NordDesign 2006
August 16 - 18, 2006
Reykjavik, Iceland

# Synergy-Based Approach to Engineering Design Quality

**Tiit Hindreus and Vello Reedik**

Institute of Machinery
Tallinn University of Technology
*vello.reedik@ttu.ee*

## Abstract
The present paper is focussed on the research of human behaviour in quality management environment of the engineering design process where product development planning, design and resource management, product realization process and its analysis are also concerned. The main goal of the present research is to make clear the essence of the so-called "bad engineering", concentrating on the specification of its human and technical aspects. The statistical results are presented covering most common human faults/mistakes at the design and application of the different complexity artefacts. The research scope ranges from factory automation and equipment control systems to the design and realization of lightfittings and follow-up product development of office machines. Special attention is paid to the analysis of human shortcomings cleared up at quality management systems certification. To avoid bad engineering a framework for the synergy-based design of interdisciplinary systems is presented capable of adapting to the competences of the design team.

*Keywords: Product development, quality management, engineering design, design structure matrix, synergy-based design.*

## 1 Introduction
The diving force of the research is to find an effective approach to fighting against the so-called "bad engineering" in such sensible areas that need the integration of engineering skill and knowledge from different fields of technologies. For a long time there has been hope that it is possible to compensate and overcome shortcomings in engineering design by planting strict prescriptive design methodologies. Now it is generally accepted that engineering design is not a pure technical problem any more but a complex activity, involving artefacts, people, tools, processes, organisations and conditions of the real economic environment. Depending on the above-described change of the engineering design paradigm a new wave of research into human behaviour in engineering activities can be noticed.

However, the product quality continues to be a key driving force of the product development process. The main difficulties related to the quality dimension are associated with the matter that it is at the same time both a perceptual and a technical concept [1]. It is obvious that maximum quality is attained in safety-critical systems, like space, nuclear and military technology. The cost of these products is an order higher than the same purpose consumer goods. As a result, quality and reliability problems for non-safety-critical products have changed into market driven factors. 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, and the service network must be expanded and the reputation of the organisation may suffer.

