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ON SYNERGY DEPLOYMENT IN ENGINEERING DESIGN

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Abstract: *An overview of the progress in the deployment of synergy effects in engineering design is presented. On the example of the development of fludic sensors the difficulties to discover qualitative synergy through experimental search of are evaluated. It is arrived at the truth that using the tools of computational intelligence may be the faster way to the solution. Further the paper is focussed on the latest research efforts in the quantitative synergy area where engineering design quality is concerned. The success in the development of adaptive tools for synergy-based design of interdisciplinary systems is analysed. It is shown that using the synergy-based design approach in quality management context makes it possible to create an effective synergy-supported quality assurance environment.*

Keywords: synergy, engineering design, human shortcomings, quality assurance, soft computing

1. INTRODUCTION TO THE SYNERGY TREATMENT

In the beginning it is necessary to define the concept of *synergy* used in the present context. According to Oxford Dictionary the word *synergy or synergism* refers to the integration or cooperation of two or more drugs, agents, organizations, etc. to produce a new or enchanced effect compared to their separate effects. So there must be “something” that makes integration successful and it is called (positive) synergy. However, sometimes we are also the witnesses of unfortunate integration and it is called *asynergy* (negative synergy). However, synergy also has a qualitative side, where changing the input parameters of the system results in dramatic changes in the system’s behaviour. The reason for such changes is allocating the system to order or enslaving parameters that can be interpreted as the amplitudes of the macroscopic patterns at the self-organisation of microscopic ones [1]. Qualitative changes in synergy have enabled to use the lattice dynamics, laser technology, superconductivity etc. However, the same synergy may result in unfortunate piling up of negative inputs leading to the situation of catastrophe.

The synergy-based approach has been used successfully in physics, chemistry, sociology, medicine, business and also in engineering [2]. Despite the wide existence of synergy effects in nature and artefacts, the real deployment of synergy in engineering is often hidden behind the terms of optimization, rationalization, effectiveness, self-development etc. Probably the best example of using the synergy-based approach in engineering is ferroconcrete where the compensation of mutual weaknesses and amplifying their common useful effects (physical optimisation) has an outstanding effect. Observing the nature we are witnesses to general striving to synergy caused by natural selection. From the beginning of ages people have been trying to find synergy of their activities which has also been transferred to the development of artefacts. Already Aristotel noticed that the whole is bigger than its components. It is quite natural that at solving an engineering task all activities must be aimed at attaining maximum positive synergy and pressing down negative synergy.

It is obvious that synergy problems cannot be treated with scientific methods of reductionism as they reveal themselves only in complexity of nonlinear dynamics and may be followed by tools of computational intelligence (soft computing) integrating fuzzy technology, artificial neural networks and genetic algorithms [3]. The key to synergy is optimisation in its wider interpretation including its logical, mathematical and physical basis. So such a type of optimization may be aimed at attaining the maximum synergy level for safety-critical products like space and nuclear technology. However, for non-safety-critical products the optimization of the synergy level is market-driven and closely related to the moral aging and wearing of the products. In order to strike a high level of reliability, and therefore low service dependability, the cost of the product rises and it is difficult to sell. If the dependability is too high, the level of warranty costs rises, the service network must be expanded and the reputation of the organisation may suffer. To guarantee successful business it is necessary to find a clever compromise between the previously described matters in the quality level of products designed.

2. SEARCH FOR QUALITATIVE SYNERGY

At the birth of the science of synergetics in the late 1960s, the only way to explore synergy effects was experimental research. Unfortunately, such a search for synergy in technical artefacts and processes has been quite accidental, needed good intuition and was very time-consuming. The experimental research here was based on looking for Ginzburg-Landau order or Haken's enslaving parameters where a system's behaviour changes dramatically [1; 3]. The research into fluidic interruptible and conical jet backpressure sensors has proved that suitable order parameters can be found as a result of a capacious experimental research which might last up to some years. The classical experiments' planning strategies were of no help as they exclude nonlinear dynamics and therefore also the synergy in the examined processes from the beginning.

