quality assurance. *Estonian J. Eng.*, 2009, **15**, 87–98.
8. Källo, R., Eerme, M., and Reedik, V. Ways of increasing synergy in automated factory design and commissioning teamwork. *J. Mater. Sci. Eng. B*, 2013, **3**(9), 597–604.
9. Haken, H. *Synergetics*. Springer-Verlag, Berlin, 2004.
10. Hindreus, T., Kaljas, F., Källo, R., Martin, A. Tähemaa, T., and Reedik, V. On synergy deployment in engineering design. *J. Mater. Sci. Eng. B*, 2012, **2**(6), 408–413.
11. Ivancevic, V. G. and Ivancevic, T. T. *Complex Nonlinearity: Chaos, Phase Transitions, Topology Change and Path Integrals*. Springer-Verlag, Berlin, 2008.
12. Mikhailov, A. S. and Calenbuhr, V. *From Cells to Societies: Models of Complex Coherent Action*. Springer-Verlag, Berlin, 2002.
13. Eppinger, S. D. and Browning, T. *Design Structure Matrix Methods and Applications*. Massachusetts Institute of Technology, Cambridge, MA, USA, 2012.
14. Cho, S. H. and Eppinger, S. D. Product development process modelling using advanced simulation. In *Proceedings of ASME Design Engineering Technical Conference DETC'01*. Pittsburgh, Pennsylvania, USA, 2001, 1–10.

Kaose juhtimisest paljuagentsetes hierarhilistes süsteemides

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On käsitletud kaose juhtimist paljuagentsetes hierarhilistes süsteemides, mis on iseloomulik ka tehaste automatiseerimisprojektide käivitamise protsessidele. Uurimus põhineb unikaalsel inimlike vigade ja eksimuste empiirilisel andmebaasil, mis on kogutud paljude tehaste automaatjuhtimissüsteemide projekteerimise ning käivitamise käigus. On tõestatud, et esmaseks kaose juhtimiseks sobib suurepäraselt projekteerimise struktuurimaatriksite (DSM) tehnoloogia, mis võimaldab sünergiapõhiselt kirjeldada seoseid kõikide meeskondade liikmete vahel, lähtudes nende omavahelise infovahetuse sagedusest ja mahust. Edasiseks kaose juhtimiseks on välja pakutud efektiivne süsteem inimlike vigade ja eksimuste jälgimiseks ning tõkestamiseks meeskondade hierarhilises koostöös. Süsteem põhineb kõrgetasemelisel simulatsioonitehnikal: diskreetsete sündmuste modelleerimisel. Pakutud metoodika inimlike vigade ja eksimuste tõkestamiseks tagab meeskonnatöö suurema sünergia ning seeläbi aitab uute tehaste käivitamisel oluliselt vähendada organisatoorseid kulutusi.