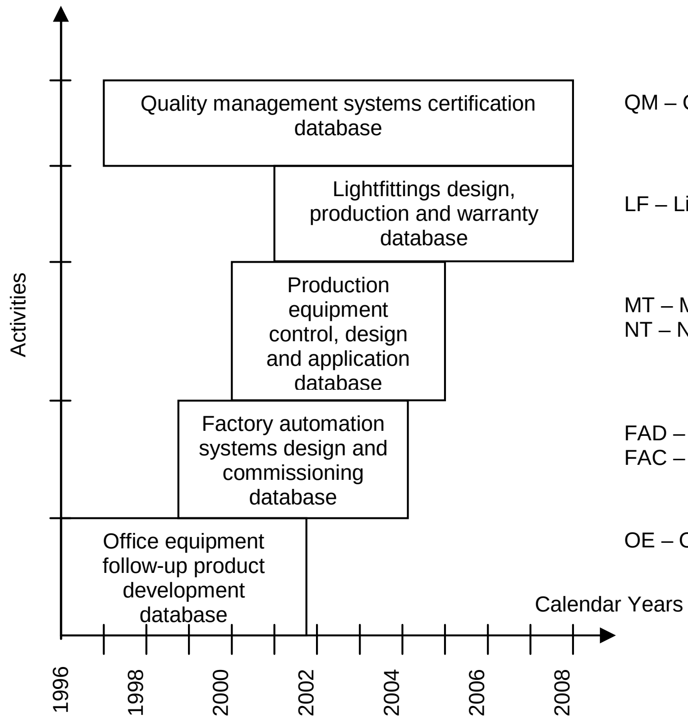



**Figure 1. Development of human shortcomings databases**

The ever-growing competition on the markets has caused the need for radical cuts in product development time and therefore more frequent renewal of product models. Therefore new products have to be developed in conditions of limited feedback information concerning the reliability and performance of previous products. That has put the industry into a difficult position and has forced it to change the design for quality and reliability paradigms. As a result, the influence of human factors on new product development is growing remarkably. In this situation, it is appropriate to study the real essence of the so-called “bad engineering”, concentrating on the specification of its human and technical aspects. However, there are still few and dispersed data available about the quantified influence of human shortcomings in full-scale engineering activities from the early stages of design towards the application and follow-up product development. An analysis of the compiled human shortcomings databases (see Fig.1) has given a good chance to solve this problem. At the same time it is a very sensitive domain and so for understandable reasons the companies involved are anonymous. To evaluate the validity of findings it is necessary to underline that the companies concerned are worldwide known strong contributors to the field of engineering.

Returning to Fig. 1 it is seen that the variety of databases almost covers the complexity of different areas of engineering design. At first a 5-year service statistics database for non-safety-critical mechatronic office equipment was compiled where 4 generations of office machines were under observation [2]. The database consists of up to 3,000 service actions solved in 2,000 work hours with the total turnover of 350,000 EUR. The second database for shortcomings of factory automation was completed for two levels: for factory automation design **(FAD)** and for commissioning process **(FAC)**. In general, **FAD** is virtual arranged at the system supplier's factory and ends by Factory Acceptance Test (FAT). During **FAC**, the plant begins, for the first time, to produce the product that it has been built for. The basis for this database is the experience of applying 5 large factory automation systems [3]. The third database of human shortcomings is completed for equipment control systems where the experience of 13,000 design and application cases are analysed [3]. At equipment control systems the cooperation between customers and the systems' design and application teams is so close and intertwined that only a joint analysis of shortcomings is possible. But in this case quite an interesting difference between well-established maturity (**MT**) and comparatively new technologies (**NT**) can be observed. The fourth database **LF** was compiled for the analysis of human and technical shortcomings in the design and production of a serial product – lightfittings. The scope of this database is also 5 years and more than 700 descriptions of human and technical shortcomings are analysed. The fifth database **QA** is focussed on the research of human behaviour in quality management activities of the product development process where product development planning, design and resource management, product realization process and its analysis are also concerned. The 10-year database of human behaviour is compiled where the results of more than 200 production companies' real quality management systems certification processes are analysed. This database serves as an integrating basis of the earlier compiled databases.

## 2 Human shortcomings analysis of systems design and application

In this part of the paper mainly statistical results of the separation of human shortcomings and technical problems at systems design and its application are presented. However, it is appropriate, at first, to specify the terms used in the further analysis. On the large scale (see Fig. 2) all shortcomings revealed in the process of interdisciplinary systems design and application may be divided into faults **F**, mistakes **M** and technical problems **T.** Faults are wrong decisions that have no justification. Communication misunderstandings between the client and the design team or between design team members belong to the faults' category **F1**.