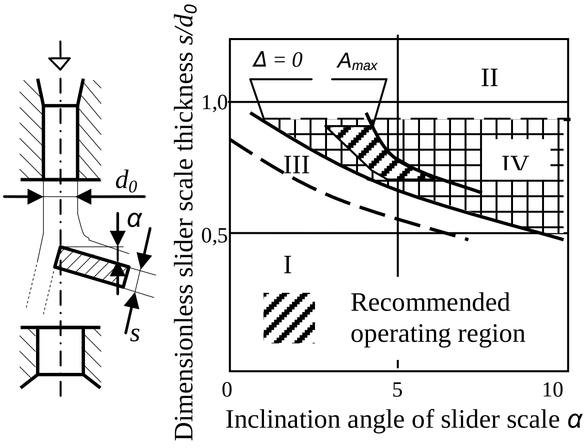

Fig. 1. Areas with different states of the interruptible sensor's working regime

I – pure deflection (analog output signal);

II – high hysteresis of switching;

III – unstable tearing off and reattaching the jet to the edge of scale;

IV – high accuracy aerodynamic effect (relay output signal);

Δ – hysteresis of switching;

A_{max} – amplitude of the output relay signal.

Let's follow the story of discovering the high accuracy aerodynamic effect in the interruptible jet position sensor shown in Fig. 1. Such a sensor is based on the inclination of the laminar or turbulent jet by penetrating an inclined cross riding scale into it that causes the pressure change in the outlet canal of the sensor digitalised by the pneumatic threshold element. At the end of 1960s the accuracy of such position sensors was around ± 0.01 mm. The reason for low accuracy is the high noise level of turbulence and high hysteresis of sticking and tearing off the jet from the edge of the scale. For creating a linear pneumatic sensor it was necessary to achieve an accuracy of at least ±0.0025 mm or 4 times more of the existing solution at that time.

In this hopeless situation a hypothesis was set up that in this type of sensors parameters room must be the combination of dominating parameters calling forth dramatic qualitative changes in the aerodynamics of the sensor leading to a remarkable sensitivity growth of the described sensor. A very capacious experimental research was initiated, covering all room of the possible sensor's parameters, using high accuracy mechanical modelling combined with experiments provided under the microscope. It needs about 1.5 years of intense experimental research when one of the most promising qualitative synergy changes in the sensor's behaviour was reached (see Fig. 1). In a very limited combination of few dominating parameters – the laminar jet, inclined scale and certain ratio of scale thickness to the laminar jet diameter – a tiny area was found where the so-called high accuracy aerodynamic effect occurs. The effect allows building up sensors with unbelievable accuracy for that time ± 0.0006 mm [4]. In this figure there is an interesting combination of qualitative synergy (closing to the area of high accuracy aerodynamic effect from the area of high hysteresis of switching II) and quantitative synergy (closing to the same area from the area of pure deflection I). From the outside view the accuracy of this sensor is based on very sensitive sticking and tearing off of the jet from the inclined scale edge with a built-in threshold function into aerodynamics of this process. Only later, during a joint research at London City University the essence of the accurate aerodynamic effect was opened [5]. As a result of the visualization of the process of interaction of the jet and penetrating into it scale, it was proved that the accurate aerodynamic effect is based on a very sensitive balance of sticking the core of the jet to the scale edge due to local turbulisation and tearing it off by forces formed at the impingement to the scale by the outside layers of the jet. This experimental research was already supported by computer modelling using finite volume modelling software PHOENICS which enabled to understand the aerodynamic processes better. After that it was possible to build up the theoretical model of the interaction of the laminar jet and inclined scale.

The success in increasing the accuracy of the interruptible sensors encouraged to use the same philosophy at pneumatic conical and triangular nozzle backpressure sensors. The research hypothesis was similar to the previous research. The huge amount of experimental work met with success – the order parameters symptomatic to synergy were found where in the sensor's recirculation bubble, which is formed by the jet and the detected object, an aerodynamic resonance occurs which in its turn is very sensitive to positioning [6]. The use of this resonance effect allows increasing the accuracy of the positioning sensors of this type about 2.5 times.

So it was proved that the qualitative synergy landmarks – the Ginzburg-Landau order parameters – can be found in an experimental way. In those times there was no alternative way to carry out capacious experimental work to attain the goal. However, already at that time it was possible to understand the established synergy by solution or modelling of the complicated nonlinear differential equations. However, it was impossible to discover the parameters' area where the qualitative synergy effects occur. This situation changed only in the middle of the 1990s when the concept of computational intelligence was established [3]. The ultimate precondition for the search of qualitative synergy is the use of genetic algorithms. Integrating genetic algorithms with fuzzy technology and artificial neural networks into the framework of soft computing has an impact on the analytical approach to synergetics opening faster ways to reach synergy effects.