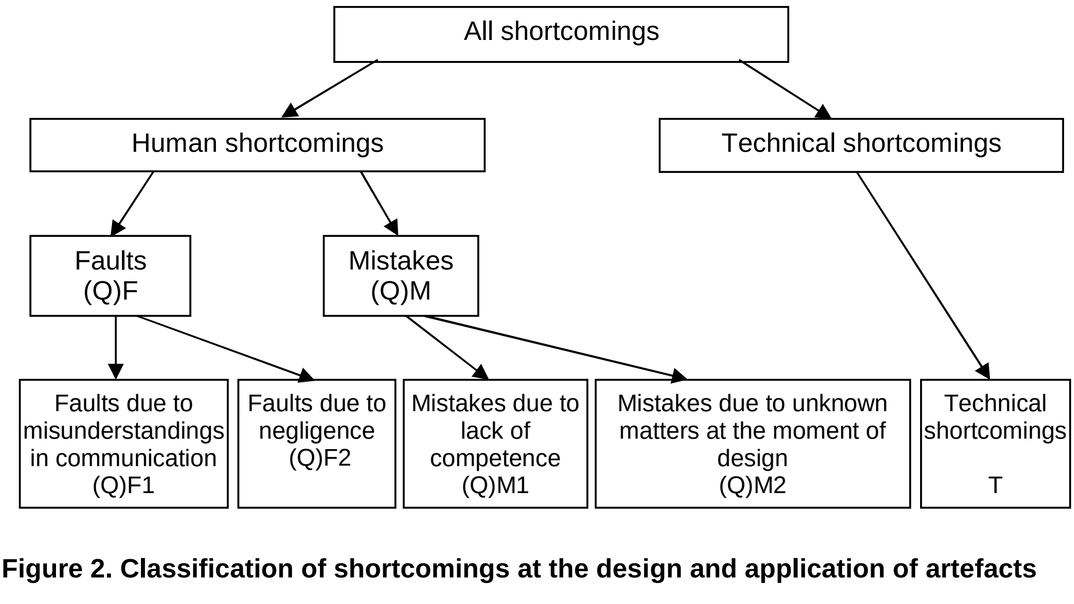



**Figure 2. Classification of shortcomings at the design and application of artefacts**

To the category of faults **F2** belong all shortcomings connected with negligence. Mistakes have a far more complicated nature. To this category belong wrong decisions **M1**, caused by lack of core competence in the integration of different technologies. Another category of mistakes **M2** is conditional and is caused by unknown matters at the moment of design and they may be resolved in further research or during the system's testing or use. A special category here is technical problems **T** where classical reliability problems are involved. Unlike the above-described classification in the quality assurance system database all shortcomings are marked as **QF** and **QM.**

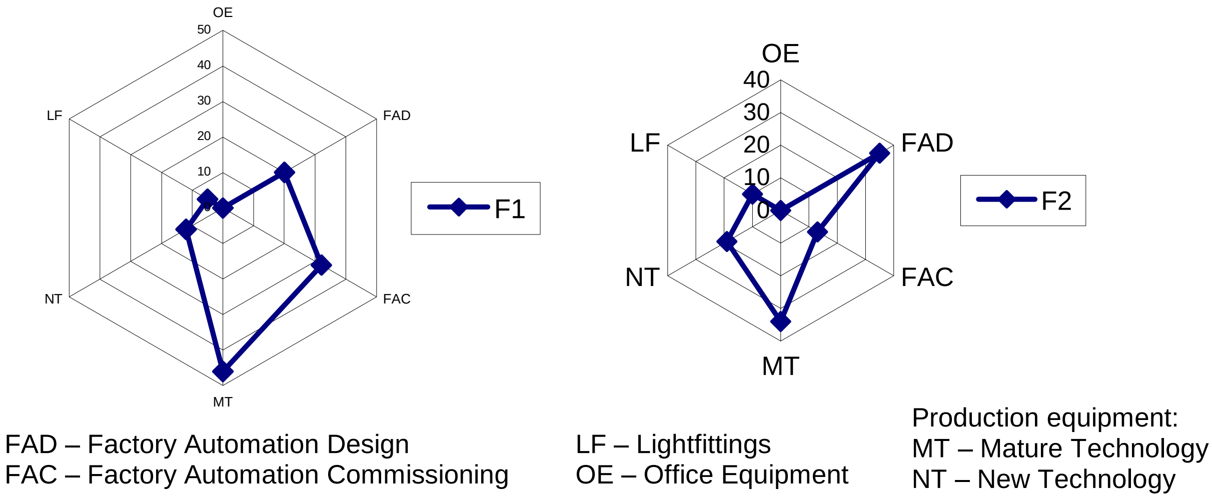
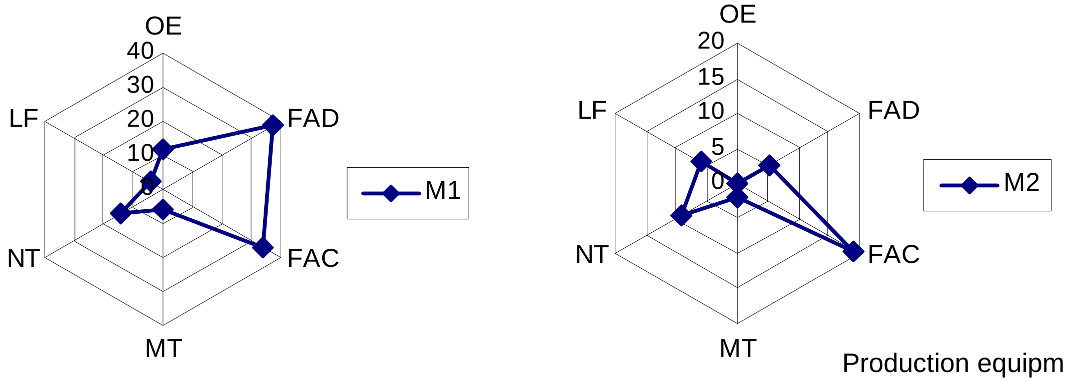



**Figure 3. Analysis of human faults**

In Fig. 3 the statistics of the faults **F1** is presented. On the vertical axis of radar diagrams the percentage scale of present shortcomings in the whole basket of shortcomings is indicated. In the office equipment service database **OE** the user faults were classified as lack of competence and therefore faults have here 0 value. Factory automation databases show the comparatively high share of faults **F1**. These faults are mostly born on grounds of inadequate initial information, difference of understanding in component functioning, late proposals for the user interface, fragmentary perceptions concerning the functioning of the whole system, etc. At first sight there seems to be a surprising relation between faults **F1** and **F2** in the **NT** database. However, it is necessary to take into account that the dominating share of technical shortcomings in the **NT** database compresses the share of other shortcomings. In the category of **F2** at the **LF** database the main reason of faults has been too high self-confidence and loss of attention and self-control while doing fatiguing repetitive work. In the **FAD** database comparatively simple faults **F2** dominate that can usually be easily corrected by changes in software. In the **FAC** database faults in the cabling and installation of sensors and drives dominate.

In Fig. 4 the statistics of the shortcomings due to the human mistakes is presented. The mistakes **M1** and **M2** in the **LF** database are trivial, as the factory is specialised in the production of lightfittings and the staff are experienced and stable. However, some lack of knowledge in materials and electronics behaviour at high temperature can be perceived. In factory automation databases the share of mistakes **M1** clearly dominates. It is mainly due to the incompetence of the design team in the main technological process. In the **OE** database the bad engineering side certainly comprises the combined failures **M1** mainly caused by the wrong integration of technologies.

In the category of mistakes **M2** tuning and regulation dominate, as the prognosis of preset parameters may appear to be wrong for the real conditions. The elimination of these mistakes needs some new knowledge about the real processes and automation system functioning. It is clear that the database **NT** and especially **FAC** lead here as it is possible to establish or to tune the exact parameters of the controlled processes only during their commissioning.



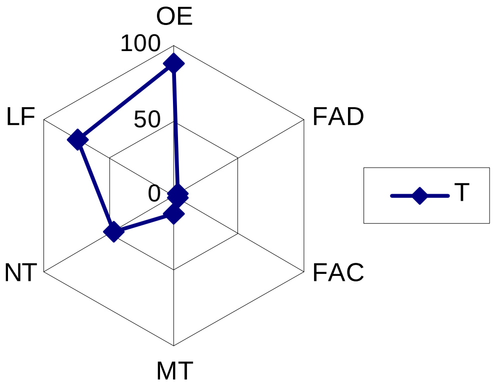

FAD – Factory Automation Design
FAC – Factory Automation Commissioning

LF – Lightfittings
OE – Office Equipment

Production equipment:
MT – Mature Technology
NT – New Technology

**Figure 4. Analysis of human mistakes**

In Fig. 5 the analysis of shortcomings for technical reasons is presented. If the share of **T** is comparatively low, it can be explained by the maturity of the components used, and if it is high, brand new components are usually used. The difference between the reliability of mature and brand new components certainly belongs to the category of bad engineering. The main reason for the outstanding share of technical problems in the **LF** database is the failure of electronic components. The problem is that they are very sensitive to voltage fluctuations. As light fittings are installed in the process of the construction of buildings when electrical systems are still temporary, it is difficult to protect them. The basic reason for the high share of mechanical failures in the **OE** database is either wear or fatigue and the number of electronic failures is growing in older models too.