3. QUANTITATIVE SYNERGY IN ENGINEERING

During the last 15 years our team's research activities were focussed on empirical research of quantitative synergy in the field of engineering design quality. In other words the research efforts were devoted to fighting against the so-called "bad" engineering using the synergy-based approach to empower quality assurance. Talking about synergy and quality relations it is possible to notice that everything that is done to achieve bigger synergy leads to better quality. Looking into the field of quality assurance it is possible to set up a hypothesis that the quality of artefacts depends fully on synergy in human activities creating this artefact.

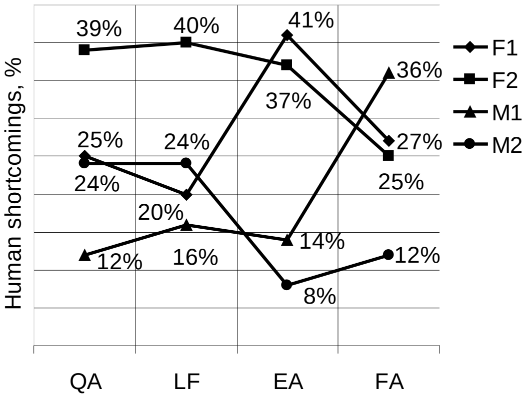

Fig. 2. Comparative analysis of human shortcomings

To prove this approach a wide empirical research into human activities in engineering design was initiated covering different levels of its complexity. 4 unique databases of human shortcomings were compiled, the results of the comparative analysis of which are shown in Fig. 2. However, first of all, the abbreviations used in Fig. 2 should be specified. In the first column the human shortcomings revealed at quality certification (QA) of more than 200 production companies are presented [7]. In the second column the results of human shortcomings in the design and production of a serial product – light fittings (LF) – are given. The scope of this database is 5 years and more than 700 descriptions of human and technical shortcomings are analysed [8]. In the third column the data on human shortcomings for the design and application of equipment control systems (EA) are presented where the experiences of 13,000 cases were analysed [9]. In the last column the data on the design and commissioning process of factory automation systems (FA) are given. The basis for the last column is the experience of applying 5 large factory automation systems [9].

On a large scale all the revealed human shortcomings can be divided into faults **F** and mistakes **M.** Faults are wrong decisions that have no justification. Communication misunderstandings between the client and the design team or the members of the design team belong to the faults' category **F1**. To the category of faults **F2** belong all shortcomings connected with negligence. Faults may be treated as a result of negative synergy in teamwork or a person's inner negative synergy. Mistakes have a far more complicated nature. To this category belong wrong decisions **M1**, caused by lack of core competence in engineering design and accompanying technologies or in quality management activities. The only way to reduce the mistakes **M1** lies in upgrading the staff. Another category of mistakes **M2** is conditional and is caused by unknown matters at the moment of design and may be sometimes cleared up in further testing and maintenance of the designed equipment.

While compiling these databases a lot of efforts were made to clear up the border between human shortcomings and technical reasons (reliability) on different complexity levels of engineering design [10]. It was arrived at the truth that it is very difficult to distinguish between the failures due to reliability problems (wear, aging of the materials, etc.) and those which occurred because of wrong decisions at the choice of materials. In the systems assembled from maturity components the comparative importance of technical problems is marginal and therefore they are not shown in Fig. 2. Also, it can be difficult to detect the borderline between average negligence and negligence caused by physiological fatigue or stress due to wrong organisation of work. Summarising the points discussed above one can see that the majority of the problems accompanying "bad" engineering are caused by human shortcomings.

An analytical background to the described teamwork of engineering design is supported by joint action and adaptation psychodynamics based on adaptive path integrals and topology change [3]. Studies of human co-action suggest [11] that cognition and neural processes supporting co-operation include joint attention, action observation, task sharing and action coordination. The joint performance of engineers depends on how well they can anticipate each other's actions. In particular, better coordination is achieved when individuals receive real-time feedback about the timing of each others actions. The model of dynamics of co-action may be built up on Riemann n-dimensional Life-Space manifold of time-dependent trajectories of the actors [12].