FAD – Factory Automation Design
FAC – Factory Automation Commissioning

Production equipment:
MT – Mature Technology
NT – New Technology

LF – Lightfittings
OE – Office Equipment

**Figure 5. Analysis of technical shortcomings**

## 3 Human factors in quality management

This research is based on a representative database of the analysis of human shortcomings in the framework of quality management. The 10-year database of human shortcomings was completed where the results of more than 200 production companies' real quality certification processes were analysed. As one can see that the quality management system is fully based on human behaviour, it is appropriate, at first, to go deep into the human activities in the quality management context (see Fig. 6). In the further analysis only the most repeatedly noticed shortcomings are listed.

Product development planning → Design and resource management → Product realization and its analysis

**Product development planning**

- Documentation review
- Management involvement
- Outlining the company's quality policy
- Product strategy planning
- Quality management system's planning
- Management reviews timing

**Design and resource management**

- Provision of resources
- Evaluation of human resources
- Infrastructure deployment
- Work environment review
- IT support and security systems analyses

**Product realization and its analysis**

- Market research
- Planning of product realization
- Design and development
- Production and service planning
- Assurance of technical quality
- Bad engineering management
- Monitoring, measurement and improvement

**Figure 6. Deployment of quality management activities**

In Fig. 7a the statistical analysis of human shortcomings at the product planning phase is presented. In the section of **QF1** the typical shortcomings are as follows: the responsibilities inside the organisation are not fully defined, documentation confirmation path and procedure are not clearly legitimated, absence of the overviews about clients' requirements, etc. Faults **QF2** - valid instructions are not used, the introduced procedures are not followed and there is anarchy in the drawings system. Mistakes **QM1** - inadequate knowledge of legal acts, as a result of which the requirements set up are insufficient and therefore, cannot be followed. Mistakes **QM2** are born on grounds of lack of future perspectives when the current procedures are outdated and better solutions are available.

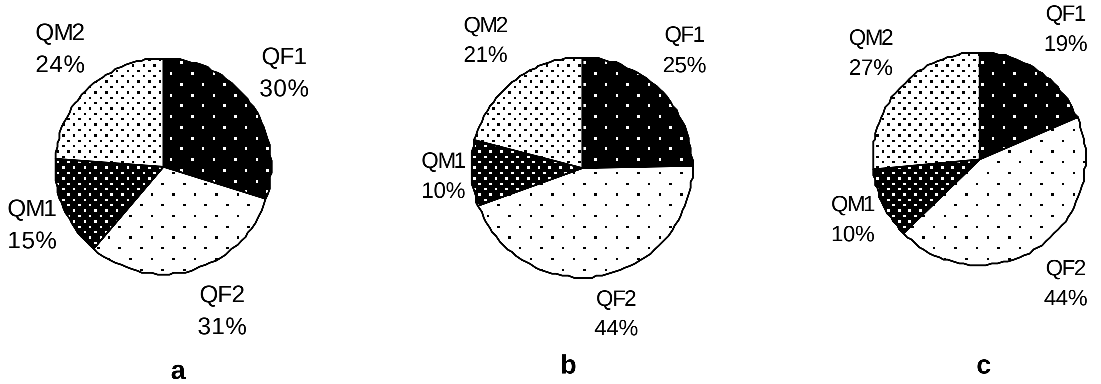



**Figure 7. Human shortcomings in quality management**

In Fig. 7b the analysis of human shortcomings for the product design and resource management phase are shown. **QF1 –** professional instructions do not include qualification requirements, working environment does not correspond to standards, professional training plans are not followed, etc. **QF2 –** personal development talks are not provided, professional knowledge cards are not filled in, safety regulations are not followed, warning signs are absent, etc. **QM1** - misleading warning signs and incompetence in storekeeping. **QM2 –** the existing attestation systems are not used but at the same time new ones are planted.