As a practical outcome of the described research, a new methodology for the product development of interdisciplinary systems based on the synergy of integration of allied technologies and engineering power has been evolved in recent years. In this context a new family of adaptive design tools has been developed based on the level of competence and expert knowledge of the design team to synthesize their own roadmap algorithm to move ahead on the way of design process [13]. The proposed methodology makes it possible to take into account both "soft" parameters of integration – market conditions and human aspects. The second practical outcome is the use of synergy effects in quality assurance by developing a novel approach to empower synergy-based human activities in the framework of quality management. The involvement of synergy in the quality assurance process is possible by integration of design and quality management dependency structure matrixes [14]. An important step is to evaluate all possible interactions from the point of their possible synergy: 0 – synergy is marginal, 1 – synergy may be moderate and 2 – synergy is strong. The most important task is to determine which interactions should be allocated to synergy-based optimisation taking into account market driven financial and time resources. So far the choice of interactions in matrixes allocated to synergy optimisation has been based on intuition and focussed on stronger interactions. It is highly qualified and time-consuming to compose useful and suitable dependency structure matrixes and it may be a great challenge to the team as professional knowledge of product architecture, the product development process and quality management experience is simultaneously required.

4. CONCLUSIONS

In the present paper the problems of attaining synergy at the engineering design of interdisciplinary systems are discussed. On the example of fluidic sensors development it is arrived at the truth that it is too time-consuming to discover qualitative synergy through experimental search and that using the tools of computational intelligence may be a faster way to the solution. Due to the progress in soft computing in the past 10-15 years synergy-based optimization has changed into an increasingly widening field of optimization in engineering.

The latest research efforts in the quantitative synergy in the area of engineering design quality have given sufficient evidence that most of the troubles with quality are caused by shortcomings in human activities. It is shown that by using the synergy-based approach it is possible to develop adaptive tools based on the level of competence and expert knowledge of engineers in the company to synthesize their own roadmap algorithm to move ahead on the way of quality assurance.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Haken, H. *Synergetics.* Springer-Verlag, 2004.
2. Mikhailov, A. S., Calenbuhr, V. *From Cells to Societies: Models of Complex Coherent Action*, Springer-Verlag, 2002.
3. Ivancevic, V. G., Ivancevic, T. T. *Complex Nonlinearity: Chaos, Phase Transitions, Topology Change and Path Integrals.* Springer-Verlag, 2008.
4. Leschenko, V. A., Pochtar, J. S., Reedik V. Fluidic Transducers for Sensors of Exact Positioning Systems. *Control Systems and Devices*, 1974, **1**, 40-42. (in Russian)
5. Neve, R. and Reedik, V. An Experimental and Theoretical Investigation of the Interaction between Jet and Penetrating Inclined Scale in Positioning Elements, In *Proceedings of 7th Cranfield Fluidic Conference,* Stuttgart, Germany, 1975, D1-1-D1-16.
6. Reedik, V. Ways of Achieving Desirable Output Parameters of the Fluidic Proximity Sensors, *Fluid Control And Measurement,* Pergamon Press, Tokyo, 1985, 577-584.
7. Hindreus T., Reedik, V. Synergy-Based Approach to Engineering Design Quality. In *Proceedings of International Conference NordDesign 2006.* University of Iceland, Reykjavik, 2006, 158-168.
8. Martin, A., Kaljas, F., Reedik, V. Synergy-Based Approach to Bad Engineering, In *Proceedings of the 8th Biennial Conference on Engineering Systems Design and Analysis*, ASME Publications 1746CD, ESDA2006-95432, 2006.
9. Kaljas, F., Källo R., Reedik, V. Human Aspects at Design of Mechatronic Systems. In *Proceedings of the 9th Mechatronic Forum International Conference.* Atilim University Publications, Ankara, 2004, 147-157.
10. Tähemaa, T., Reedik, V. Positive and Negative Synergy at Mechatronic Systems Design. In *Proceedings of International Conference NordDesign 2000,* DTU Publications, 2000, 35-44.
11. Fogassi, L., Ferrari, P.F., Gesierich, B., Chersi, F., Rizzolati, G. From Action Organisation to Intention Understanding. *Science,* 2005, **29**, 662-667,
12. Ivancevic, V., Aidman, E. Life-Space Foam: A Medium for Motivational and Cognitive Dynamics, *Physica*, 2007, A **382**, 616-630.
13. Kaljas, F., Reedik, V. On Using the DSM Technology Approach to Synergy-Based Design of Interdisciplinary Systems. In *Proceedings of the 15th International Conference on Engineering Design ICED 05.* Institution of Engineers, Melbourne, Australia, 2005, 498-499.
14. Hindreus, T., Reedik, V. Synergy-Based Approach to Quality Assurance, *Estonian Journal of Engineering,* 2009, **15**, 87-98.

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