In Fig. 7c the overview of human shortcomings for the realization and analysis phase is presented. The typical deviations are: **QF1 –** the timing of measuring equipment verification is not established and the real situation is out of control and the client's requirements are not followed. **QF2 –** safety regulations are not followed, internal audits are missed, suppliers' evaluations are not provided, etc. **QM1** - in the procedures there are references to non-existent requirements and conformity documentation is absent. **QM2 –** absence of market investigations, superficiality in the planning of future strategies, absence of risk analysis, etc.

At the first sight, the provided analysis of human shortcomings seems to be too bureaucratic but it opens the full spectre of everyday human faults and mistakes that may lead to very serious problems in case of events coincides. While having closer look at the trends extending over the whole quality management process, it is seen that communication faults are reducing with time and it seems that in the planning phase the behaviour of staff is too chaotic. However, at the same time the faults due to negligence are dramatically growing reaching to half of all the shortcomings in the last phase. The main reason here is the trend to ignore the procedures and standards. The competence level seems to be stable but the mistakes addressed into the future seem to form too big a share of all the shortcomings.

## 4 Synergy-based approach to the quality of engineering design

The goal of the present research is to initiate a framework for the effective use of the information on human behaviour in order to increase the quality of the engineering design and application process. To decrease the effects of bad engineering it is obvious that a meta-approach is needed. In the launched race between research groups to fill this gap it seems that one of the possibilities is to involve a new paradigm – the synergy-based approach to design [2]. The synergy-based approach makes it possible to collect design parameters, market conditions and human factors under one umbrella. Faults in engineering design activities may be treated as a result of negative synergy in teamwork or negative synergy in a person's inner communication.

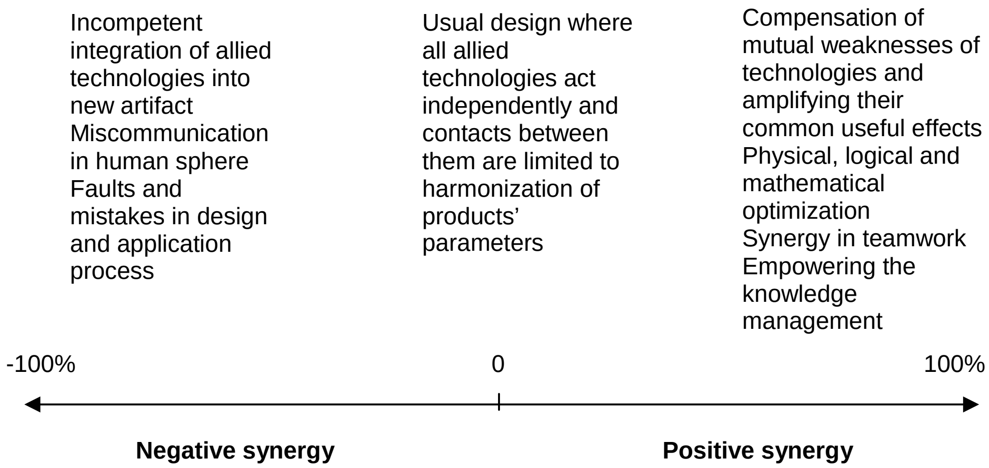



**Figure 8. Deployment of positive and negative synergy**

Firstly though, it is necessary to define the concept of “synergy” used in the present context. The term “synergy” is derived from the Greek word *synergeia* that means collaboration. Linguistically the word “synergy” defines the situation where the summary effect of different factors due to their mutual empowering is greater than their sum. Sometimes it is called the 2+2=5 effect. The essence of the synergistic approach to engineering design and its application is seen in Fig. 8.

However, product quality continues to be the key driver of the product development process and it is shown that the quantitative characteristics of the positive and negative synergy of allied technologies interactions are suitable quality metrics for interdisciplinary systems [4]. However, one must understand that in any design process the main driving factor is the engineer with their experience, inherent faults-mistakes and competence. Bad engineering is possible only through human activities or lack of competence. The main goal of the research into the interdisciplinary systems’ design is to propose methodologies for product development, helping to attain the maximum positive synergy of allied technologies and teamwork at the same time avoiding human shortcomings and to prevent the growth of the negative synergy. Sometimes we have noticed a critical attitude to the possibilities of the synergy-based approach to engineering design accenting on its speculative nature. But in the same way we reach to the negotiation of the training principles in sport or in other professional training which have a final goal to achieve a maximum synergy of physical and mental capabilities.

At first sight it seems that in case of quality assurance of engineering design we have to choose between two classical ways – either the prescriptive/administrative or the descriptive/case-based approach. In fact, we need there should be an interactive and adaptive design environment between them. On the prescriptive/administrative side the results of the present research may be used for reduction in human shortcomings, especially faults in human behaviour. The most important problem here is how to improve the synergy in teamwork to avoid the faults based on mutual communication. Nowadays information technology offers better on–line communication possibilities for dispersed teams and over time the share of this type of faults has to decrease. It is absolutely necessary to run a dated database to so that all of the changes made in the systems would reach all of the people involved. It is possible to reduce most human casual negligence faults by checking the design process continuously using special design-checking tools, which help to uncover the most common deficiencies. At the same time the upgrading of the professional level of the personnel and taking unpopular measures to increase the responsibility of the personnel are appropriate. On the mistakes side most of the problems are caused by lack of competence. To the newcomers in the automation area of different technologies it is recommended to rely more strongly on a consulting service in the beginning. Special attention must also be paid to the continuous upgrading of the personnel. It is the most difficult to reduce the mistakes due to the state-of-the art of the used technology. At the same time these problems form a springboard for further research. Despite all the efforts it is usually impossible to avoid all negative synergy effects and it is necessary to use the change management approach during the follow-up product development.

However, there is another possibility to use the received information – to help the engineers to find a more optimal way to use their capabilities avoiding human shortcomings. In the context of the complex systems design, the DSM is a tool, which enables to monitor of the interactions when it is organised on the information flow-scheduling basis [5]. It is comparatively easy to involve quality and synergy parameters in this system. As a result, we are able to identify the independent tasks, their interfaces and natural groupings and optimise their order. On the product and organisational level it is possible to show complex interactions between product components, their design process and supporting organization to form a capable development team structure [6].

The successful separation of human and technical aspects at the design and application of systems opens up new possibilities to move ahead on the way of their synergy-based design. By integrating the technology of Design Structure Matrixes [7] and the Theory of Domains [8] it is possible to involve time and competence dimensions in the design methodology. In other words, it is possible to develop a family of adaptive design tools based on the level of competence and expert knowledge of the design team and to synthesize their own roadmap algorithm to move ahead on the way of synergy-based design [9]. This integration scheme seems to be positioned between the areas of descriptive and prescriptive design models. The proposed model makes it possible to take into account both "soft " parameters of design - the market conditions and human aspects. The main contribution will be the introduction of an additional synergy dimension for integration. The synergy dimension is introduced to the DSM in the form of the evaluation of its integration power in parameters and processes on a 3-step scale. By the transformation of the DSM matrixes it is possible to solve product architecture problems and also resolve the scheduling of processes. In this process, the statistical probability evaluation of the time for iterations, reworks and learning may be used [5].

Synthesizing a design team's own roadmap algorithm to move ahead in the design process makes it possible to realize negative synergy filtration principles and to reach the optimal synergy level set by the market in minimal time. A full exploitation of the possibilities of the proposed approach requires an experienced professional team and provides significant returns for a complicated system. It is highly qualified and time-consuming to compose a useful and suitable DSM matrix, and this may be a great challenge to the design team. Thus, simultaneous professional knowledge of product architecture, the product development process and organizational work is required. The low competence of the design team results in an imperfect DSM where some important interactions may be absent or incorrectly evaluated. However, it is obvious that teams with a different competence level cannot develop products of the same quality. Yet, the main task of stepping up the synergy level of allied technologies is to reach the market-driven performance with minimal possible expenses on product development and production.

## Conclusions

The most important contribution of the present paper is to give a true picture about human shortcomings in the design and application of engineering systems to both industrial and academic people.

In the launched race between research groups to integrate human effects and market conditions into design methodologies the synergy-based approach to engineering design seems to be a valuable contribution. It is proved that all substantial parameters in the design process, including quality, reliability, human aspects and competitiveness can be expressed in the synergy-based manner. It is shown that the formation of the negative synergy effects is the lack of synergy in teamwork or in a person's inner communication.

A conviction has been reached that the proposed close interrelations between quality and synergy indicators in the product development process are an obvious reality. In the line of usual quality characteristics positive and negative synergy are suitable quality metrics. It is pointed out that optimal quality and synergy are not only a technical problem but also a market driven one.

The successful separation of human and technical aspects at the design of interdisciplinary systems opens up new possibilities to move ahead on the way of their synergy-based design. It is shown that the integration of the structure matrix technology and the theory of design domains form a most suitable basis for the synergy-based design and it allows it to form a hybrid platform between prescriptive and descriptive approaches to design methodologies. In other words, it is possible to develop a new family of adaptive design tools 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 synergy-based design.

Finally, the conclusion has been reached that the synergy-based approach to engineering design is a good chance to avoid bad engineering and to raise the quality of engineering design.

**Acknowledgements**
The authors of the present paper would like to thank the Estonian Science Foundation for their kind financial support to the project 6190 “Structural-Matrix-Based Methodology of Product Development to Attain the Synergy of Allied Technologies”. Special thanks belong to Prof. M.M. Andreasen from the Technical University of Denmark for inspiring discussions on human action synergy issues and to M. Veveris at the University of Derby in England for valuable linguistic advice.

**References**

[1] Robotham A. J. and Guldbrandsen M., “What is the New Paradigm in Product Quality?” *Proceedings of International Conference NordDesign´2000,* Denmark, Copenhagen, DTU Publications, 2000, pp. 149-157.

[2] Tähemaa T. & Reedik V. “Prognosis of Competitive Dependability of Mechatronic Products”. In *Proceedings of 13th International Conference on Engineering Design ICED’2001, Design Methods for Performance and Sustainability,* WDK28, Professional Engineering Publishing, London, 2001, 3-10.

[3] 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, Turkey, 2004, 147-157.

[4] Hindreus T. and Reedik V., “Quality dimension in Complexity Management of Product Development Interaction Patterns”, In: *Proceedings of International Conference NordDesign’ 2002,* held in Trondheim, Norway, August 14-16, 2002, Norwegian University of Science and Technology, 2002, pp.129-136.

[5] Cho S.-H. and Eppinger S.D., “Product Development Process Modelling Using Advanced Simulation”. In: *Proceedings of, ASME Design Engineering Technical Conference DETC’01,* held in September 9-12, 2001 in Pittsburg, Pensilvania, USA, pp.1-10.

[6] Eppinger S.D. and Salminen V., “Patterns of Product Development Interactions”, *Proceedings of the 13$^{th}$ International Conference on Engineering Design, Design Research – Theories, Methodologies and Product Modelling,* London, UK, 2001, pp. 283-290.

[7] Malmqvist J., A “Classification of Matrix-Based Methods for Product Modelling”, In: *Proceedings of Design-2002*, Dubrovnik, Croatia, 2002.

[8] Hansen C.T. and Andreasen M.M., "Two Approaches to Synthesis Based on the Domains Theory", In: *Engineering Design Synthesis*, Springer-Verlag, 2001.

[9] Kaljas F. and 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),* held in August 15-18, 2005 in Melbourne, Australia, Institution of Engineers, Australia, pp.498-499.